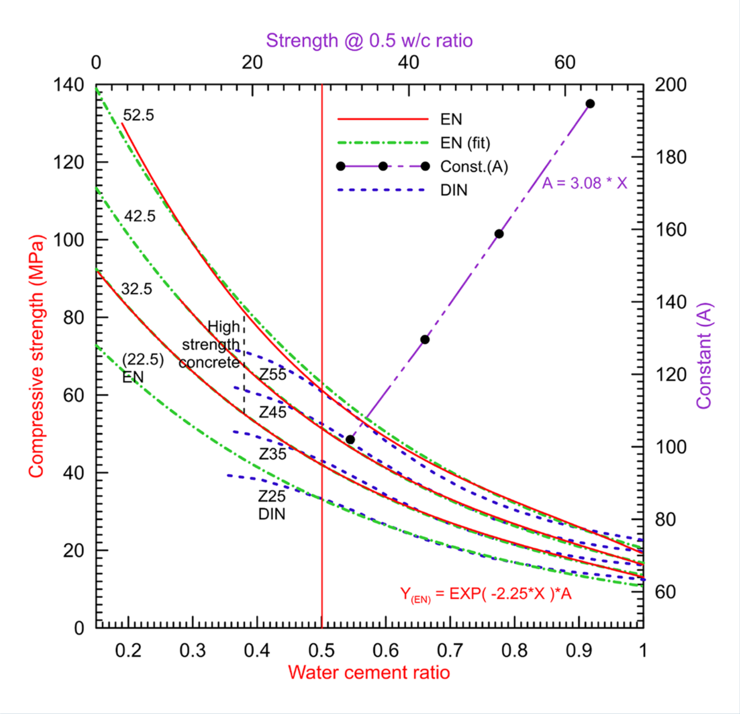
MATHEMATICAL MODELING OF CONCRETE MIXTURE PROPORTIONING



GANESH BABU KODEBOYINA

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Preface

Concrete as the material of construction has undergone phenomenal changes over the years, making it invariably the most preferred economic and high performance material of construction with significant possibilities to ensure a very high sustainability. Incidentally, many of these modifications have often been touted as entirely new materials, in spite of the fact that the constituents and overall design philosophy has always been derived from the design principles of the so-called normally vibrated concretes already available for over a century. Under these circumstances, it is only obvious and prudent to look at the design principles involved in the formulation of normally vibrated concretes comprehensively before attempting to understand the essential modifications required for obtaining the different concrete variations proposed. The present effort is essentially a step toward this objective, involving a critical analysis of the various design principles enunciated by the different national bodies over the years, while trying to discern the way forward for making concretes of high performance and sustainability.

The importance of the need for a reasonable first estimate of the strength of concrete for structural applications is well recognized, even though it is recommended that the resulting design strength be proof checked for its compliance in all respects at the very start of the project. There have been several attempts toward such a design methodology based on an understanding of the guiding principles, be it the water cement ratio to strength relationships, the water content requirements from the wetted surface area considerations, or even the packing density of the aggregates constituents in the system. Mathematical models have also been proposed to further each of these criteria, starting with some very simple proposals to those that are highly complex in their formulation. In fact, it is probably most appropriate to modulate the approach, whatever be the mathematical model adopted, with a reasonable level of experimental verification and appropriate correlations. Incidentally, the semi-empirical approaches proposed as a part of the various national recommendations, the American, British or the European, appear to have all evolved from such a verification of the fundamental relationships by several different organizations and researchers. It is in this context that this effort tries to focus its attention on the various methods suggested by these national bodies explicitly. It was also felt appropriate to have a direct grip on the results obtained from the various formulations of these national bodies in the form of suitable nomograms so that one can have a first-hand understanding of at least the basic mix resulting from these for a comparative understanding if necessary. It can also be seen that most of these recommendatory bodies appear to resolve the performance requirements through specific limitations on some of the major parameters like the maximum water cement ratio, the minimum cement content, the maximum chloride content in the constituents, the maximum cover to reinforcement, etc. A few of these aspects, their relevance as well as the need for a possible reassessment of the present status, was also attempted.

It is also obvious that the various national recommendations available presently are primarily directed toward the design of normally vibrated concretes. In recent times, most of the newer cementitious compositions have also had their proponents suggesting explicit design methodologies, which are vaguely similar, but yet are apparently shown to be categorically different form the normally vibrated concretes. In view of this, it is felt that there is a need to establish a common thread between the available recommendations for mix design of the normally vibrated concretes and the more modern alternatives consisting of essentially the same primary constituents. It is also to be emphasized that such an effort should critically consider the requirements of performance and sustainability of the concrete compositions at the various strength levels, to ensure the appropriateness and economy of their use.

In brief, the book essentially is an attempt to look at the broad domain of the available knowledge in its appropriate perspective, starting from the very basic and fundamental aspects of concrete mixture design and its modifications over the past century. It also presents an overall perspective of the present status and modifications possible to ensure high strength, high-performance sustainable concrete compositions for the different applications in the various environmental regimes. The book also offers an insight into the possible relationships that enforce a reasonable understanding of concrete mixture design and has something to offer to a student, a researcher as well as a professional in the field.

Acknowledgments

There have been several efforts to model appropriately the design of normally vibrated concrete mixtures in general. However, the need for a methodology that could recognize effects of the various newer constituents that came into practice in recent years in concrete mixture design is obviously the need of the hour. It is probably necessary to have a critical understanding of the design philosophies propounded by the various national bodies for normally vibrated concretes for a possible integration of the newer concrete compositions effectively. The author relies on the abundant past research efforts that undoubtedly explains many of the facets of concrete mixture design starting from the conventional concretes for general-purpose applications to the ultrahigh strength high-performance cementitious compositions of the recent times.

It is only natural that in this quest for an understanding of the concrete mixture design panorama, the contributions of several individuals at various stages were obviously a great help. In the first place, I should be highly thankful to my teachers and mentors who always pointed me to look in the right direction. In fact, it was a privilege that I was always received with open arms by several distinguished personalities in concrete technology and science, who were more than willing to spend time in explaining the intricacies of the concrete behavior over the past four decades. It may not be possible to individually list each one of them who helped me in this effort, but from the bottom of my heart I thank each and every one of them for their compassion and tolerance in replying to several of my queries.

I should also gratefully acknowledge that it was an honor to be a fellow of the Alexander Von Humboldt Foundation, which helped me to not only interact with several eminent professors and researchers from the German universities, but also facilitated learning the German language so that I can have a direct understanding of the literature published apart from being a member of their research and social community. Some of the basic axioms and intricacies in the adaptations of concrete are hidden in the earlier literature that was largely published in German, and for individuals educated through the English medium, there is only a limited possibility of getting to know them.

Also, over the last four decades, it was indeed a pleasure to be research advisor to a very large group of students at all levels, who during their research efforts inadvertently posed several intriguing questions that need be answered. Some of the information presented in this particular book went through several iterations of refining and reorienting the facts by many of them at different times to be put in its proper perspective.

I am indeed thankful to all of them for their untiring efforts to do all that was required even if it was a repetition of what was done earlier by me to start with.

Finally, I am extremely happy to express my deep sense of gratitude to my family, my wife Devi, daughter Deepti and son Srikanth Aditya, for their support and love during my quest for knowledge over the last many decades.

Author

Ganesh Babu Kodeboyina has been a Professor of Structures and Materials in the Department of Ocean Engineering at the Indian Institute of Technology Madras for over 35 years. His passion for teaching and research in the areas of offshore and coastal structures; materials in marine environment; high performance cement and concrete composites; durability, corrosion and rehabilitation of structural systems; and residual life assessment apart from fiber reinforced composites of both cementitious and polymeric nature including UHPCs endeared him to both students and industry professionals. Naturally, he was a retainer consultant to some of the largest cement industry giants as well as construction chemicals and repair materials manufacturers, both for evaluating the performance of the cements and composites produced by them and for their appropriate utilization in construction and repair and rehabilitation activity in field. He single-handedly put together and was the head of an exceptionally comprehensive Structures, Materials, Applications and Rehabilitation Technologies (SMART) laboratory in the department, which produced excellent research output through the very large crop of his several masters (both MTech and MS by research) and doctoral students.

He was also the Director of the Central Building Research Institute (CBRI), Roorkee, a constituent laboratory of the Council of Scientific and Industrial Research (CSIR) of Government of India for a few years. His emphasis on preservation of ancient monuments, while being at the forefront of R&D of today, made sure that the one and only available double shell structure in the world, originally conceptualized, designed and built by none other than the first director of CBRI, Prof Kurt Billig, was completely refurbished from almost ruins to the present day display center of the CBRI. This facet of his passion also endeared him to the Archaeological Survey of India and others, seeking his advice and the assistance of his laboratory for several problems that are associated with the World Heritage structures like the Taj Mahal, the Sun Temples of Konark and Katarmal, and Red Fort, just to name a few.

Prior to his almost lifelong stint at IIT Madras, Prof. Ganesh Babu worked as a scientist at the Structural Engineering Research Centre (SERC) of the Council of Scientific and Industrial Research of Government of India for about six years, immediately after his PhD. There he was coordinating research in several areas, like large diameter prestressed concrete pipes, concrete technology, fiber reinforced concrete, ferro-cement, and also established the polymer concrete laboratory through UNDP assistance. He was a consultant to the National Highway Authority of India for proof checking the several prestressed concrete bridge designs throughout the country, repair and rehabilitation of several large bridge structures, design and repair of important port and harbor facilities apart from being a committed teacher and a research worker. His research efforts resulted in the production of very high strength, high-performance concretes of about 120 MPa with almost all available pozzolanic admixtures like fly ash (from first field), silica fume, GGBS, metakaolin, RHA, and zeolite etc, in concrete. This was achieved through an assessment of the cementitious efficiency of the pozzolanic admixtures in terms of their general efficiency and percentage efficiency factors defined by him, enabling the prediction of the strength of the concretes at the different pozzolanic replacement levels possible.

His studies on the design and thermal cycling effects on heavyweight concretes for nuclear applications like prototype fast breeder reactor (PFBR), and the rehabilitation, residual life and life extension assessments for fast breeder test reactor (FBTR) at Kalpakkam are certainly noteworthy. His work on the corrosion of galvanized reinforcement as a part of the multinational research effort of the International Lead Zinc Research Organization (ILZRO) was highly acclaimed by the industry. Also, his contributions to high-strength high-performance concrete composites and performance, durability and corrosion of steel and concrete apart from fatigue and fracture mechanics of fibrous composites have been published in several national and international journals and conferences providing ample testimony to his understanding of the intricacies of these materials and structures, both on land and in the ocean space. He is presently an active consultant and is also a Professor at the Mahindra École Centrale, Hyderabad.

1

Concrete and Modeling Concepts

1.1 Concrete—The Material

Concrete has been serving humanity as a material of construction in some form or the other from time immemorial. A look at the broad spectrum of progress in the production of concrete, like compositions and the various facets of their more recent modulations in trying to cope up with the requirements of sustainable construction, is highly fascinating. In a way, the present day concrete science and technology can be attributed to the seedlings of our ancestors in the eighteenth century, which was advanced and nurtured by the efforts of the nineteenth century investigators, culminating in phenomenally rapid advancement during the twentieth century. A lot of it can also be attributed to the influence and urgency in housing and infrastructure needs during and immediately after the two world wars. Apart from this, though concrete was the largest produced construction material and its use is considered to be one of the benchmarks of the standard of living of a community, it was often branded as a material of the past several times during its long history. However, its resurgence in many other forms and modifications, apart from the extraordinary progress made in its strength levels, always endeared researchers to look at it with fascination, if not admiration. There are also several other aspects that are often not so clearly understood even in its conventional utilization form, wrongly identifying it to be the primary culprit for all the inadequate and inappropriate practices adopted. This reinforces the need for a proper understanding of the design, production, transport, placement, curing and maintenance of the various concrete alternatives possible and their utilization potential for the vastly varying needs of society today. In addition, if appropriately deliberated and judiciously adopted, concrete has several advantages over its nearest rival, steel, with the different possibilities it offers, particularly the inexpensive maintenance and substantial lifespan of structures built with it.

The general perception of the professionals involved with the formulation, production and processing of cementitious composites like concrete is that with the substantial variations in the characteristics of the constituents as well as their quantities and distributions in the structure, it is not possible to put together a mixture design methodology even for the most basic strength parameter. It is indeed for this reason that the recommendations of most national organizations presenting the concrete mixture design methodology opine, suggest or insist that the resultant design should be appropriately modulated through trial mixes before its adoption in field. Naturally, if this was to be the status of knowledge or the efficacy methodologies being presented, one should presume that the idea of even attempting any mathematical modeling is evidently not even meaningful. Notwithstanding all this, there have been several efforts to bring about a semblance of clarity and order through various techniques into this aspect.

Concrete as a material of construction has made a huge difference due to the possibility of being able to essentially utilize local materials as a bulk of its content. Also, though the primary constituent, cement, is factory produced, the fact that it can be used by local artisans even with a very limited skill set makes it the choicest material for most construction. The complexity of the concretes required for the more intricate and demanding requirements, however, need an in-depth understanding of their production, transport, placing, curing and maintenance. Essentially, concrete is a conglomerate in its true sense, and in attempting to devise methodologies of arriving at the best stone-like mass, one could look at the examples of the different natural processes that led to the formation of the conglomerate itself. In a conglomerate, one could see that the different constituents have to be appropriately packed to ensure that the final fused mass due to the chemical, thermal and pressure effects over time result in the different possible strengths of the composite stone mass, varying from very high strength sand stones to the highly porous and fragile laterites that exist. Another aspect that may be of relevance in this context is to note that while the hardest of sand stones are in general fused mass of highly siliceous agglomerates formed under temperature and pressure, laterites are weak and mostly fragile masses of iron and aluminum oxides. This in a way shows the contribution of the basic constituents and the effectiveness of the binder in the final product, which probably is a good guiding principal for ensuring the appropriate characteristics in the case of concrete as well. In effect, the constituents of concrete have to be appropriately chosen and compacted to ensure a defect free system which, after the effects of hydration, could have the highest strength possible. Incidentally, it is clear from the above that neither just an effective packing nor alternatively an efficient bonding mechanism alone will ensure the highest strength. Herein lies the principal that it is actually the density and porosity that dictates the strength of concrete. One should also recognize the fact that it is the continuity in pore structure, which allows the permeation of the environment into the concrete mass, that is responsible for the deterioration and durability of the concrete composites.

The idea of bringing together even some of the widely varying thought processes of several research workers over the millennia or even attempting to comprehend all that has happened over the years even in the limited arena of concrete mixture designs is a daunting task, or to be more precise, next to impossible. However, it would probably be more appropriate and cohesive to look at the underlying principles that have guided the development of the concrete composites in general. Obviously even in such an endeavor, probably it is only possible to look at the broad perceptions of the individual research attempts and the processes that dictate the recognition of the various concepts. Needless to say, there are several different possibilities and paths that could be directing the way for the ultimate objective of being able to arrive at a logical conclusion and also project a broad perspective of what lies ahead.

1.2 Historical Developments

In an apparent answer to the self-generated question about the service life of concrete, Kanare (2009) suggests 9800 years as a possibility, reflecting on the building concrete floors at Yiftahel—a pre-pottery Neolithic culture unearthed in Israel. Studies on these floor samples show that they were made from calcined limestone combined with sand and stone aggregate, similar to present day concrete, with the limestone being completely carbonated and achieving a concrete strength ranging from 4900 to 6500 psi. It is apparent from the investigations that the civilization had sufficient knowledge of calcining lime for cementitious purposes and also producing different mixture combinations, clearly showing the rough porous base layer and dense bright white sanded finish coat. It was also opined by some that the reactions between oil shale and limestone during the crustal formation in Israel appear to have resulted in the formation of naturally occurring cementitious compounds.

The fundamental concept of cementitious composites is essentially very simple, driven by the requirement of having to bind the inert and appropriately graded aggregate and filler matrix through the cementitious binder paste. The concept in itself is nothing new and owes its existence from prehistoric ages of times immemorial where in the use of simple mud mixed with clay initially for stone walls which later was translated into the use of lime and even lime volcanic ash combinations for various Mesopotamian and Babylonian constructions of over 10,000 years old and much later Egyptian and Roman structures dating back to about 3,000 years. There have been several modifications of these initial principles of understanding of how to accommodate a maximum amount of inert filler materials while utilizing the least quantity of binder that is needed, as the binder is the one that needs to be specifically processed and thus becomes the most expensive of the entire cementitious composite.

1.3 Concepts of Modeling

Model by definition is a representation of an object or a concept, more often used to present it in a scale smaller or to depict it in a format that allows the visualization of the same from afar. Models could be direct visual representations of the object in the form of physical entities, drawings or sketches or could even be highly abstract representations of the concept. Most noteworthy of these are ancient scripts as in cuneiform writings or even the more modern scripts of certain languages that could be traced back to similar beginnings without having transformed or mutated into more accommodative scripts by themselves or through their transfusion with some others.

In the domain of structural engineering, physical scale models are often utilized to investigate the characteristics of materials, members and even structural systems. The modeling process is often defined by the requirements of the parameter that is being investigated. The use of models of half scale or smaller using actual materials in the structure or models of several orders of magnitude smaller using micro-concrete or even polymeric (acrylics or epoxy) materials was also adopted for simulating certain characteristics, essentially the stiffness. Acrylic models used to understand the stress distributions through fringe patterns as in photo-elastic experimental stress analysis techniques have been adopted successfully.

Comprehensive modeling of materials such as concrete, which is actually a composite, is often highly complex. Most often attempting to model the effects of size of the member, size of ingredients like aggregates, which will have an effect on the distribution as well as the microstructural properties of the interface, apart from the number of discontinuities that could affect overall behavior of the structure, particularly in terms of the failure characteristics, is a utopian task. At this stage, it is not proper to introduce all these parameters without an understanding of their existence and implications appropriately. It is enough to say that there is a phenomenal amount of research and discussion on the specimen size, making and testing for even establishing the simplest and most often considered the representative parameter, the compressive strength of concrete. This being so, a simple and yet representative mathematical model of the behavior or even the mixture design methodology for a concrete of a specified strength appears to be almost impossible, but yet attempted by several researchers through several different avenues, probably depending upon their experience and perception. The simplest of such efforts is just to relate any two specific engineering parameters through mathematical relationship, most often through a specific but yet in most cases a limited experimental investigation.

In this context it is only appropriate to recognize that many of the earlier interpretations of strength behavior of concretes is based on traditional experience and parameters that are probably generated as a part of broad spectrum of scientific knowledge. Even so, many of these have been time tested and give an insight into the fundamental mechanisms of concrete strength development of time. The volumetric proportions proposed earlier are indeed some part of such efforts to define the behavior of concrete in simple terms. Later efforts to understand individual constituents and the cement particularly have led to better understanding and interpretations of these traditional theories, which saw the use of scientific knowledge generated from experimental investigations into an understanding of concrete behavior. Naturally, methodologies which utilize reorganization of the experimental investigations through process like the design of experiments to evaluate a limited set of complex interactive parameters have come into existence for this purpose. However, overemphasis on simple constituent qualities or quantities for defining such design of experiments have resulted in erroneous if not highly myopic views on the behavior of concretes and their extended family of materials containing supplementary cementitious materials. Another group who are more at home with the theoretical and mathematical solutions has gone to apply the scientific axioms essentially generated for an entirely different scenario into an interpretation of concrete characteristics with limited success. Many of these methods present the behavior of concrete as a bound medium of particulate material with some interface. Analytical tools to visualize and discretize the distribution of particulate matter of different sizes in a medium is one way to look at the evolution, while a more global binary constituent materials behavior is the other extreme. Apart from all this, direct application of the effect of the different constituents through well-known mathematical solutions like partial differential equations, expert systems, fuzzy logic or even neural networks and combinations thereof have all been attempted and reported. It is certainly not possible to present this entire gamut of information in the simple topic of concrete strength behavior alone (without even looking at the possibility of understanding its durability and performance in the different environmental regimes) is a herculean task and probably will not serve any useful purpose other than being able to just be a rigorous compilation if at all.

1.4 Concepts of Mathematical Modeling

Mathematical modeling as accepted in recent times in simple terms is an effective representation of a process based on certain accepted and fundamental relationships that drive it. The need for such a representation was obviously felt by the scientific and engineering communities specifically to be able to predict outcomes without having to go through physically the entire investigation or experimentation involved in the process. Conceptually, in the most fundamental terms, mathematical modeling could simply mean a representation of the relationships between two parameters in the form of a graph or an equation.

In an effort to mathematically model engineering processes particularly, researchers have adopted several different avenues, each of which have their own positive and not so positive effects in predicting the process. One of the first limitations and one can say is probably the size and representative panorama of the sample as many look at, which is often really the most obvious limitation. The second aspect that needs real clarity is regarding the representative parameters selected for establishing these relationships, which on several occasions appear to be arbitrary and without consideration to the known factors relating these. In a nutshell, the entire mathematical modulation of the modeling process can be described by a modeling tree presented in Figure 1.1. This can be explained briefly

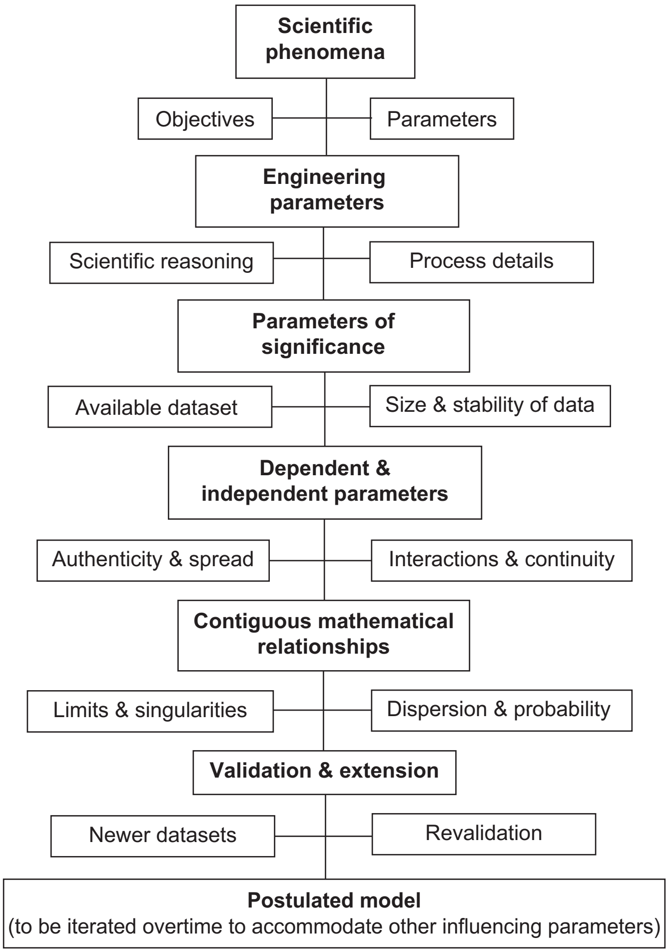

FIGURE 1.1
The outline of a modeling tree.

by the following few lines, which attempt to touch upon the major requirements to ensure that the processes are reasonably sound and could result in an appropriate solution.

In the first place, there should be a clear understanding of the scientific processes that are the backbone of the resultant effect. The parameters that control the scientific process and their relevance to the various branches of the resultant effects have to be enumerated first. From amongst these parameters, the dependent and independent parameters and the order of dependence have to be understood. At this stage, probably it is best to look for a dataset that has the spread and range to depict the process in full has to be chosen, while ensuring the authenticity of the dataset itself. It is not always possible to look at a dataset that has an overarching capacity to depict the entire process and the full range. Naturally, it is best to specify in advance the limitations in terms of the applicable limits as well as any singularities that could be an actual characteristic of the process. One can also establish the interactions and connectivity between different subsets chosen from the dataset if one wants a more accurate recognition of the factors representing specific aspects that depict the process. At the same time, one also has to recognize the fact that some of these parameters change with time, temperature and other environmental factors. These have to be incorporated appropriately in the subsets if possible so that the objective of establishing the right perspective through mathematical modeling is not corrupted due to the extraneous variables that were not appropriately accounted for.

Once the range validity and the acceptability of the dataset required for an understanding of a specific aspect is ready, it only remains to ensure that the mathematical formulations are appropriate to depict the process. Also at this stage, while it is always possible to look at the various trends and mathematical simulations possible, it is necessary to record and ascertain that the variability of the proposed prediction equation is not too high. The correlation coefficients and the probability levels of variation should be limited to values as low as possible, and it is even suggested that these are appropriately recorded. Only then can one say that they have established a corresponding coherence between the proposed mathematical model and the process that it represents. Only after such a validation could one be satisfied that there is an appropriate representation of the process.

The last part of the mathematical modeling process is to look at the validity of the model, both in terms of the changes over time in the internal parameters and in terms of the available datasets from other sources that represent the same process. This means that there is a need for additional data either from within or from external sources (in fact preferably the external sources) to ensure validation of the process detection through the existing mathematical model. It is possible that sometimes there is a need for additional parameter identification, which must be incorporated into the method to ensure that it represents a broader perspective. Another important factor is that while doing so, either the initial mathematical model or the revalidated model need not necessarily represent the mean values alone with the possible percentage variation acceptable on either side. It is possible that one could propose simply a near lower bound approach to be on the safe side. Alternatively, one could even suggest the near upper bound formulation to ensure that the effort is to achieve the highest possible outcome in the process, particularly through better control over the various constraints on constituent process. In any case, once such a representation is proposed, it is necessary to actually state both the reasons for such a decision and the constraints that must be reinforced to ensure that the highest possible outcome is achieved. It may not be inappropriate or out of place to state at this stage that this book in fact utilizes some of the concepts as proposed and discussed in the above paragraphs, and one can clearly see the benefit of such an approach.

The mathematical modeling approaches can be broadly subdivided into three fundamentally different types:

- Deterministic models—defined by the fundamental laws of nature as in science,
- Probabilistic models—often dictated by the human perception as in commerce, and
- Deterministic-probabilistic model—which is a combination of both.

Several of the problems associated with the present-day need for an understanding of a highly complex nature with intricately interdependent parameters is that many times they are not clear either by themselves or in their dependence. Such a highly complex situation naturally needs a broader conceptual and phenomenological understanding, which can later be broken down to simplistic and more readily quantifiable sub-platforms. Each of these sub-platforms could then be analyzed by two different methodologies based on either known relationships or perceived conjugations possible and could be in forms such as:

- Purely empirical relations,
- Semi-empirical formulations, and
- Characteristically definitive or unique relationships.

All these can be mathematically modulated into appropriate equations for direct application. This is because, in the realms of engineering, it is always an effort by the researcher to bring it down to an understandable two-parameter system that can be depicted in the form of a simple table, a graph or maybe even sometimes by a definite mathematical equation.

During the initial efforts of modeling, a very large effort was placed on the dimensional stability of the model in terms of the fundamental units.

Particularly in structural strength evaluations, the similitude laws that were enforced were more directed toward the stiffness and moment of resistance rather than simply modeling purely the dimensional characteristics of the member. Simultaneously, efforts are always on to ensure that the mathematical formulations developed were also dimensionally stable before any such postulations. However, this approach was not always possible, and many a time this aspect is given a go by, suggesting that the formulation is simply empirical. This obviously means that the internal mechanisms of how the different properties on either side of the equation are related was not understood or cared for, and in an effort to make it look dimensionally stable, a few constants involved are introduced with attributed dimensions for stability. These are known as the purely empirical relationships in practice. It is possible that in a few cases part of the reasons for such correlation may be understood through some part of the complementary parameters that exist, yet it may not be possible to fully ensure that the equation is dimensionally stable. Such formulations are called semi-empirical relationships, which are often the most adopted in engineering practice.

However, while dealing with highly random processes like vibrations, fatigue, or oscillatory fluid flow as in wind and wave characterizations, it is probably very difficult to put the transient characteristics into their correct perception. In these cases, one of the simplest methods is to look at methodologies for understanding the response characteristics in terms of certain estimated forces through averaging techniques such as moving averages (MA) or auto regression (AR) or even auto regression moving averages (ARMA) models for local response. However, an understanding of the larger global response is only possible through statistical evaluations through probability methods such as Gaussian or normal distribution, Raleigh distribution or some other distribution characteristics that they may exhibit. Some of these methods of depicting the variabilities in specific parameters help in reducing the complexity while maneuvering through the complex characteristics of the different parameters in mathematically modeling the process itself, by reducing its apparent divergence.

In the actual practice of scientific domains (natural atmospheric sciences, life sciences and material sciences) or human psychological domains (behavioral sciences, trade and economics), the complexity of interaction between the various cohesive yet contradicting requirements of the understanding of the parameters makes it highly difficult to have definitive relationships that can simply boil down to similar mathematical equations. These complex systems are often investigated through a set of simulations that could represent a part of the whole, facilitating the possible simplistic solution. The simulations could be in the form of experimental investigations or argumentative perceptions of different individual viewpoints, simulating either the whole problem or a specific segment of it with several of them complementing to establish the whole through an appropriate integration of the different segments.

Most often, the evaluation of these systems is driven by datasets specifically looking at each of these coordinated dependent parameters, which would be put together and later reanalyzed to arrive at an understanding of the complex system itself. The mathematical models for each of these procedures are typically outlined in several mathematical and, in more recent times, maybe even in computer program modules like:

- Ordinary differential equations,
- Partial differential equations,
- Linear programming,
- Non-linear programming and
- Finite element formulations.

These mathematical approaches such as solving the different relationships depend primarily on the complexity of the dataset and a number of parameters, along with their grouping and related evaluation priorities assumed and set.

- Techniques such as regression analysis, fuzzy logic and neural network approaches can all be used in defining these relationships.

Even while looking at such relationships the efficacy and the accuracy of each of these relationships are also established using statistical concepts—starting from simple regression coefficients to the more complex error analysis procedures.

In general, the entire formulation for the evaluation of any scientific or engineering system is by and large a continuous process of evolution, with several individual researchers following different routes and varying mathematical approaches, depending upon their own understanding and sometimes their availability or individual familiarity. There is often a lot of discussion about the suitability of each of these formulations as well as the mathematical modeling methodologies, but seldom there is any concurrence amongst these various researchers regarding the appropriateness of one over the other. Maybe it's not inappropriate to recapitulate the statement of a Popovics (1998) at the start of his book,

> Always use the method that works best.
> Whether it is scientific or empirical or in-between,
> that is secondary

This in the opinion of the author is probably the most important and is also the guiding principle in most of the formulations reported as a part of this book. It is also important to recognize that there is already a considerable amount of literature available on the topic by several eminent researchers over the past hundred years, even if one were to try and limit the understanding of the methodologies involved in the design of concrete mixtures to the present day context alone.

In an effort to have a fix on the parameters that influence concrete mixture design, several alternatives suggested earlier have been attempted, postulated and published. In line with what was proposed above, the total formulation of an appropriate methodology to understand the parameters that influence primarily the strength characteristics of concrete mixtures are seen through a set of directly related characteristics.

1.5 Fundamentals of Mixture Design

Concrete essentially is considered as a part of the composite with this cement paste coating the aggregates and binding them together to form a rock-like mass. Because the most expensive material is the cement, it is only prudent to minimize its quantity and ensure that the remaining aggregates nearly fill the void spaces appropriately, resulting in a dense matrix. It is thus a fine balance between cement paste required to bind and the most appropriate gradation of aggregate to fill in the form with minimum voids. In effect, the use of the two components must be optimized appropriately to ensure the highest strength possible for a given set of constituent quantities. In most mixture design procedures, strength is the most important design parameter (which probably also governs the performance to a certain extent), and the water cement ratio to strength relationship is well accepted. It could also be seen that the water content in the mixture depends upon the finer fractions in the mix, or the total wetted surface of cement and aggregates involved. The simplified way to look at this is to specify a water content based on the maximum aggregate size, ensuring that the distribution of aggregates is only appropriate for arriving at a dense matrix. Naturally, the grading distribution of aggregates is also an essential component of the mixture design.

These fundamental guidelines have over time evolved into the various national recommendations for concrete mixture design. It is only appropriate to look at these individually to get an insight into their formulation and address how they can be appropriately depicted mathematically. One important observation at this particular stage is to be informed that the concrete mixtures have undergone substantial changes, particularly with the introduction of high range water reducing admixtures as well as supplementary cementitious materials. Another factor that needs attention is that the introduction of the dry process production for cement and more efficient raw meal combinations, pre-calcination and grinding practices of more recent years have made it possible to ensure cements of higher strengths. Naturally, primarily in an effort to capture the market potential, there was an urgent need to evaluate particular combinations, particularly with the newer admixtures, for the specific application requirements in practice. Obviously, there have been attempts to propose design procedures looking at these studies. Also in an effort to have a global understanding, there have been efforts to compile a dataset of the possible matrix constituents and look for abstract relationships through mathematical procedures like regression analysis, fuzzy logic and neural network algorithms. All these efforts and procedures have their own proponents as well as detractors as is always the case. At this point an effort is being made to look at the time-tested relationships such as water cement ratio to strength, and the water requirement for consistency as well as the gradation of aggregates for ensuring a dense matrix on which most of the national and international recommendations are based. However, for the sake of at least contrasting, a few of the other mathematical attempts are also reviewed broadly.

1.6 Design Concepts for Strength

The most fundamental property for which the concrete mixture proportioning is attempted is the compressive strength of the material, this being the parameter used in the design of the structural member. It is thus imperative that the concrete in the structural member should be guaranteed to have this minimum strength at all locations. Naturally, given the possibility of a marginal variation due to deficiencies of the constituents, production, placement, compaction and curing the concrete is designed for specific target strength, depending upon the quality assurance envisaged. It is also known that the water cement ratio to strength relationship is a parameter that defines the strength, and most national bodies have incorporated such a relationship into their recommendations in one form or the other. Having said this, it is to be understood that there is a broad band in terms of the amount of cement (required for coating and binding the aggregates appropriately) and water (required for wetting the surface of both the cement and aggregates) for any concrete at a specific strength. It is this dynamic that essentially poses a question while the designer is trying to put together the most appropriate concrete matrix for a given situation.

Apart from this, concretes of today invariably contain superplasticizers which facilitate a significant reduction in water content (up to about 20%), making it possible to ensure adequate consistency even after such reduction in the normally designed concretes. It is also possible that these could be used, as high range water reducing admixtures facilitate much lower water cement ratios that ensure a significant increase in strength. This allows the possibility of utilizing supplementary cementitious materials (SCMs) to modulate the cementitious contents in the mix, both in the lower strength regions (essentially through low-end pozzolanic materials like fly ash and ground granulated blast furnace slag) as well as for arriving at the very high strength concretes (utilizing the significantly higher end pozzolanic materials like silica fume and calcined clays) have taken root in the concrete industry today. The specific modulations required to incorporate these finer fractions with varying cementitious efficiencies invariably necessitate additional water for wetting. The use of superplasticizers in conjunction these SCMs obviously complicates the design procedure. Almost every national body presenting recommendations on concrete mixture designs has attempted to resolve this complexity through specific limitations on the quantity of SCM along with a factor to account for the cementitious efficiency. In fact there are a few who do not subscribe to the philosophy of the cementitious efficiency but still allow a marginal quantity of any specific SCM as a part of the cement itself. The possible methodologies by the various national bodies for combining the different constituents to ensure an appropriate concrete mixture in a given strength, with or without chemical and mineral admixtures, has been dealt with in the later chapters.

1.7 Design for Performance and Sustainability

The second important aspect of concrete mixture proportioning is to ensure that finally the concrete will have the capability to serve without serious distress the intended lifespan of the structure in the particular environment it is supposed to exist. This complex requirement calls for an understanding of the environment first; specifically if the porosity of the concrete will have the capability to restrict the ingress of the environmental forces that deteriorate the concrete. This is attempted through specific limitations on several factors such as the following, just to name a few.

- The minimum and maximum cement contents
- The maximum water cement ratio
- The type of cement
- The type and even gradation of aggregates

The above factors incidentally are all reflected in establishing the minimum strength of concrete needed for the specific environment, which in a way is to limit the porosity on permeability of the concrete for inhibiting the environmental ingress. Apart from these, there are other specifications related to the concrete structural member such as the clear cover to reinforcement, the allowable crack widths, etc., which are all a part of the structural design. Notwithstanding these limitations on type of cement, strength, water cement ratio and cement content, it is imperative to enforce the idea that the maximum size of aggregate to suit the structural needs as well as an appropriate consistency to ensure ease in compaction have also got to be looked at. Even from the standpoint of performance, the use of superplasticizers and other chemical admixtures and the supplementary cementitious materials, either independently or together, present a lot of avenues for addressing. The later chapters present a more detailed discussion on some of these aspects, along with a possible mathematical appreciation of the available recommendations.

1.8 Offshoots in Concrete Formulations

Concrete over the years has been the material for construction for not just roads and buildings but found application in several other engineering structures like bridges, dams, harbors, pipes, water tanks and many more, as well as its use in the more exotic applications like offshore platforms and even nuclear containment structures. In fact, one can even say that it is this quest for its applicability and potential in fields like bridges, offshore platforms and containment structures that forced engineers and researchers to look at concrete with a new perspective. Because of the inadequate performance of conventional concrete in the most severe natural environment of the oceans, particularly when it was required to design concretes for offshore deep ocean platforms, some of the more modern advancements in concretes and concrete technology have come into existence. The nuclear and industrial applications necessitated a further dimension to this particular development of concrete composites. The necessity for spatial compaction procedures like high frequency vibration, spinning, vacuum dewatering and pressing in combination with or without vibration have all had their existence and importance over the years, and are still in their own way finding relevance even today. The advent of plasticizers and superplasticizers along with other chemical admixtures, as well as the confidence with which pozzolanic supplementary cementitious materials could be used to alleviate the limitations of concrete to address the water and cementitious contents provided several avenues for the modification of the basic concrete of yesteryear. These different applications of concrete composites have invariably lead to the recognition of the different types of concretes and their modifications over the years through the various concrete designations as described by the "Zement Taschenbuch" (VDZ, 2002) listed below. One important observation therein is that these are all essentially the same concrete composites that are designated differently depending upon the specific properties, production process and their application regimes only. These could be grouped under different categories depending upon how they came into existence and can be listed as the following:

TABLE 1.1
A Few Types of Concretes with Different Nomenclature

Nomenclature Basis	Designated As
Based on properties	Normal strength concrete, High-strength concrete, Early high strength concrete, Lightweight concrete, Aerated concrete, Heavyweight concrete, Porous concrete, Fibrous concrete, Flowing concrete, Self-compacting concrete, Acid resistant concrete, Wear resistant concrete, Slip-formed concrete, Concrete for marine applications, Refractory concrete, Recycled aggregates concrete, Self-curing concrete, High performance concrete, Ultrahigh performance concrete
Based on manufacture	In-situ concrete, Ready-mix concrete, Dry-mix concrete, Roller compacted concrete
Based on processing	Pumped concrete, Sprayed concrete or shotcrete, Spun concrete, Vibrated concrete, Heat-treated concrete, Tremie concrete, Vacuum concrete
Based on structural member type	Exposed concrete, Mass concrete, Precast concrete, Plaster, Lining mortar, Screeds, Grouts

It is easy to see from Table 1.1 that while these are all different concretes in their own way, it is essential to understand that the major constituents in almost all cases are essentially the same as that for normal concretes. In a way one can say that the normal concrete itself is appropriately modified either by adjusting the quantities of the constituents or by adding a very small quantity of an ameliorative constituent called admixture that helps in ensuring the required property. Thus it can be seen that the overall structure of the mix design for most concretes, if not for all concretes, is essentially the same, and if one has a good comprehension of the basic knowledge then it is possible to arrive at the required modifications and adjustments including the additives that may be needed for altering the concrete characteristics to be suitable for any particular application. The corollary or an outcome of the earlier discussions is to recognize that a clear and accurate understanding of the basic principles and doctrines behind the mixture design of conventional concretes of yesteryears is obviously a very important aspect to ensure an appropriate modulation or modification for arriving at the various compositions that exhibit the so-called significantly different characteristics which make them appear to be material of a different kind. It may be noted that in basic terms, even the representative of concrete in the small 150 mm strength test cube specimen is subdivided into and presented as the top-crete, bottom-crete and side-crete, depending upon its location, and indeed some of the properties could be seen to be different even if only marginally. The idea or the differences between top, bottom, side or corner-cretes has not really occurred to these advocates of macro-management.

1.9 Modern Trends and Adaptations

It is only obvious that with the available methods of characterization and quality assurance, strength characteristics of cements in particular could be modulated to achieve very high strength and reactivity. Coupled with this is the fact that there have been several studies looking at the possibility of utilizing high reactivity pozzolanic materials like silica fume and calcined clays in conjunction with the latest generation of superplasticizers like the poly carboxylic esters to achieve concrete strengths of the order of 100 to 150 MPa. It is also possible to demonstrate that the extreme brittleness of such materials could easily be maneuvered through the use of fibrous additions of various kinds. In principle the broad outline of these efforts involve the following background:

- The higher strength characteristics of cements are achieved through both the chemical modifications as well as appropriate particle size distribution using better grinding techniques;
- The appropriate packing density methodologies in improving the cement characteristics using one or more high efficiency pozzolanic materials, which not only help in improving the strength of the paste but also enhance significantly the durability characteristics;
- An appropriate grading distribution of the aggregates to achieve a good packing density while ensuring a reasonable loosening effect;
- Choose an acceptable fiber or micro fiber to ensure suitable ductility of the matrix as desired by the structural requirements;
- The minimization of the water content through specific production methodologies;
- And, finally argument the compaction and curing through pressure and temperature.

In fact some of the major cement producers have indeed been promoting patented cementitious systems with specified qualifications that will ensure all the above without the need for other manipulations. However, this obviously means that the user community cannot modulate specific parameters and will have to go by the dictates of suppliers and their recommended procedure for achieving the best result, which is not the best practice.

1.10 Future Prospects and Interdisciplinary Avenues

It is probably an interesting fact that the scientific discoveries and inventions are sporadic and are what can be as singular points of singular events in the history of the progress of mankind. However, in a total and absolute contrast, the developments in the engineering progress in utilizing scientific knowledge effectively are certainly known to be incremental, even if one says that it follows the Moore's law. Naturally, the developments in cement and concrete composites follow the engineering route and, similar to what was discussed earlier, the usable strength of general structural concrete doubled almost every few decades in the modern era. All these developments were possible not just by the introduction of modern high strength cementitious material manufacturing techniques alone, but had support from the developments in plasticizers of the past as well as the age-old knowledge of incorporating supplementary cementitious materials. However, pushing the limits beyond the present levels appear to lie not just in the upgradation of these materials alone but also in the adoption of fibrous and distributed reinforcing materials along with other well accepted as well as unconventional reinforcement methodologies. Some of these possibilities and their effectiveness, if only as an outline, will be more appropriate for discussion after we go through the characteristics and modulations of the present day concrete materials and their design, apart from the structural requirements in the present day industrialized environmental scenario.

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2

Constituent Materials and Processing

2.1 Introduction

In today's world, concrete is a part of man's everyday life and is considered an index of the standard of living of a nation in recent years. It is obviously the largest man-made material used in the world, at approximately one and a half to two tones per person per year. Naturally such a ubiquitous presence and utility of the material generated a lot of interest over the years as reflected by the enormous volume of published literature, be it about the design, production, transport, placement and curing of concrete or its various modifications, alternatives and advances and their applications. The obvious fact that all these concretes needed to use locally available materials have made coherent comparisons quite hard. However, there have also been several attempts to put in place an effective and efficient methodology for the design of conventional concretes at the least. The enormous variations in the characteristics of the complex range of materials used in its production made it difficult to put in a specific set of recommendations that could ensure an effective and economic solution. Notwithstanding the above, there have been several attempts to broadly delineate the various major parameters governing the design and to appropriately prescribe values based on a semi-empirical approach, through both a sound theoretical background and the results of the experimental investigations and field practices, by the various national and international organizations.

In this context, the characteristics if the individual constituents play a very important role in ensuring that the design procedures result in an appropriate concrete mixture for the specific application. The factors that have to be ensured to arrive at an appropriate concrete mixture are obviously dependent on primarily fixing the defining characteristics of the concrete needed for the environment in the first place. Ensuring that these are adequately defined is necessary to use materials of appropriate characteristics to make sure that the resulting concrete is what was sought to be designed. The specifications invariably suggest explicit guidelines in most part, though it is possible to enforce and achieve stricter limits and better compliance by consciously adopting a few minor yet effective practices to ensure appropriate results.

Many of these are not new, though they do not appear to be explicitly mandated. Maybe in some cases some of the limits on the characteristics have to be made tighter, while explaining the advantages in adhering to stricter limitations. It is with this view that the present effort tries to present the characteristics of the different constituents and their influence on the concrete mixture, while at the same time deliberating on the need for the appropriate limitations, particularly depending on the concrete strength grade. It is obvious that for most part many of the present day specifications of the national and international bodies appear to look at only commonly adopted concretes in the normal range of 20 to 50 MPa. Even in those situations, the advantages of ensuring better compliance and tighter regulations are probably overlooked, primarily because there are different committees looking at each of the subsets, be it the cement, aggregates or admixtures, etc. While many of these are interconnected and cross referenced in the concrete mixture design recommendations, the appropriateness of ensuring the referenced regulations is not a matter for discussion or was assumed to be a responsibility of the individual user. Some of these aspects and advantages of ensuring adherence to these recommendations appropriately are discussed not only just in this chapter, but also are explained and elaborated in later chapters.

Concrete is essentially a two component system, the major component being the aggregate fillers, which is rendered into a solid rock-like mass through the use of a cementitious binder. However, the need to ensure the maximization of the filler volume for effective economy necessitated the use of coarse and fine aggregates which could be of different origin. In about the same way, the binder, which is generally cement, could also have pozzolanic admixtures or even inert fillers incorporated in it to enhance the extendibility of the coating capacity. These two simple aspects play a vital role in the distinction between the mundane normal concrete that is often discussed as we know it and even the very high-strength, high-performance cementitious composites which need specific modulations in terms of both the physical and chemical characteristics of all the constituents to arrive at the synergistic effects sought.

Generally, in trying to understand the nuances of concrete technology perspectives, it is often presumed that the fundamental characteristics of the cements in terms of their physical and chemical characteristics are already guaranteed as they are factory produced and ensured to conform to national standards in particular. Even so, many a time the need for ensuring the conformity of the cement to the specified national standards is often recommended or even mandated in larger construction scenarios. Some of these aspects have to be necessarily explained and understood to ensure that the expected outcome from the mix design procedures recommended by the various national or international organizations can be reasonably realized. This only helps in ensuring an appropriate outcome from the design philosophies advocated by these bodies. However, if one has to go beyond such a limited scope of the making of concrete and really look at extending the boundaries of concrete in all its perspectives, it is only appropriate to look deeper into the various facets that characterize, influence and enforce the appropriate participation of each one of the components involved in the system.

It is appropriate at this stage to look at the primary objective of the present effort, which is mainly to be able to present a mathematical background to the paradigm of concrete mix design. Even in this particular perspective, the need for an in-depth understanding of the characteristics and compositions in relation to the effects that they will have on the resulting concretes is certainly obvious. In fact, it is probably some of these basic characteristics of the individual constituents, be it the reactive cementitious composites or the inert fillers, which will pave the way for arriving at methodologies that could lead to an appropriate and effective mathematical representation. It is the absence of such an approach that appears to have led to an indiscriminate use of mathematical techniques or an available analytical procedure to fit a certain set of experimental results to arrive at some complex prediction equation. Some of these aspects as well as the efforts in that direction will be discussed a little later, while looking at the specific aspects regarding concrete mixture designs.

It is with this perspective that the characteristics of the constituents that form the concrete composites are discussed in the following paragraphs. Depending on each one's role and the activity that it supports, the concrete constituents can be grouped into the following categories for a broad discussion. At this stage maybe it is appropriate to understand that the presentations depict the broad outlines on the generic materials in these categories. The aspects that are not covered under these discussions are actually covered wherever necessary in the later parts of this effort, essentially to ensure that the relevant information is available at hand for a comprehensive understanding. These generic groups are primarily the:

- Cements (as binders)
- Mineral admixtures (as supplementary cementitious materials)
- Water, superplasticizers and chemical admixtures (mostly as liquid reagents)
- Aggregates and inert powder extenders (as fillers)
- Reinforcing materials (as crack bridging agents)

It is indeed obvious and even customary that a broad account of the various constituents of concrete is a part of any book on concrete materials or structural concrete. While this may be so, an appropriate understanding of these materials, specifically to facilitate a better approach toward the mathematical modeling of structural concrete proportioning, is somewhat scarce. One obvious explanation for such a limitation could be that those involved with the modulation of concrete mixtures who are dealing with concrete technology in terms of its production, transport and distribution usually are engrossed in the upgradation of the final product. The intricacies of the individual constituents' characteristics, particularly the chemical constituents like cements and admixtures, are essentially left to the discretion and the guidelines suggested by the supplier. It is only appropriate if not imperative that in dealing with the concrete mixture proportioning one have a larger comprehension of the chemistry behind a cementitious materials and chemical admixtures, without which it is very difficult to formulate comprehensive guidelines, not to mention find avenues to mathematically model these proportioning methodologies.

Incidentally, while it is not obvious at this stage how these characteristics are interrelated in formulating an effective and maybe even a high performance concrete mixture proportioning, it is probably appropriate to list some of the aspects that need to be looked into in such an attempt.

Effect of cements and hydration

- Primarily, it is the chemical characteristics and the corresponding hydration reactions of the cements that are responsible for binding the aggregates together.
- Incidentally, the cement hydration being an exothermic reaction, the intrinsic heat can influence the rate of hydration itself, while it has to be appropriately dissipated to reduce thermal cracking.

Effect of chemical admixtures

- Also, the effects of chemical admixtures on the various compounds of cement, in particular the effect of superplasticizers, need to be better understood.

Effects of mineral admixtures or supplementary cementitious materials

- The need for an understanding of the efficiency of the different supplementary cementitious materials possible is indeed a key to their effective utilization.
- Finally, there is a fine balance between the water required for wetting the surface of all the different constituents (particularly the fines, which obviously present the highest wetted surface), and the minimum fines requirement to ensure that the cementitious paste is able to cover all the surfaces of aggregates that need be bound is probably of the highest significance in ensuring the highest strength possible for the composite.
- This obviously means that the total fines, including cements and mineral admixtures, should be limited to the requirements for coating the surface of the graded aggregates and making them slide over each other, and not be a constituent filler material in the concrete matrix.

Effect of aggregate gradation

- Considering the above, it is necessary to understand the effects of the grading distribution of the aggregate matrix on the strength of the cementitious composites.

It is in this focused yet restricted perspective that the characteristics of the different constituent components of the concrete mixture have been discussed. Table 2.1 presents a very broad picture of the various constituents, their general specifications and the corresponding effects on both the green and hardened state characteristics.

TABLE 2.1

Parameters and Effects of Major Structural Concrete Constituents

		Effects on	
Constituents	**Specifications**	**Green State**	**Hardened State**
Cements			
OPC; (Strength class)	32.5, 42.5, 52.5 (250–550)	Consistency Strength gain rate	28-day strength PSD variations
Blended cements	% SCM	Hydration	Early strength
Composition	C_3S (50–55)	Hydration	Alkalinity
Composition	C_2S (5–12)	Setting	Sulfate resistance
Fineness, particle size distribution	Blaine 3000–5000 >50 µm	Heat of hydration, water demand	Strength and strength gain rate
Water, Superplasticizers and Chemical Admixtures			
Water Superplasticizers/ Water reducers Accelerators/ Retarders Air-entrainers Water-proofers VMAs and others	Potable Solid concentration (min. 0.5, max. 2.5) • *All the liquid chemical admixtures can be considered to be a part of water for w/c calculations*	Consistency, segregation, bleeding, set modulation, strength modulation consistency	Strength due to water reduction, freeze–thaw resistance, permeability, specific effects
Supplementary Cementitious Materials			
Fly ash Ground granulated blast-furnace slag Silica fume Rice husk ash Calcined clays (Metakaolin, Zeolite, etc)	Low-end pozzolan Low-end, cementitious High-end pozzolan Medium efficiency Medium efficiency	Reactive silica, SiO_2, Al_2O_3 fineness, % addition, consistency, water demand, thixotropy, unburnt carbon, SP dosage, calcination	Setting times, strength gain rate, plasticizer requirement, heat of hydration, shrinkage, self-desiccation

(*Continued*)

TABLE 2.1 (*Continued*)

Parameters and Effects of Major Structural Concrete Constituents

Constituents	Specifications	Effects on: Green State	Effects on: Hardened State
Fine Powders and Extenders			
Limestone powder Quartz powder Silica dust Kiln dust	Fineness, quantity • *Minimum cement ensured, these can form part of fines required.*	Water demand, paste quantity, consistency	Improved density, reduced porosity
Fine Aggregate			
River sand Manufactured sand Quarry dust	Grading, fine dust, clay/silt	Water demand, paste quantity, consistency	Improved density, reduced porosity
Coarse Aggregate			
Normal Light weight, EPS Heavy weight lead and iron pellets	Max. agg. size, grading, fine dust, density, absorption	Packing effect, paste demand, consistency, flow, segregation, bleeding, ASR	Density, strength, porosity, aggregate interlock
Fibrous Materials			
Steel fibers Micro-steel fibers Glass fibers Polymeric fibers Ceramic fibers Natural fibers	Diameter, length, section, shape, ends, stiffness, modulus, alkali reactivity, absorption	Distribution, volume %, balling, nos. per cubic vol., shrinkage reduction	Density, ductility, fracture energy, impact resistance
Reinforcements			
High strength deformed bars Prestressing steels Welded wire mesh Polymeric bars	Diameter, bond, modulus, ductility, bendability, weldability	% sectional area, bundling, lap and joint distribution, spacing	Moment of resistance, stiffness, ductility, rotation capacity

2.2 Classification of Cements

The material cement as can be seen has been in existence for a long time, and naturally a large number of types have come into existence over the years, though the general-purpose ordinary Portland cement is the most common of them all. In specific a broad classification exists in the ASTM standards which presents the cements of different types and can be broadly summarized as below (ASTM C 150, 2009). The compositional characteristics of the cements as proposed by the ASTM (ASTM C 150, 2009) are also presented in Table 2.2.

TABLE 2.2

Typical Composition of the American Portland Cements

		C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	LoI	Blaine
Name	**Type of Cement**				%			m^2/kg
Type I	Ordinary	45–60	20–30	812–	6–12	2.5–3.4	0.5–2.0	~350
Type II	Moderate sulfate Resistant/Modified	40–55	20–35	5–8	8–15	2.2–3.2	0.5–2.0	~350
Type III	Rapid hardening	50–65	15–30	8–15	6–10	2.5–4.0	1.5–2.5	~450
Type IV	Low heat	40–55	35–50	4–7	8–15	2.5–3.5	0.5–1.5	~300
Type V	Sulfate resisting	40–50	30–45	1–5	8–15	2.5–3.5	0.5–1.0	~350

Source: ASTM C 150, Specification for Portland Cement, Annual Book of ASTM Standards, West Conshohocken, PA, 2009.

- Type I—Normal Portland cement for general construction applications,
- Type II—Moderate sulfate resistant cement for concretes in contact with soils containing sulfates,
- Type III—High early strength cement which essentially has a higher fineness for early strength gain required in applications like pre-casting,
- Type IV—Low heat cement for with a higher C_2S content suitable for mass concrete applications, and finally
- Type V—Sulfate resistant cement for applications for alkali or high sulphate resistance in ground water.
- There are naturally others such as high alumina cements, colored cements and blended cements, which are not directly represented as a specific type, that are also available.

The earlier British specifications also followed the very nearly similar system akin to the above, through each of them evolved independently, and maybe it is not essential to present the entire spectrum once again. Incidentally, it is to be recognized that the present Euro international standard (EN 197-1, 2000) presents a much broader classification of the cements that encompasses a much larger spectrum of the possible cementitious alternatives.

There are a total of 27 different cementitious compositions proposed by the Euro standard (EN 197-1, 2000), which is quite comprehensive and up-to-date. The simplified version of the same along with the basic characteristics of these cements is presented in Table 2.3. Incidentally it can be clearly seen from the note that each of these cements has to comply with the minimum cement strength requirements at the prescribed water cement ratio corresponding to the Euro standards. It is also made clear that the 5% additional minor constituents (could be the cement kiln dust, limestone powder, or other very fine material that could have a synergistic effect on the cement) are considered

TABLE 2.3

The 27 Different Cementitious Compositions

Cement	Type	Clinker (%)	Additional Constituents Apart from 5% Minor Constituents (95%)
CEM I	Ordinary Portland cement	95–100	
CEM II	Pozzolanic (individual)	80–94; 65–79	Fly ash, slag, silica fume, burnt shale, lime stone, composite all
CEM III	Slag (high)	35–64; 20–34; 5–19	Slag alone
CEM IV	Pozzolanic (composite)	65–89; 45–64	Fly ash (F/C), silica fume, Pozzolan (N/C)
CEM V	Composite	40–64; 20–38	Fly ash (F), Pozzolan (N/C)

Source: EN 197-1, Cement—Part 1: Composition, specifications and conformity criteria for common cements, Brussels, Belgium, 1–29, 2000.

Note: Minimum 28-day strength of 52.5 MPa at a water cement ratio of 0.5 should be guaranteed. This corresponds to the Euro-International C 42.5 grade cement, which is presently considered as cement for conventional applications.

appropriate even in the ordinary Portland cement. The present classification also mandates that the characteristics in terms of heat of hydration, setting times and strength are indeed not part of the cementitious compositions specifications and have to be addressed appropriately. The earlier enumerated list can be treated probably as the necessary and sufficient conditions for an informative utilization of any of these cementitious systems.

Apart from this classification, the characteristics of each of these cements have to be appropriately assessed for a complete understanding of the cementitious system and also to ensure that they comply with the necessary regulations. Though it is not possible to have a look at the complete spectrum of these regulations, their test methodologies and alternatives along with their relative merits and demerits, a list of the most important of these tests that could have a bearing on the performance of cement could be listed as—Fineness of cement, consistency, initial and final setting times, soundness and strength, and strength gain rate in particular.

It is obvious that there could be several other characteristics that need a better understanding for specific applications, but the above parameters influence a much larger spectrum of the characteristics of cement and can be very helpful in modulating the construction activity appropriately. While some of these are available from the manufacturer's specifications or reports provided, it is probably most appropriate to have a handle on these to be sure that the characteristics reported are indeed representative of the available cement site. The cement producer naturally conducts several of these tests to comply with the regulations at regular intervals, and marginal variations in a very large production facility are indeed unavoidable and need to be addressed in critical construction activities.

2.3 Characteristics of Cements

As already stated, modern day concrete was essentially formulated as a reasonably homogeneous mixture of well graded aggregates, both coarse and fine, completely encapsulated and bound with the help of a paste of Portland cement and water, finally having the right consistency for fulfilling the structural formwork. Needless to say that the characteristics of cement, which performs the requirement of being the binder after hydration and which is also the most reactive component in the constituents that can be degraded through the environmental interaction, is of utmost importance.

Cements are produced through the high-temperature reactions of a mixture of the siliceous (SiO_2) and calcareous (CaO) materials, modulated by small quantities of alumina (Al_2O_3) and iron oxide (Fe_2O_3) primarily to modulate the fusion reaction temperatures in a rotary kiln. The resulting mixture on cooling forms the cement clinker, which is then finely ground to the average particle size of about 10 μm (1–100 μm). The fact that the hydration reaction is a surface phenomenon makes it easy to understand that the characteristics of the cement are influenced both by the chemical composition and the fineness (particle size distribution) of the cement. The chemical hydration reactions are certainly driven by the various chemical constituents at the surface of the particle and their relative percentages in the cement produced.

A well accepted representation of the potential competition of cement is through what are known as the "Bogue's compounds"—tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF)—calculated based on the oxide compositions through expressions given by Bogue. These relationships for calculating calcium silicates and aluminates are:

$$C_3S = 4.07(CaO) - 7.60(SiO_2) - 6.72(Al_2O_3) - 1.43(Fe_2O_3) - 2.85(SO_3) \quad (2.1)$$

$$C_2S = 2.87(SiO_2) - 0.75(3CaO \cdot SiO_2) \quad (2.2)$$

$$C_3A = 2.65(Al_2O_3) - 1.69(Fe_2O_3) \quad (2.3)$$

$$C_4AF = 3.04(Fe_2O_3) \quad (2.4)$$

Apart from these there are other minor constituents, primarily the magnesium oxide (MgO) and alkalis (Na_2O and K_2O), that could also be of interest in understanding and explaining the performance behavior of cement and concrete.

In a nutshell, the primary characteristics of cement that form an essential component of the quality assurance and quality audit of cement and concrete in general as already stated earlier can be listed as the following:

- Fineness and particle size distribution
- Standard consistency
- Initial and final setting times
- Heat of hydration
- Strength and strength gain rate
- Soundness
- Alkali silica reactivity in some cases, though there are several other characteristics that may be of relevance for specific aspects.

Their relevance and a broad outline of the test methods along with the ameliorative solutions, if any, are discussed in later chapters. However, it is imperative that one should have a fundamental understanding of the effects of at least some of the major characteristics of cement to be able to do justice in ensuring an appropriate mixture design of structural concrete for applications in the various environmental zones that can be envisaged in practice. These are briefly discussed in the following sections.

2.3.1 Hydration of Cement

The chemical reactions associated with the various compounds of cement (C_3S, C_2S, C_3A, and C_4AF) have been discussed at length in the several reports that followed the original publication of Bogue (1934). He also presented the strength development characteristics of each of these compounds showing clearly that C_3S imparts almost 50% of the strength of cement in the first seven days while the remaining strength gain happens of primarily over the next 180 days. The strength effect of C_2S in contrast will predominantly start after 28 days and will continuously gain strength over the next one year with C_3A, and C_4AF having more or less a negligible effect on the strength of the cement composite. It is probably appropriate to assume that the reactions are independent of one another, particularly because they are essentially driven by the interaction of the compounds on the surface of the cement grains with the available water during hydration. A general outline of the reactions and hydration effects of these major compounds is presented in Table 2.4. As such there have also been attempts to directly relate the strength of cement in the concrete composite through the effects of these chemical constituents at the various ages (Zhang and Napier-Munn, 1995; Kheder et al., 2003), probably one of the simplest mathematical attempts to arrive at the strength of the concrete mixture.

TABLE 2.4

The Major Compounds of Portland Cement, the Reactions and the Effects on Hydration

Bogue's Compound (Cement Notation – % wt. range)	Reactants	Products		Effects			
				Setting	Strength Development	Ultimate Strength	Heat of Hydration
Tricalcium silicate (Alite – C_3S – 50–70) 2(3CaO SiO_2)	11(H_2O)	Calcium silicate hydrate (C-S-H) 3CaO 2SiO_2 8H_2O	Calcium hydroxide 3(CaO H_2O)	Rapid (hours)	Rapid (mainly 7–10 days)	High (10s of MPa)	Medium (~500 J/g)
• Major 28-day strength giving compound of the Portland cement. Major calcium hydroxide supplier for the pozzolanic reactions.							
Dicalcium silicate (Blite – C_2S – 15–30) 2(β2CaO SiO_2)	9(H_2O)	Calcium silicate hydrate (C-S-H) 3CaO 2SiO_2 8H_2O	Calcium hydroxide CaO H_2O	Slow (days)	Slow (weeks/months)	High (10s of MPa)	Low (~250 J/g)
• Strength development after 7 days.							
Tricalcium aluminate (Aluminate – C_3A – 5–10) 3CaO Al_2O_3	3(CaO SO_3 2H_2O)	26(H_2O)	Ettringite 6CaO Al_2O_3 3SO_3 32H_2O	Instanta-neous	Very rapid (1 day)	Low (few MPa)	Very high (~850 J/g)
Tricalcium aluminate 2(3CaO Al_2O_3)	6CaO Al_2O_3 3SO_3 32H_2O	4(H_2O)	Calcium monosulfoaluminate 3(4CaO Al_2O_3 3SO_3 12H_2O)	—	—	—	—
Tricalcium aluminate 3CaO Al_2O_3	Calcium hydroxide CaO H_2O	12(H_2O)	Tricalcium aluminate hydrate 4CaO Al_2O_3 13H_2O	—	—	—	—
• Unstable in water. Highly vulnerable to sulphate attack.							
Tetracalcium aluminoferrite (Ferrite – C_4AF – 5–15) 4CaO Al_2O_3 Fe_2O_3	Calcium hydroxide 2(CaO H_2O)	10(H_2O)	Calcium aluminoferrite hydrate 6CaO Al_2O_3 Fe_2O_3 12H_2O	Very rapid (minutes)	Very rapid (1 day)	Low (few MPa)	Medium (~420 J/g)
• Imparts the Portland cement its characteristic grey color due to the iron compounds.							

Source: Saroka, I., *Concrete in Hot Environments*, E & FN Spon, London, UK, 272, 1993.

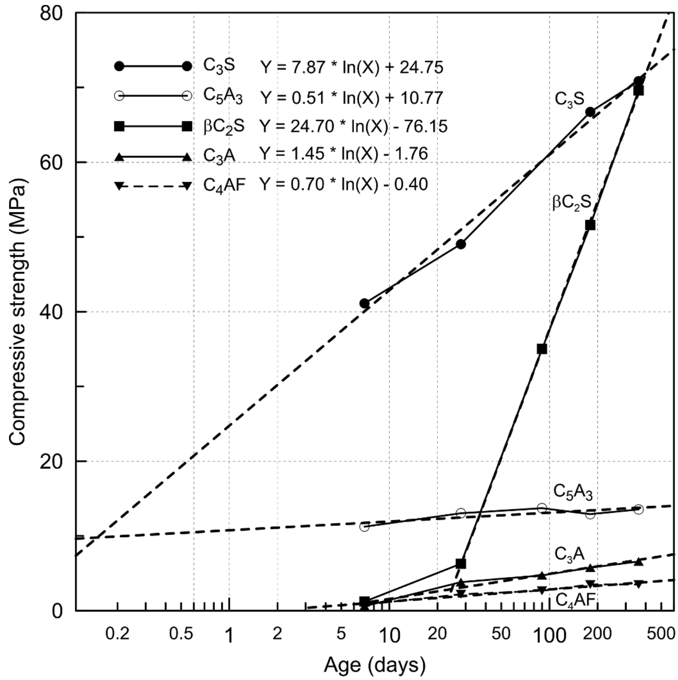

FIGURE 2.1
Compressive strength development of the major constituents of Portland cement. (After Bogue, R.H. and Lerch, W., *Ind. Eng. Chem.*, 837–847, 1934.)

In an effort to look at the strength gain characteristics of these compounds in cement, the original values of the strength gain properties of the compounds with age have been replotted to see if any specific relationships can be ascertained to have an easier mathematical solution (Figure 2.1). As can be seen, strength gain rate for the four compounds can be defined by the equations presented in Figure 2.1 itself.

It may be noted that the seven-day strength value of C_3A was not included in the calculation of its relationship as it was very low and will not have any appreciable influence on the strength calculated, particularly given the fact that the quantity of C_3A itself is very small. It is obvious that the relationships were extended to the levels of almost final setting, which is not supported by the experimental investigations reported, but any minor variations will not really have a major effect on the predictions if at all attempted.

A few specific aspects that should be kept in mind are that while the hydration reactions of these compounds could be independent of each other, the effects of the changes in percentages of C_3A and C_3S investigated by Lerch and Bogue (1934) show how an increase in these can significantly increase the heat evolved specifically, immediately after the dormant period. Without going much further into the percentage increases in the heat evolved, it is important to see how adjustments in the contents could lead to the production of low heat cements by limiting the C_3A content to between 3% and 7% as in the ASTM C 150-09 Type IV low heat Portland cement. In contrast, the C_3A content was proposed to vary from 7% to 17% for the ASTM C 150-09 Type III rapid hardening Portland cement while the same was suggested to vary from 5% to 14% for the ASTM C 150-09 Type I ordinary Portland cement. One should also remember that the variations in any specific component will have its own effects on the percentage of the others in the composition and will certainly affect the heat evolution process, particularly the variations originating from C_3S being more significant as has already been presented.

2.3.2 Heat of Hydration

The different chemical reactions associated with the hydration of cement generate heat during the formation of the calcium silicate hydrates or the other hydration compounds. The amount of heat generated or the time at which it is generated are all dependent on the kinetics of the chemical reactions and the associated quantities of the reactants themselves. A broad outline of the rate of heat generation during the hydration process can be understood from the five stages depicted in Figure 2.2. In brief, the total heat of hydration effect can be subdivided into these five different stages associated with the following phenomena.

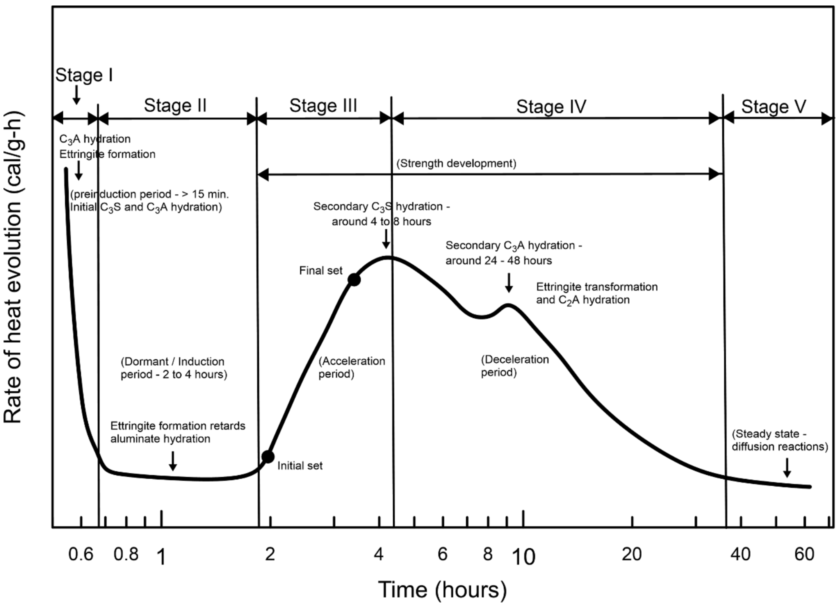

FIGURE 2.2
Effect of hydration reactions on the heat evolution rate.

- Stage I—the instantaneous hydration of C_3A along with the formation of ettringite by reacting with gypsum preventing the flash setting off cement, associated with a large exothermic instantaneous peak,
- Stage II—the later dormant period or the induction period permitting the mixing, transport and compaction of the concrete in the moulds,
- Stage III—the acceleration phase in which the hydration of C_3S forming the CSH gel and the reaction rate accelerating, leading to the initial and final setting times,
- Stage IV—the deceleration period with the reaction rates slowly lowering to the steady-state level with initial strength development, and finally
- Stage V—the steady state phase which is limited by diffusion reactions.

The further process of hydration will continue as long as there is water available generating not only the CSH gel that imparts the strength as the hydration process but also the other reaction products, essentially the calcium hydroxide. The calcium hydroxide that precipitates near the surface of the aggregates is the reason that the material in the interfacial transition zone is the weaker product that could dictate the failure characteristics of concrete. The possibility of entrapped water lenses under the aggregates could aggravate this particular phenomenon significantly.

2.3.3 Effect of Fineness

The hydration reactions being essentially a surface phenomenon, the fineness in general and particle size distribution defining the distribution of the finer fractions of cement in particular have a specific influence on the strength and strength gain characteristics of the material. Broadly, the fineness of the material cement is expressed in terms of its specific surface (cm^2/g). It is also recognized that the different strength grades in cement are predominantly influenced by its fineness apart from its chemical composition.

It can be broadly stated that the different grades of cement like C 32.5, 42.5 and 52.5 grades of the Euro standards could be seen to have finenesses in the range of 3000, 4000 and 5000 cm^2/g, respectively. Also the percentage of material retained by weight on a 90 μ sieve appears to be generally around 10.6% and 1% respectively for the corresponding cements discussed above.

Also, as already discussed, being a surface phenomenon, the strength gain characteristics of the cement will significantly improve with an increase in the finer fractions in the cement. The typical compressive strength gain characteristics with age for the different granulometric sizes were reported by Locher et al. (1973). As can be seen from Figure 2.3, the strength variation of the different granulometric sizes appear to follow log linear relationships

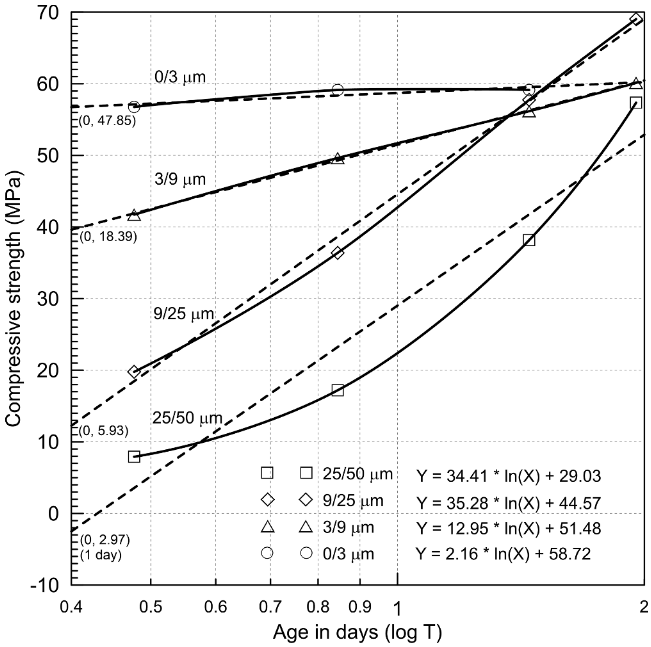

FIGURE 2.3
Strength gain rates of the different granulometric sizes in cement. (After Locher, F.W. et al., *Zement-Kalk-Gips*, 349–355, 1973.)

defined by the equations presented therein. It is thus possible to be able to fix an approximate strength level of a cement knowing the distribution of the different size components.

However, the compressive strength gain rates of two different cements having a specific surface of approximately 2500, 3000 and 4500 cm^2/g as presented by Odler (1991) appear to have different strength gain rates indicating that such a direct estimation is not possible. This is probably because the compositions associated with these cements could also influence the strength gain rate of the individual cement. Figure 2.4 also shows that the strength gain rate is essentially a log linear relationship, but for the few initial hours (maybe during the first 2 days). Some of these aspects will be quite useful for extrapolating the strength characteristics, while taking into consideration that the initial strength gain rate is not the same. The concepts of maturity and the relations associated with the same are discussed in later chapters.

2.3.4 Soundness and Alkali Silica Reactivity

While some of the aforementioned parameters have a direct bearing on the strength and strength gain characteristics of cements, the performance-related parameters are influenced differently. In brief, the soundness and

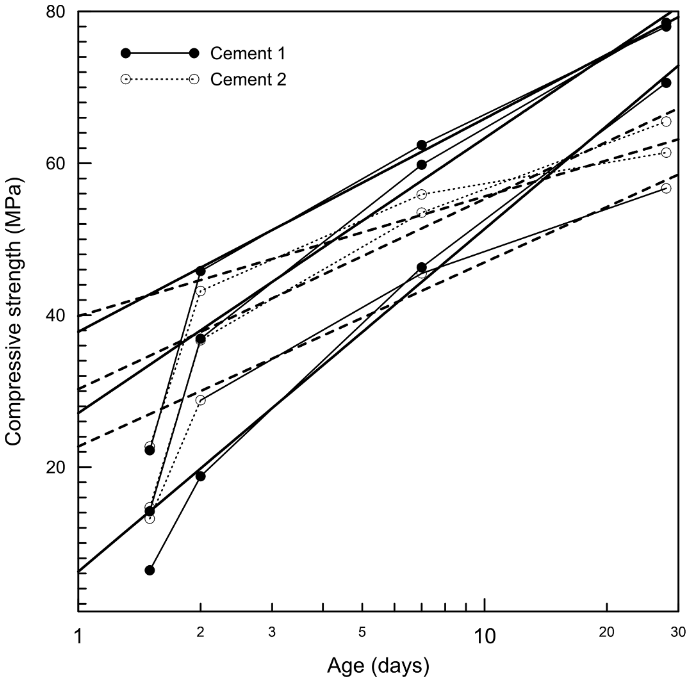

FIGURE 2.4
Strength gain rates of different cements of equal fineness. (After Odler, I., *Mater. Struct.*, 143–157, 1991.)

the associated expansion characteristics are primarily related to the magnesium oxide (MgO). The effects of unreacted calcium oxide (CaO) and calcium sulfate reacting with the excess gypsum in cement forming ettringite can also contribute to the expansion associated with soundness.

It is also known that the alkali hydroxides of Na_2O and K_2O in cement will react with aggregates containing reactive silica constituents on the surface. Some of the aggregates of such nature can be listed as opeline cherts, siliceous limestones, volcanic tuffs, etc. that contain active silica sites on the surface, which will react with these alkalis. An essential prerequisite for this to happen is adequate moisture content or the possibility of wetting and drying. In specific this type of deterioration is observed in waterfront structures and dams.

It may be stated at this particular stage that there are several other parameters that are associated with concrete durability, characteristics like permeability, chemical attack including acids, sulfate attack, freezing and thawing effects of fast action, and thermal effects, that could all ultimately influence the performance of the structure. Some of these aspects and their appropriate redress mechanisms are discussed in later chapters.

2.4 Chemical Admixtures

The need to comply with demanding requirements such as limitations on water cement ratio and cement content for higher strengths and earlier strength gain admixtures have become an essential component of construction activity. Though admixtures have been used for a very long time, continuous research efforts over recent years have made it possible to modulate the characteristics of concrete for specific applications. Chemical admixtures naturally have to be water soluble to be effective in cementitious compositions. One of the first principles of ensuring a reasonable handle on the performance of admixtures is to have a specific understanding of the solid content in the admixture. Apart from that, it is also important to account for the quantity of water associated the admixtures added to have a clear picture of the water cementitious materials ratio required for an understanding of the strength characteristics of concrete. A simpler approach could be to simply consider the quantity of the liquid admixtures as a part of the water content for calculating the water cement ratio and the corresponding strength characteristics of concrete.

There are several different admixture types available to suit the different demanding applications, and of these, superplasticizers, accelerators, retarders, water proofers and air-entrainers are the most utilized. Superplasticizers are used to enhance the workability characteristics of concrete and as a corollary the same could be called high range water reducing admixtures to ensure a higher strength through the possible reduction in the water content required keeping workability of concrete at the same level. Plasticizers have been in existence for a long time. Superplasticizers were earlier classified into four categories: sulfonated melamine formaldehyde condensates (SMF) like "Melment"; sulfonated naphthalene formaldehyde condensates (SNF) like "Irgament Mighty"; modified lignosulfonates (MLS); and others. The more modern poly carboxylic esters introduced recently have changed the possibilities of portability modulation in concrete even more significantly. One of the primary concerns with some of these superplasticizers is a possible additional air entrainment associated with them that could have an adverse effect on the strength characteristics if not addressed appropriately in its formulation. One important observation from the experimental investigations in the laboratory is that the superplasticizing effect associated with these admixtures is generally enhanced when used in combination with other chemical admixtures like those for accelerating or retarding the concrete, even after accounting for the additional water involved in the system because of such additions.

Accelerators are helpful particularly in ensuring early strength development in applications related to precast concrete and in ensuring the required strength at transfer of prestress in prestressed concrete applications. However, any significant strength acceleration through admixtures, while being helpful in enhancing the early strength gain characteristics, could indeed have an adverse effect and lower the strength at later ages. Accelerators for concrete include alkali hydroxide silicates and fluorosilicates, calcium formate, calcium nitrates, chlorides of aluminum, potassium, sodium and calcium. Incidentally, calcium chloride used as an accelerator will certainly promote the corrosion rates considerably and has to be addressed appropriately if at all considered for utilization.

Retarding admixtures essentially are used to enhance the working time associated with placement and compaction of concrete in construction. The set retarders invariably improve the workability to a certain extent due to the retardation, and may also show a marginal improvement in the strength characteristics at later ages. Materials used for controlling setting characteristics include modified lignosulfonates, salts of hydroxylated carboxylic acids apart from hydroxylated polymers like polysaccharides and silicones.

The need for water proofers is considered by some only as a matter of opinion, as it is possible to modulate the concrete mixture designs including the minimum fines contents required appropriately through a proper mix design. Even so, it is possible that there may be specific situations that demand additional support measures. Calcium and aluminum stearates, and hydrocarbon resins perform well as water proofers without affecting the air content in plastic concrete. However, water repellent materials like soaps and fatty acids could entrain air to break the integrated porosity in the concrete that makes it impermeable to water. It is to be recognized that large quantities of air entrainment could be detrimental to the strength of concrete. Designed appropriately, the naturally entrapped air in the concrete mixture could be effectively redistributed as fully enclosed air bubbles improving the impermeability of the matrix. Air-entraining admixtures help in making cohesive concretes of high workability. The entrained air bubbles form pockets of air in the pore system, inhibiting the passage of water and consequently the diffusion of electrolytes that cause deterioration and corrosion.

It is most important to be cognizant of the fact that many of these admixtures have compatibility issues with the cement in particular and also with each other when used in combination. Combining two admixtures to have a specific affect is always not guaranteed without having established a synergy earlier, particularly in relation to the cement being used. The compatibility with the cementitious materials could also be a serious question as was observed in laboratory investigations. Notwithstanding these limitations, chemical admixtures have been responsible for realizing several ameliorative measures in concrete and have come to stay. The most important and probably the biggest advantage is that the possibility of water reductions of well over 20% through superplasticizers has led to the enhancement of the strengths of normal concrete from around 50 MPa to about 80 MPa without any significant change in the cement content. This obviously shows that there is a considerable economy in using these materials if appropriately addressed. One can also understand that the use of mineral admixtures, which necessarily increases the wetted surface area of the cementitious part (particularly while using super fine compounds like silica fume and precipitated silica), and the use of superplasticizers in particular is totally essential.

2.5 Supplementary Cementitious Materials (SCMs)

The need for economizing cement in the huge volumes of concrete that are being manufactured for the various infrastructure applications is paramount in the minds of engineers and planners. From a fundamental understanding, low strength concretes requiring limited cement quantities need to be augmented in terms of the fines to be able to coat the aggregates adequately for binding, while at the same time for high strength concretes it is necessary to limit the total cement content, specifically to lower the heat of hydration. Invariably secondary or supplementary cementitious materials play an important role to address these needs. Specifically, supplementary cementitious materials are mineral admixtures that exhibit pozzolanic reactivity. ASTM C 618–88 defines a pozzolan as a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in the finely divided form and in the presence of moisture, react chemically with the calcium hydroxide (liberated during the hydration of cement) at ordinary temperature to form compounds possessing cementitious properties. In fact, the use of pozzolans like volcanic tufts as binders in combination with lime was known from the early Roman period. Recent years have seen an increasing use of supplementary cementitious materials as partial replacements for cement because their presence in concrete could improve the properties of concrete in green state (like workability, cohesiveness and bleeding) as well as in the hardened state (like compressive strength, chemicals resistance, alkali silica reaction and permeability). SCMs can be of a natural origin (like volcanic tuff, calcined clay, etc.) or may be artificial (like the mineral waste by-products—fly ash, silica fume or ground granulated blast furnace slag, etc.). The important characteristics and potential of a few of the most prominent SCMs are discussed herein.

2.5.1 Pulverized Fuel Ash or Fly Ash

Fly ash, available in abundance due to the combustion of coal in thermal power stations, is gaining importance, particularly because the resulting concrete is not only economical but can be durable. The primary characteristics of fly ash, the associated pozzolanic reaction and its influence on the green and hardened state characteristics apart from durability have been topics of discussion in several research efforts to date. The characteristics of pulverized fuel ash primarily depend up on the geological factors related to the coal deposit, the combustion condition and the collection devices. Physical characteristics of fly ash like fineness, particle shape and size, and density appear to have a greater influence on the performance of fresh concrete such as workability, bleeding, segregation, etc. According to American standards (ASTM C 618, 1994), fly ashes are classified based on their CaO content, as class C (ashes from lignite or subbituminous coals having CaO >10%) and class F (ashes resulting from anthracite coals having CaO <10%). To be effective as SCMs, it is required that the total of $SiO_2 + Al_2O_3 + Fe_2O_3$ should be a minimum of 50% in case of class C while the same should be a minimum of 70% in case of class F (ASTM C 618, 1994). The carbon content of fly ash having a high porosity and a very large specific surface causes the absorption of water and chemical admixtures in concrete, resulting in a reduction in workability to ensure the limited to appropriate values specified.

2.5.2 Silica Fume

Silica fume, a condensation product resulting from the reduction of high purity quartz with coal in electric arc furnaces during the manufacture of silicon and ferrosilicon, is one of the most reactive pozzolans available. While it was reported that for applications in concrete silica fume should have an SiO_2 content in the range of 85% to 98%, a mean particle size in the range of 0.1 to 0.2 microns having spherical shape with a number of primary agglomerates in amorphous state, there are provisions that accept an SiO_2 content in the range of 75%. Apart from the SiO_2 content, to be a highly pozzolanic material silica fume should have a high specific surface area (20–23 m^2/g) and an amorphous structure. Incorporation of silica fume into concrete improves both the properties in the green state as well as in the hardened state (Sellevold and Nilsen, 1987). Silica fume as a mineral admixture in concrete (mostly combined with superplasticizers to address the significantly high wetted surface even with lower addition levels) has provided concretes of around 100–120 MPa. It is felt that the high efficiency of silica fume (its cementitious efficiency in terms of strength) can lead to significant reductions in the basic cement content, which may affect the durability of lower strength concretes adversely, while at the same time be an appropriate material of choice for realizing very high strength concretes where the cements contents are never too low. Apart from the development of high strength, silica fume can also significantly improve the performance of concretes through the combined action pore filling as well as pozzolanic effects.

2.5.3 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag (GGBS) is used to produce Portland blast furnace slag cement (PBFS) through inter-grinding with clinker.

It is gaining a lot of prominence as a cement replacement material due to its improved performance characteristics of the resulting concrete in addition to the economy achieved. The granulation process due to instantaneous cooling induces an amorphous structure in the slag which is responsible for the pozzolanic property. The material in itself is actually self-cementitious and requires no additives for hydration, but the reactions are significantly slower. GGBS as a cementitious material does not depend solely on the pozzolanic reaction and hence can replace cement in much larger proportions (replacements of the order of 70%–80% have been reported) compared to other mineral admixtures. GGBS in concrete produces relatively low heat of hydration and also exhibits improved sulfate resistance. The limitations associated with the specific cements with the fixed proportions of slag and cement at the time of production can be addressed by site mixing to suit the needs of the various environmental conditions. Through a proper proportioning and a judicial choice of the replacement percentage, GGBS concretes can be designed to exhibit the required strength and durability. Incidentally, the high alumina content in this material improves chloride binding of the concrete, making it best suited for a marine environment.

2.5.4 Calcined Clays

Pozzolans are broadly divided into two major types: natural and artificial. The use of natural pozzolans as binders in combination with lime has been known for a long time. Volcanic glass, volcanic tuff, calcined clay or shale and raw or calcined opaline silica are natural pozzolans. The artificial pozzolans include fly ash, silica fume, GGBS, rice husk ash, etc. Metakaolin, obtained by calcination of kaolin (a naturally occurring clay mineral), was found to be most effective as a pozzolanic material for applications related to even a marine environment. It was observed that both temperature and period of calcination will influence the reactivity of the metakaolin produced. Metakaolin, a poorly crystallized powder, exhibits a specific surface of 12,000 m^2/kg (Khatib and Wild, 1998), and the average particle size varies from 1.5–2.5 μm (Caldarone, 1994). The proportioning levels or the replacement percentages possible in cement and concrete compositions for these calcined clays are still being studied. However, the improvements in strength and more specifically the durability are reported by several investigators. Another material of a clay origin is zeolite, which could be used in both its natural and calcined forms in concrete. Laboratory investigations show that the strength improvements due to pozzolanic reactivity of zeolites appear to be fairly higher than that of fly ash though it is certainly a little below that of silica fume. The addition of such fine powders as metakaolin and zeolite ensures a cohesive mix that is less prone to bleeding.

2.6 Inert Filler Constituents

The need for inert filler constituents either as a part of the cement or maybe even as additional powder extenders to the cement is probably very much felt in concretes of low and medium strengths, as the required cement contents tend to be extremely low and insufficient to coat all the aggregates and bind them appropriately. It is possible to choose a wide variety of fine materials, including very fine sand or even siliceous stone dust for this particular purpose. However, for a long time the use of limestone powder (LSP) has been prevalent due to its ready availability in the cement manufacturing process. Apart from the use of a simple 5% in addition as permitted under the various international cement regulations, there have been attempts to use up to about 30% LSP and maybe even sometimes beyond. Recent research efforts have shown that the material in its fine form (generally finer than the cement at around 5000 cm^2/g) may exhibit some chemical reactivity akin to the pozzolanic reactivity. However, the cementitious strength efficiency of the LSP is certainly very small and may not improve the strength characteristics significantly. However, in its fine state, it may still exhibit a level of pore filling effect and is the most suitable powder extender. It should be recognized that the additional fine material will significantly enhance the wetted surface area requiring additional quantities of water at the same workability level.

2.7 Aggregate Characteristics

Aggregates occupy a substantial volume of the concrete mixture, nearly a third of its volume in the normal concretes for general purpose application. Natural aggregates are obtained from the geological formations locally. Incidentally, rocks could be classified into the three different categories of igneous (granite, diorite, basalt, rhyolite, etc.); sedimentary (conglomerates, sandstone, shale, limestone, dolomite, etc.) and metamorphic (schist, slate, quartzite etc.) types. Depending on the formation, the intrusions and maybe even the environmental degradation, these could have strengths ranging from 25 MPa to well over 250 MPa. Apart from the natural riverine deposits, they could also be produced by crushing the parent rock boulders for use as aggregating concrete. In the design of concrete mixtures, a specific distinction is made between the rounded (of natural origin) and the crushed aggregate because of the water content needed in each type for the same consistency and workability. Obviously is the fact that the more uneven and rough surface of the crushed aggregate will need certainly a higher amount of water or maybe even a higher level of paste content. The maximum size and gradation are indeed parameters in design of the concrete mixtures. A brief set of parameters that are essential for an appropriate characterization of the aggregates is broadly listed as the following.

- Origin, type and strength
- Size, shape and texture
- Density
- Moisture content
- Absorption characteristics
- Deleterious substances
- Chlorides or other impurities
- Grading characteristics

It is possible to view the aggregate as a single entity and define a combined grading curve as is adopted by a few national codes like the DIN norms. However, it was customary in both the British as well as the American concrete mixture design philosophy that aggregates be referred to in two separate fractions called the coarse and fine aggregates. The relative merits and demerits of each of these approaches is appropriately discussed later while looking at the performance of these concrete compositions. It is also necessary to characterize both these fractions appropriately and assimilate the influence of each of these and the characteristics of the concrete produced finally. The various tests and specifications for ensuring their suitability in concrete compositions will also be discussed in later chapters.

2.8 Production, Transport and Placement

It is obvious that the concrete mixture design procedure could be defined to ensure a specific strength and/or durability. However, the actual performance of concrete as it exists in the structural member is always defined by the processes involved not only in its making but also in its transport, placement and curing. In general the mixing operation could be performed using either drum or planetary mixers, depending on the batch volume and speed of production required. It is obvious that planetary mixers could ensure a more uniform mix in a much shorter period. In most cases, particularly with the present trend of adopting ready mixed concrete (RMC), weigh batching of the various constituents is indeed taken for granted.

It is in fact extremely difficult and may not even be environmentally sustainable to produce concrete very close to the construction site, necessitating a close look at how it can be transported appropriately from the production site to the actual construction location. At present the practice of using transit mixers, which inherently have the capability to keep the concrete agitated in the slowly rotating drum, is well accepted. Transit times of about an hour are an accepted norm, and in large metros this could even be higher. Admixtures play an important role in ensuring that the well-proportioned concretes are indeed transported over this distance without bleeding and segregation and are still suitable for the required application without either a loss of strength or performance. Methods such as re-tempering or re-plasticizing with an additional dose of the admixture are indeed processes that are accepted and even recommended in certain cases.

Finally, for large construction practices, the material delivered to the site could be placed in the appropriate location using either crane and bucket systems, or alternatively through pumping. The consistency characteristics of concrete may have to be appropriately adjusted based on the requirements of the member characteristics as well as the method of placement. The advent of concretes of the self-consolidating nature has placed additional constraints as well as requirements not only on the pumping systems but also on the moulds adopted.

2.9 Consistency and Compaction

The appropriateness and authenticity of the concrete mixture design being one aspect of arriving at the correct material for structural member; a more important part of the solution is to ensure that the material delivered is of the consistency proposed. In fact it is not just the water content that defines the consistency and an appropriately compacted element. It is important to ensure that the constituents, particularly the aggregates, have appropriate grading and also that there are enough fine materials in the concrete mixture to allow the aggregates to slide over each other during the compaction process. The factors are inherently taken care of in traditional mix design of normal concretes through broader outlines contained within. However, it is felt that for higher performance regulations like the minimum cement content and maximum water particularly, unreasonable cement ratios are recommended. One simple fact that can be stated is that high performance concrete need not necessarily be only beyond a certain strength grade. It should be realized that there could be a concrete of the highest performance for a particular strength grade itself. Needless to say, a lower strength concrete of about 20 to 30 MPa could still exhibit a very high performance attribute, be it the permeability or the chloride diffusivity or for that matter any other specific characteristic that could be the performance criteria for the particular application.

Apart from this, the consistency or workability of the concrete mass should essentially be suitable for the application at hand—like slip forming, though compaction, self-consolidating, etc. The use of external tools like vibration and pressure has its own place in the making of concrete structural elements. Some of the compaction techniques adopted could be listed as:

- Vibration and high frequency vibration
- Vacuuming and vibro-vacuuming
- Spinning and vibro-spinning
- Pressing and vibro-pressing
- Combinations of the above

It may not be possible to explain the variety of different methods and procedures adopted for compaction, starting from the earlier ones like packerhead methods in the pipe manufacturing to the more recent ones like the thermal-vibro-pressing adopted in producing ultrahigh performance cementitious composites in an effort like this. It is also obvious that flowing and self-consolidating concrete mixture compositions have their place in application potential of their own, and it is not necessary to have the level of fluidity that they bring with them for several other applications that require level of cohesion and shape stability like in the case of concrete printing.

2.10 Early-Age Effects in Concrete

The fact that using appropriate constituents confirming to the required norms goes a long way in making concrete composites perform well is to be recognized, while at the same time the consistently, delivery and placement methodologies also need a due consideration. Notwithstanding, all the above the behavior of concretes in its early ages has a serious influence on the performance of the hardened concrete and requires a reasonable understanding. The wet, highly flexible, unhydrated cementitious mixture has a delicate balance both due to the internal hydration aspects as well as the interaction with the environment to which it is partly exposed. The physical effects of the settlement of solids with the escaping bleed water creates a pore system that is indeed a pathway for the later permeability and the diffusion of ions into the concrete mass, leading to its degradation and the corrosion of steel in concrete.

In the first place, the water escaping the system and the consequent settlement from the loss of water surface of the concrete and the water absorption by the moulds or soil results in the reduction in volume known as plastic shrinkage. The amount of plastic shrinkage is significantly affected in most cases due to the evaporation of water from the surface, which is primarily influenced by the relative humidity, ambient temperature and the wind velocity. Once the hydration progresses to a certain degree, the capacity to bleed will reduce and there may not be any further supply of water at the surface for evaporation. It is at this stage that the continuously hydrating concrete, due to its stiffness, will not be able to take the tensile forces created by surface evaporation, and the effect is reflected as crazing cracks (with a diamond pattern primarily) on the surface. These are essentially shallow surface cracks that could easily be avoided by misting the surface (not impounding with water as can influence the water cement ratio of the surface concrete significantly). This is of utmost importance particularly when the concrete of high strength containing invariably higher cement content is exposed to sunny, hot and windy weather conditions. It is also to be remembered that the plastic shrinkage effects need not necessarily be limited to the surface of all, and end concretes of very high flexibility can also reflect in cracking along the reinforcement (also called plastic settlement cracks), which could cause corrosion of reinforcement and failure of the cover concrete particularly when there is inadequate cover. At this stage, it is appropriate to look at the possibility of estimating the water loss due to the environmental effects on the surface of the concrete. The possible effects of the different environmental parameters have been collated and presented by ACI 305.1, 2006. ACI presents the nomogram for this estimation given the environmental factors associated with the concrete construction.

It is indeed a fact that concrete is a porous material, and the movement of moisture due to environmental variations is always a factor that will cause volume changes within the concrete. Specifically, a decrease in the moisture content is associated with drying shrinkage, which causes cracking because the tensile strength of concrete is rather low. This could lead to the inadequate performance of concrete in terms of both durability and corrosion of steel within. It is also possible that the depletion of moisture content with in the pores could be due to the self-desiccation effects from the unhydrated cement (at higher cement contents) or from highly reactive supplementary cementitious materials like silica fume which tend to hydrate by absorbing moisture from the already formed calcium silicate hydrates and thereby disturbing their characteristics. This type of shrinkage is generally referred to as autogenous shrinkage. This may have to be viewed more seriously as more than the effects of shrinkage, the strength retrogression due to self-desiccation may be much more serious. The present effort to address some of these problems is to ensure a reasonable quantity of water through what are known as self-curing compounds.

Apart from shrinkage, the heat generated during the hydration process could also lead to both local and global effects. The fact that concrete is a poor conductor of heat ensures that there is a substantial temperature difference between the core concrete and the concrete at the surface, even after the concrete has set and probably achieved some strength. The restraint offered by the outer cover concrete to the thermal shrinkage effects could lead to cracking and failure, particularly in mass concrete structures. A similar phenomena can also occur when a layer of new concrete of sufficient thickness is placed on top of an older concrete. The massive temperature reinforcement provided in large concrete foundations is to counter the effect of such cracking and separation of the foundation into smaller segments. It is also possible that an appropriate modulation of the heat generated could be used for accelerating the hydration process by ensuring that there is not much of a heat loss on the surface, which is used as a remedy in some cases. Notwithstanding this possibility of significantly large failure planes in massive structures, it is also to be realized that the internal heat of hydration could set up apparently insignificant micro-cracking within the concrete mass. Associated with the micro-cracking due to shrinkage, these could significantly influence the strength and failure characteristics of the concrete material itself. Some of these aspects will be looked at in the later chapters.

2.11 Curing

The necessity for curing is only obvious from the discussions in the preceding paragraphs. In simple terms it is to ensure that the hydration is not stifled process (both during the early stages as well as in concretes after hardening) due to the lack of moisture necessary. One of the primary aspects that is often discussed is the length of curing time after the concrete has set, though a more important and relevant factor is to decide when to start and maybe even how to cure. A simple answer could be to state the obvious, that it depends on the concrete's necessity for an unhindered hydration. The environmental factors that drive the of moisture from the surface of the concrete decrease the availability of the small amount of bleed water from the surface, which ensures that the water cement ratio envisaged originally is indeed preserved during the initial hydration. This part of the curing necessity probably defines the starting point adequately. However, it is important at this particular stage not to supply too much water as that will greatly influence the water cement ratio at the surface of the member (probably the most critical location requiring the actual compressive strength in a bending member). Even the occurrence of a light rain could have serious detrimental effects on the strength of at least the top layers before the final set. In practice it was seen that this could be as early as 3 to 4 hours in concretes of higher strength even without a direct exposure to sun. An appropriate and practical approach would be to adopt misting at the surface when the concrete attains enough strength to walk on without leaving an impression and the surface looks to be dry. In high strength concretes with heavy admixture dosages, this point could be quite abrupt and needs specific attention. The application of membrane curing compounds that are supposed to seal the moisture within the concrete is generally applied at this particular stage.

The second aspect is to ensure that the water in the pore system in the hardened concrete, once again particularly during the early days of its hydration, need be replenished for ensuring an adequate strength gain rate. Apart from the temperature and humidity in the external environment, the internal temperatures due to the heat of hydration could be a factor. At this stage, moist curing through wet fabrics like hessian or burlap is the most optimum. Periodic waiting of the fabric means a constant vigil or controlled spray that involves additional inputs. The length of the curing period is a parameter essentially dependent upon the type of cement, and with the advent of the several different combinations of cementitious materials in the market, it becomes difficult to have specific norms and could only be judged from site conditions. However, it is most important to state that in almost all cases, and a minimum seven-day moist curing is indeed appropriate. Even so, the ill effects of inadequate curing during the first three days can never be overcome through any effort at a later stage. For very slow setting cementitious compositions, the length of curing is necessarily longer and a broad guideline could be to continue the curing for 14 days.

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3

Concepts of Cementitious Mixture Design

3.1 Introduction

A material like concrete, with its ubiquitous presence in every continent and even in the oceans, should have had a reliable and consistent design methodology, at least in that part for what is utilized conventionally in the day to day general building activity (most often termed as normal concrete) for ensuring at the least the one single design parameter, the strength. However, it is often stated by several investigators, committees, and national and international bodies that are responsible for the formulation of recommendations and codal provisions that the variations in the local materials could simply make the above very difficult if not impossible. Even so, there have been several methods used for the design of the normal concrete composites by these very same national and international organizations, backed up by experience from several research investigations into the so-called normal concrete for conventional applications. However, it can be seen that even these recommendations suggest that any such concrete design should always be proof checked through trial mixes to ensure its validity, in a way negating the very concept of design which should ensure a reasonably acceptable material if the recommendations were followed. Maybe the necessity of the series of trial mixes often presumed essential is in a way only perpetuating the age old practice from yesteryears. In fact, with the experience of several decades in formulating the concretes, both research in the laboratory and for structural applications in field, it is felt that the recommendations in most cases present a fairly accurate approach if only they are adopted appropriately. It is obvious at this stage that some of the more important aspects of the design and their interactions should be understood explicitly to ensure the desired objective of arriving at a specific strength concrete in most cases. The present effort is a step in that particular direction so that not only normal concretes but those other modifications of concrete that have come into vogue can all be designed and put together appropriately with a reasonable certainty through these recommendations.

At this stage, a broad outline of the various fundamental design parameters that came into focus over the years for understanding the behavior of normal concretes in the conventional strength range of about 20 to 50 MPa, required for most of the constructions in practice, appears to be the appropriate fragment with which to start. A very large number of national recommendations focus their attention on this requirement primarily. The regulations that are prescribed to ensure the durability of concrete are also simplified to the extent possible and are built into the above design recommendations, in the form of acceptable minima or maxima, to ensure adequate protection against environmental degradation. Some of these broader aspects have to be specifically looked at and appreciated before actually trying to focus attention on the very regulations that the various national bodies have put forth. It is obvious that most of this background information that forms the basis for recommendations is not adequately or explicitly presented in the design procedures proposed, essentially to have the focus only on design and to keep the document brief for use by practicing professionals.

3.2 Concrete Design Concepts

Concrete mixture design is essentially a compromise between the conflicting requirements of performance and economy in a given environment as is the case with most engineering designs. The need to ensure strength and performance of the concrete at any specific point of time as the structural requirement requires a look at the hydration and strength development aspect as well. The complexity of the structural form and shape apart from the aesthetics and service life characteristics that need be ensured define the consistency and compactability of the concrete into the various forms and shapes of the members. In retrospect, these two aspects have indeed influenced the design of concrete mixtures in various ways, presenting several different concepts emanating from the different points of view, depending on the importance given to any specific aspects of the design of these mixtures. An appreciation of the various factors that could and that had influenced the thinking, deliberations and recommendations over the years as discussed will present an opportunity for defining a way forward. These critical discussions have indeed been the background for the discussions and the modeling efforts discussed in later chapters.

The design methodologies proposed have been widely varying, probably depending upon the concept and the criteria envisaged as the primary objectives like the following.

- Recommendations based on fundamental characteristics of the materials and their behavior in concrete
- Recommendations based on practical experience with the concretes mixtures in the field that allow the translation of the concepts through a semi-empirical approach
- Recommendations that are specifically directed toward a segment of the concrete user community, to be immediately applicable

Each of these practices has their relative merits, advantages and maybe even certain limitations. In general a number of efforts were made to collate and unify the different viewpoints, or maybe the recommendations alone, by a few. Many of these design formulations are based on some fundamental approaches that effectively try to address the green state characteristics and the hardened state characteristics of the concrete. Also, while strength and performance characteristics of the resulting concrete are of primary importance, the fact that inadequate compaction would seriously impact them both is well recognized. Some of the specific aspects that need to be borne in mind for an effective design methodology could be listed as the following.

- Concrete effectively is a mass of randomly sized and distributed aggregates bound by a cementitious compound formed due to the hydration of cement. The hydration reaction in itself requires a very small portion of the mixing water to ensure the fluid mass of adequate consistency that could encapsulate the reinforcement cage effectively and fill the complex shape of the mould appropriately.
- The additional water not required for hydration will incidentally reflect in the porosity of the concrete, effectively lowering its strength. It is also to be recognized that the porosity of the resulting structural shape after final set can only be addressed by the father hydration of the cementitious compositions, effectively suggesting that curing of concrete is an important aspect in hydration and consequently the strength of the concrete.
- This hydration of cement is an exothermic reaction, and the resulting heat needs to be effectively dissipated to ensure that the microcracks due to thermal shrinkage do not affect the strength of the concrete adversely.
- It is obvious that the cement content has to be limited not only from economy considerations but also for efficiently limiting the effects of creep, shrinkage and temperature. This fundamental aspect has never been specifically appreciated and certainly never stated explicitly as a design requirement.
- The filler materials also have to be appropriately graded to ensure effective packing from both the considerations of the reduction in void space for ensuring adequate impermeability and to assist in limiting the cement content. The fact that an appropriate gradation of the constituents was necessary has never been adequately emphasized.
- However, the binder content has to be adequate to coat the surface of all the aggregate fractions and bind them together apart from occupying the remaining void space after hydration. There has never been any effort to quantify this aspect.

- The second part of the bargain is to ensure the lowest water requirement for imparting adequate flexibility to ensure the highest strength possible. In a way this aspect is taken care of by the water cement ratio to strength relationship in most recommendations.
- The participation dynamics of chemical admixtures in this scenario, particularly in terms of their effectiveness (and not the effectiveness of water in their solution), has to be appropriately analyzed and regulated.
- Having said this, in more recent times it was clearly observed that the binder could be augmented by supplementary cementitious materials that act as fillers and secondary binders imparting additional impermeability to the matrix.
- It may be prudent to recognize that these supplementary cementitious materials could increase the water demand, due to the additional wetting water requirements of such fine powders. This obviously will have the effect of increasing the water cementitious materials ratio and consequently lowering the strength if it is not addressed appropriately.

In fact, it is this delicate balance of the constituents that makes the design of the concrete mixture so intriguing, complicated by the fact that a large proportion of the constituents other than the cement are all obtained from local sources with the obviously associated variability in terms of the properties, and grading is difficult to envision in advance. Having said this, it is obvious that the broad outlines for the design of the simple and most often utilized normally vibrated concrete can be viewed and articulated through some basic axioms to start with. In fact, if appropriately extended, some of these basic axioms could still effectively ensure most of the widely varying concrete types even though they are perceived to be different. It is with this particular idea that the fundamental design parameters are being looked at presently.

3.2.1 Concrete Design Parameters

The complexity of the fundamental design parameters, the methodology to address the requirement through design and testing as the practical significance of such an evaluation is a complex web of factors that are highly interrelated and have to be understood in an attempt to simplify the concrete mixture design methodology. An effort has been made to show the complexity involved in the form of a table (Table 3.1) outlining the broad connectivity to the characteristics of the concrete during its life span.

It is recognized that many of these are interdependent and have to be investigated by a minimum of three different independent tests and cross correlated between parameters and tests as well. These keep changing with time

TABLE 3.1

Parameters and Relevance in Concrete Mixture Design

Fundamental Property	Design Requirements	Evaluation Parameters	Practical Application
Green-State Characteristics			
Consistency	Agg. size	Slump	Thin members
Passing ability	Reinf. spacing	J-ring	Joint detail
Flowability	Flow path	Slump flow	Complex shapes
Segregation resistance	Aggregate grading Paste content	Sampling	Deep members
Bleeding potential	Wetted surface Water content	Bleed water	Water content
Air entrainment	Air content	Void distribution	Frost resistance
Early Hydration Effects			
Temperature	Thickness	Heat of hydration	Thick foundations
Heat of hydration	Member size	Temperature	Limits on thickness
Shrinkage and rate	Paste content	Surface area	Floors
Hardened-State Characteristics			
Density	Heavy aggregate	Weight	Nuclear applications
Absorption/Desorption	Light aggregate	Absorption	Insulation
Moisture migration	Porosity	Absorption	Performance
Permeable porosity	Min. paste content	Absorption, UPV	Durability
Pore size distribution	Hydration	MIP/N_2 adsorption	Durability
Performance Characteristics (Mechanical)			
Strength	w/c ratio	Compressive strength	Structural design
Surface hardness	Strength	Rebound	Impact
Wear resistance	Agg. characteristics	Abrasion resistance	Heavy-duty floors
Ductility	Fiber reinforcement	Fracture energy	Energy absorption
Fracture toughness	Fiber reinforcement	Fracture energy	Energy absorption
Impact resistance	Fiber reinforcement	Fracture energy	Energy absorption
Blast resistance	Fiber reinforcement	Fracture energy	Energy absorption
Creep	Paste content	Permeability	Long-term effects
Fatigue	Paste content	Absorption	Long-term effects
Performance Characteristics (Environmental/Chemical/Electrochemical)			
Thermal degradation	Temperature	Weight loss	Strength loss
Fire resistance	Temperature	Weight loss	Strength loss
Freeze—Thaw	Porosity	Absorption	Strength loss
Sulfate attack	Porosity	Absorption	Strength loss
Acid attack	Porosity	Absorption	Strength loss
Chemical degradation	Porosity	Absorption	Strength loss
Carbonation	Porosity	Absorption	Strength loss
Ion permeability	Chloride binding	Diffusion coefficient	Corrosion resistance
Corrosion resistance	Chloride level	Conductivity	Cracking

and internal moisture conditions, and many of the tests if appropriately and consciously addressed can give information about several aspects of the behavior and performance of the material considered from different viewpoints.

3.3 Hydration and Strength Development

The hydration characteristics of cements in general have already been looked at the previous chapter while discussing the material parameters that could be of interest. However, it is important to realize that the hydration process continues well after the initial and final set though there is a deceleration ultimately ending in a steady state. The importance of ensuring moisture supply in the pore system for the hydrating cement is also discussed in terms of possible strength retrogression as well as the drying and desiccation effects causing additional shrinkage. While the strength gain rate is considered a parameter related to the maturity (a product of time and temperature), the rate in itself is influenced by the composition of the cement and more important proportions and types of the supplementary cementitious materials the system. In particular, the long-term strength aspects and the dynamics of supplementary cementitious materials on the presently advocated newer blended cements are not yet fully understood. One way to address this information gap is to consider that the normal 28-day strength as the limiting strength is the case of concrete containing high end pozzolans like silica fume and metakaolin, and the 90 day strength of the limit for lower efficiency types like fly ash, GGBS, etc.

It should be remembered that the strength of concrete is a parameter in design not just for the demolding but also for addressing the requirements for transfer of the prestress. It is also needed to assess the effects of shrinkage in layered constructions, particularly the top slab integration effects on prestressed girders. The long-term strength may also be a matter of concern in assessing the creep and temperature effects on structural members, and the effects of compatibility materials in rehabilitation of structural components.

3.4 Aggregate Distributions

A look at the concrete mix design propositions of the early times always contained within itself the recommendations regarding aggregate distributions in terms of the grading, typically as in the Road Note No. 4 (DSIR, 1969). Over the years, this part of the requirement has been presented separately, probably to ensure a clear picture of the aggregate compositions and grading all together. In the first place, the maximum size of aggregate is a parameter that is appropriately selected based on the least thickness in the structural member and the spacing of reinforcement adopted. This is to ensure that the concrete mixture could flow easily and occupy completely the cover regions in particular to have the desired composition of concrete or through the structural member. This part of the philosophy is explained in most recommendations. However, what is not explained in clear terms is the fact that an appropriate gradation of the aggregates in question will go a long way in ensuring the loosening effect in the aggregate mass itself (without the aid of the mortar matrix surrounding the aggregate). Also it would minimize the mortar component and ensure the highest density possible with the least requirement in fines, which will automatically make the concrete designed, an economic optimum. It may not be possible to explain the complete background perspective regarding the grading distributions of the aggregates, but it will be inappropriate not to mention that the combined grading of aggregate without any missing proportions will go a fairly long way in ensuring the best performance of the concrete, all other factors remaining the same.

3.5 Structural Requirements

At this stage it is important to discuss the basic requirement in design, which in most cases is its capacity to withstand the expected loading on the structure. This obviously means the concrete in particular pass the design of a specific strength to ensure adequate structural carrying capacity. Concrete being a heterogeneous material, guaranteed minimum design strength is essential. Obviously this means that there should be a method to define the expected strengths of concrete through its composition. This leads us to one of the primary axioms for the design of concrete mixtures almost over 100 years ago by several different researchers of the past.

There have been several attempts over the years to understand the behavior of concretes, particularly its strength behavior. The fact that the lower water cement ratios result in higher strengths and vice versa, and given an appropriate proportioning of the constituents concretes will have nearly the same strength at a particular water cement ratio, was well understood probably long before the first attempts to define any relationship. Feret (1892) is generally referred to be the earliest to have defined an equation for the strength of cement mortars, though there have been others who reported on this topic earlier. He suggested the relationship that the strength of cement mortar "S" to be proportional to the amount of cement "c" per unit volume of cement plus voids, which can be expressed as

$$S = K\left[c/\left(1 - V_s\right)\right]^2 \tag{3.1}$$

where "c" is the cement content, "K" is a constant and "V_s" is the absolute volume of sand. This could be modified to concrete just by closing the absolute volume of coarse aggregates as can be understood and could be presented as

$$f_c = K\left[c/(1 - V_s - V_g)\right]^2 \tag{3.2}$$

where "f_c" is the compressive strength of concrete and "V_g" is the absolute volume of coarse aggregate. Probably the most acknowledged and appreciated water cement ratio to strength relationship for compactable mixes of good workability to date probably is one enunciated by Abrams (1918). Based on the experimental data he suggested that

$$f_c = A/B^{(w/c)} = 14000/7^{(w/c)} \tag{3.3}$$

This is one of the equations which has been extensively maneuvered and manipulated to fit to the results of several investigations over the years in one form or the other. It is also to be noted that similar water cement ratio to strength relationships were also proposed by researchers in Germany around the same time, and these will be discussed more in detail in the later part of this chapter.

Bolomey (1926) suggested a linear equation for strength with the parameter cement to water ratio as the following:

$$f_c = K_1\left[(c/w) - 0.5\right] \qquad \text{if } w/c > 0.4, \tag{3.4}$$

$$f_c = K_2\left[(c/w) + 0.5\right] \qquad \text{if } w/c < 0.4, \tag{3.5}$$

where K_1 and K_2 are constants, depending upon the strength as well as the type of aggregates, natural or crashed. Lyse (1931) also observed that the water cement ratio to strength relationship of Abrams earlier expressed by a logarithmic curve is nearly a straight line, making the "cement-water ratio a simpler expression of the quality of cement paste rather than the water-cement ratio."

These apart, there have been several others who appropriately adopted or suitably modified the earlier concepts for obtaining the water cement ratio to strength relationships, based on either the whole experimental results or through an evaluation of the possible constants that could fit the available data from literature. In this part we discussed only their relevance of mathematical expressions relating to the strength characteristics, which is only a part of the design requirement. The expressions relating to the consistency part and their relevance will be discussed later. Presently, maybe it is only appropriate to have a close look at some of what has been in vogue, particularly in terms of strength to water cement ratio relationships that have relevance to the present day cements and concretes. In the first place, to begin at the beginning itself, the relevance of the strength to water cement ratio relationships to the context of present day cements is always a matter of debate. More often than not, a few of these earlier concepts which are all known for about a century are reinvented with new constants associated to present day cements. Some of these attempts have led to the so-called generalized strength relationships for concretes in recent years. Even a semi-detailed outline of these will only prove that these also have limitations of their own, both in theory as well as in scope.

In one of the attempts to understand the intricacies of the mix design methodology, Shilstone (1991) opined initially that probably we have not gone far beyond the original water cement ratio to strength relationship of Abrams in presenting the PCA manual on the "Design of Concrete Mixes." The only change probably was that the original water cement ratio to strength relationship developed for volume ratios probably got converted to the weight fractions only. However, evaluations of the actual values show that this is not the case, and there have been effective upgradations of this relationship (Kosmatka, 1991). It is for this reason it is felt that the original Abrams relationship is replotted, showing the relationships using the weight fraction of the water cement ratio along with the strengths presented in the SI units on the alternate axes of the same graph (Figure 3.1). It can be seen that the original relationship of Abrams (Equation 3.6) will be Equation 3.7 in a similar

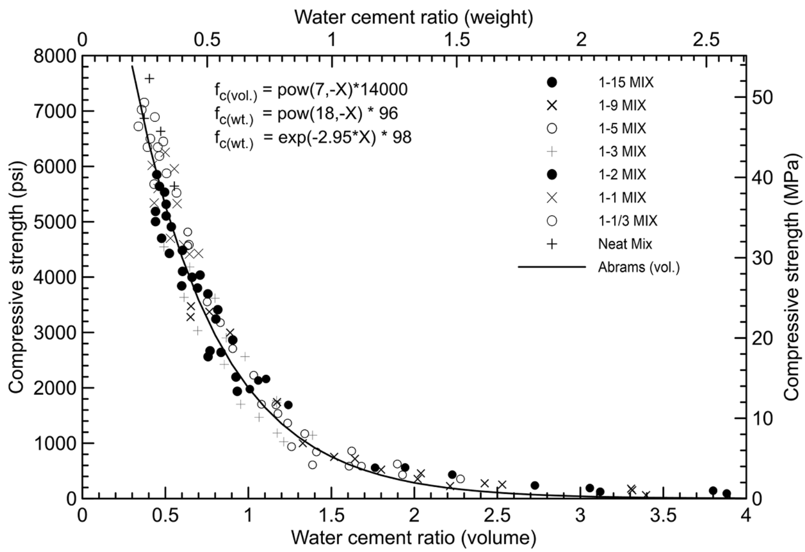

FIGURE 3.1
Water cement ratio to strength relationship. (After Abrams, D.A., Design of concrete mixtures, Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, 1918, 20 p.)

power format or can also be presented as Equation 3.8 in the exponential format alternatively (Abrams, 1918).

$$f_{c(vol.)} = pow(7, -X) * 14000 \tag{3.6}$$

$$f_{c(wt.)} = pow(18, -X) * 98 \tag{3.7}$$

$$f_{c(wt.)} = exp(-2.95 * X) * 98 \tag{3.8}$$

However, it is totally obvious that most traditional mix design methodologies recommend that the various national and international bodies have all used very similar water cement ratio to strength relationships, even if some of them were to present them as tables rather than presenting them in a geographical format. Some of the more prominent mix design methodologies proposed by these organizations are discussed in detail later in the chapter. But to give a very broad overview of the strength to water cement ratio relationships scenario, some of these relationships as proposed by the various bodies have been presented together, at least to show the wide variation in the possible relationships, similar to an attempt by Brandt (1998). It may not be in order to discuss in detail each one of these relationships, though a few broad statements could be made for a general understanding of how these are placed in relation to each other (Figure 3.2).

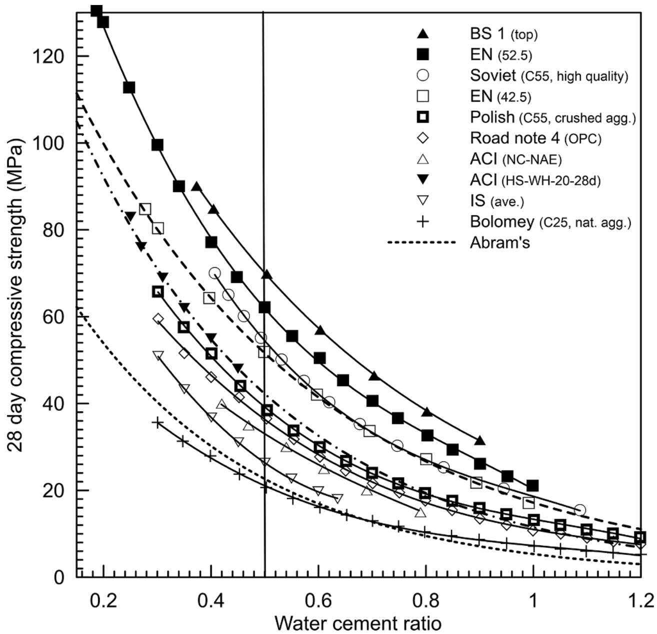

FIGURE 3.2
Water cement ratio to strength relationship. (After Brandt, A.M., *Optimization Methods for Material Design of Cement-Based Composites*, E & FN Spon, London, UK, 1998, p. 328.)

The more important facet of interest should be to see if there is any meaning in trying to look at a parameter that has such a wide variation. A further aspect is to actually look at the reasons and justifications in recommending such a widely varying parameter by almost every known national and international organization as a part of the basic design methodology itself. Finally, is there even a remote possibility of being able to explain the reasons for such a variation and a method of reconciling the same to ensure a level of authenticity and accuracy of the design procedure?

In this perspective, one can clearly see that the lowermost two curves, namely Abrams (1918) and Bolomey (1926) relationships, are probably the oldest of all, and obviously these concretes made with cement are of those times which are of a considerably lower strength. The two EN relationships proposed for the cements of 42.5 and 52.5 grades are almost at the very top, while the topmost curve happens to be the long-term strength relationship of the British DOE method. In fact, while most national recommendations present the water cement ratio to the 28 day compressive strength relationships for concrete (different types of concretes in some cases like the ACI), the British methodologies have always been looking at the water cement ratio to strength relationships at the different ages (essentially 1–360 days) as a matter of principle from the very beginning. If one is able to appreciate this aspect in specific, it may solve a lot of unease that is associated with the efforts in trying to bring some order to this design practice. There are also additional relations representing the ACI recommendations for normal and high strength concretes for a broad comparison. The details regarding some of these relations and the significance or usefulness of the same will be discussed appropriately in the respective chapters that deal with the provisions from the national bodies.

3.6 Construction Requirements

The next important parameter in the design of concrete mixture is capability to occupy the complete space in the mould, while ensuring that it fully encapsulates the reinforcement cage that is designed to provide the required tensile shear capacities of the structural member. The concrete obviously provides the compressive strength component requirements of the member, which was discussed in earlier paragraphs. Its flexibility requirement of concrete could vary depending on the member shape, size and reinforcement configuration apart from the compaction procedures adopted and the application. Various construction requirements demand concretes of varying flexibility or consistency defined through various measurement procedures like slump (varying from 0 to 200 mm or more) or VB times (varying from almost 0 to 30 seconds or more). Principally, the simple and basic constituents of concrete that can make this happen is to increase the water content for increasing the consistency or slump, given the assurance that there are enough fines supplied by cement of the total cementitious materials. The grading of the aggregates as well as the fine aggregate to total aggregate ratio as desired in some design methodologies could also be a matter for concern.

There have been several pioneering efforts to fix the quantity of water required for a specific consistency in concrete. The fundamental studies on the consistency and strength of concretes at a particular water content were first reported by Lyse (1932). Maybe the most notable concepts and criteria related to the total surface area of the constituents that have to be wetted appropriately for ensuring the required consistency were proposed by Murdock (1960). A comprehensive review of the concrete scenario is probably available through the state-of-the-art report of Popovics (1980). It is enough to say that most of these have their own theories, and each one attempts to propose a specific water content key in the aggregate matrix. In principle, the maximum size of the aggregate is the primary parameter, as it is assumed that the grading of the aggregate follows certain accepted norms. This also probably presupposes that there is a certain minimum cement content and a certain proportion of the fine aggregates which contribute to the loosening of the coarse aggregate skeleton, while at the same time contribute significantly to the water required for wetting their surface that is substantially higher than the coarse aggregate skeleton. Most national recommendations have suggested the water requirement for the various consistencies at any specific maximum aggregate size. These appear to have been prescribed based on a semi-empirical and experimental basis, while keeping the different theoretical assessments only in the background. Needless to say, one should be able to come to a reasonable understanding of the water requirements, which are also critical in arriving at the total cement content, having specified water cement ratio for the strength required earlier. The fact that none of the major concrete mixture design recommendations from the various national bodies appear to enunciate are the relationships proposed by the earlier researchers as in the case of strength to water cement ratio relationship. As already stated, they prescribe specific water requirements which could be moderated slightly for each consistency. This indeed puts a bigger burden on the understanding as well as any possible mathematical relationship for the consistency of concrete.

3.7 Environmental Requirements

Concrete as a material of construction has shown abundant promise and substantial resilience while performing even in the most severe environment conditions—be it the oceans, industrial and chemical plants, or even nuclear containment, apart from ubiquitous use in several other infrastructure facilities. This does not happen without the efforts of the designer to look at the degradation potential of the specific environment in which the structure is supposed to perform and ensure that the strengths, composition and other structural detailing factors are appropriately fixed. Incidentally, there have not been uniform specifications which are all-inclusive, as the different environmental parameters influence the behavior of concrete and the structure significantly differently. A few of these could be seen to be the following:

- The very basic environmental factors that are recognized appear to be the hot, hot and humid, cold and frost effects on the concrete constructions, some of them more critical during the construction phase while others could last its lifetime.
- The second important environmental factor that requires specific attention because of its very large presence is the ocean environment, considered the most severe natural environment for the degradation of concrete and the corrosion of steel in concrete.
- A third environmental factor is associated primarily with the sulfate levels in soils, both inland and specifically the marine and estuarine regions, where generally sulfate resistant or slag based cements are advised.
- The last factor can be seen as the industrial environment, which is sometimes extremely severe, where specific chemicals related to the industry influence the degradation and corrosion in concrete structures.

A more detailed discussion on the different environmental classifications available in the appropriate regulations that could be adopted will be discussed later while presenting the information regarding higher performance concretes in later chapters.

3.8 Aesthetics and Service Life

One of the often neglected and probably the most relevant aspect of concrete structural design is the appropriate recognition of the stress flow and load distribution, which could easily be addressed through the different structural forms and shapes (beam and column, tube, tube in tube, special and membrane types). The recognition of the physical aesthetics that merge with the topographical characteristics of the location as well as the resilience that the shapes could offer to severe environmental forces are still not largely appreciated in structural design, and are often considered to be the realm of the architect alone. Secondly, it is indeed important to effectively plan for a desired service life, which is to be ensured not just through construction but by recognizing that even concrete structures need an appropriate maintenance schedule (even if it were to be much less than that of steel in most cases). It is during the planning stage itself that the entire structural performance during its complete lifetime, even considering the possibility of having to change the usage from time to time, has to be put in place. The concept, design, execution and maintenance documents have all got to be made ready through a body that is different from the one taking care of each of the above as proposed in the *Guide for Durable Concrete* (CEB-FIP, 1992). There are of course other such recommendations by the various individual bodies concerned with construction and even some of the major construction agencies and material manufacturers as well.

3.9 Comprehensive Overview and Limitations

It can be said that while there have been several efforts toward a comprehensive understanding of the requirements of concrete constructions and correspondingly several reports and recommendations are available from these efforts, a broad bird's-eye view that summarizes the basic philosophy behind the requirement and the corresponding reports is probably not easy to find. Certainly there are excellent if not outstanding pieces that delineate the various factors contributing to the degradation of concrete and the corrosion of steel in concrete with consummate recommendations to address them in specific environmental regimes. Maybe it is because the researchers are predominantly associated with such research and naturally would like to present their domain knowledge in that form and leave it to the national and international recommendatory bodies to do the comprehensive compilation part independently. For an appropriate understanding of the concrete mixture design philosophy, it may be appropriate to look at some of these more comprehensively and understand the limitations that have to be addressed.

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4

Modeling and Unification Concepts

4.1 Introduction

The concept of modeling in itself involves finding a common ground to define the process through a set of constituent relationships, generally associated with the need to facilitate an understanding of the effects of the variations in process without going through extensive experimental investigations. It is obviously very helpful when there are several parameters defining the process and also when there is a repetitive need for at least a reasonably accurate result (within a standard level of variance). Invariably, the effective model is characterized by two distinct parameters, namely the range of parameters that can accommodate and the accuracy with which it can predict. This obviously means that there is a definite set of process results with the range of variations that the model is expected to cover initially, which form the basis in arriving at the model. Notwithstanding the fact that many times the models have the capability to predict reasonably accurately this initial set of results, there should be a completely different set of process results, maybe from a different source and if possible associated with a different background for their actual existence even, to verify if the model derived from the previous results could predict the presence with reasonable accuracy. This indeed is a tall order, and many times it is a satisfactory if the prediction capability of the model to the initial set of results on which it is based is acceptable. In concrete, cognitive models to represent the strength considering the various volumes or weights of the constituents, derived through mathematical evaluations like partial differential equations, fuzzy logic, neural network or even combinations thereof have adopted in their attempts to present mathematical models. But such a global approach without correlating the actual factors contributing to the strength of the material will at best be a representation of the dataset used. In this perspective, it is supposed to have a critical look at the mathematical modeling of the design of concrete mixtures, considering firstly the earlier attempts which are based on the generally accepted principles of the basic working of a concrete mixture design.

4.2 Concepts of Modeling Composites

The concept of combining two dissimilar materials to arrive at a composite that could compensate for the limitations of the characteristics of either or both the materials has been attempted for a long time. Fiber reinforced polymer laminates are an excellent example wherein the fibers which have very high strength and/or modulus are bound together through a polymeric material of lower strength to help the unified action of the fibers through the transfer of stress by the polymeric binder, which may be considered similar to concrete. Even in discreet fibrous dispersions in a matrix, the fibers act together essentially through the bonding action of the matrix while carrying the load across the cracks.

Attempts toward an understanding of the characteristics of binary composites in terms of the characteristics of the individual components have been afoot for a long time (Voigt, 1889; Reuss, 1929). The general rule of mixtures presents an avenue to establish the characteristics of the composite material, like the mass density, tensile strength and elastic modulus of the composite. In the case of concrete, considering the corresponding volumes of the matrix phase (mortar, p_m) and the intervening fibrous inclusions phase (aggregate, p_a), the mass density of the composite (ρ) can easily be seen to be

$$\rho = \rho_a \cdot p_a + \rho_m \left(1 - p_a\right) \tag{4.1}$$

where ρ_a and ρ_m are mass densities of the mortar matrix and the aggregate, while p_a is the corresponding volume fraction of the aggregate in the concrete. This aspect of the rule of mixtures for mass density is very much a part of several of the concrete mixture design methodologies as propounded by the various national bodies, and will be discussed later in detail.

However, the rule of mixtures for assessing the elastic modulus will depend upon the orientation of the reinforcing fibrous phase (aggregate). Assuming a perfect bond between the matrix and the fiber phase, the elastic Young's modulus of the composites (E_{vo}) as given by Voigt (1889) for an isostrain model (when the fibrous reinforcement is in alignment with the strain direction) can be established as

$$E_{vo} = E_a p_a + E_m \left(1 - p_a\right) \tag{4.2}$$

where E_a and E_m are elastic moduli of the aggregate and the mortar matrix correspondingly. Similarly, for an isostress model (when the fibrous reinforcement is perpendicular to the strain direction), the elastic Young's modulus of the composites (E_{re}) as given by Reuss (1929) can be seen to be

$$1 / E_{re} = \left(p_a / E_a\right) + \left[\left(\left(1 - p_a\right) / E_m\right)\right]^{-1} \tag{4.3}$$

Correspondingly, when the reinforcing fibrous material is randomly oriented, it can be appropriately resolved into the components along and particular to the direction of stress, and the elastic modulus of the composite can be assessed through a combination of the two models. It is also to be noted that the Voigt model corresponding to the loading when the fibers are parallel to the loading direction will result in an upper bound solution, while the Reuss model (also known as inverse rule of mixtures) with the loading perpendicular to the direction of fibers will present the lower bound solution. The estimates of the elastic Young's modulus by the hybrid solution (E_{hy}) presented below lie somewhere in between the above two values.

$$1/E_{hy} = \left[\left\{ \left((1 - p_a)/E_p \right) \right\} + \left\{ p_a / \left(E_a p_a + \left(E_m (1 - p_a) \right) \right) \right\} \right]^{-1} \tag{4.4}$$

A graphical representation of the effect of the volume fractions on the Young's modulus of the composites as discussed above is presented in Figure 4.1.

Materials like concrete are formed by cementing or binding together aggregate fillers in a matrix of mortar. Theoretically, the aggregate intrusions in the mortar matrix in concrete could also be considered to be similar to the action of fibers as in the earlier fiber reinforced materials. Apart from

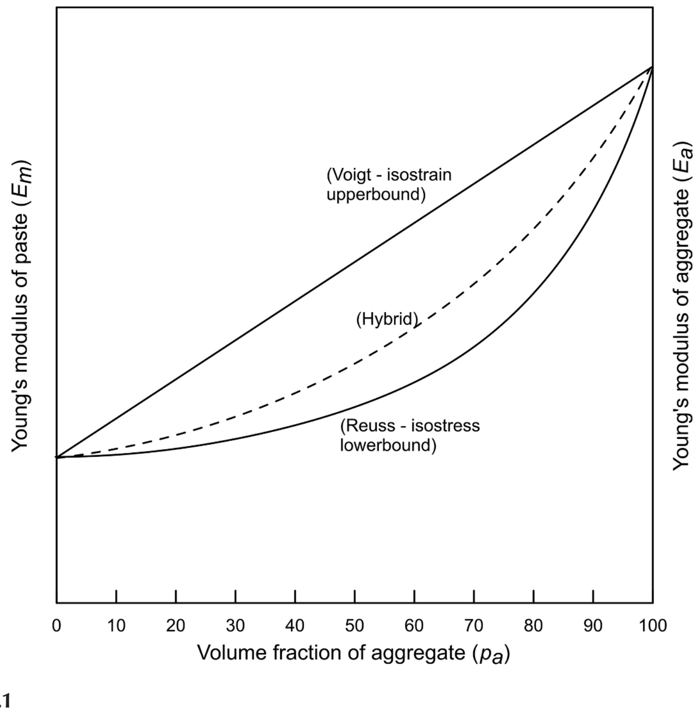

FIGURE 4.1
Effect of volume fractions on the composites.

this, the confined compression scenario of the mortar in between the concrete aggregates probably helps in ensuring that the overall strength of the material is significantly higher than that of the weaker of mortar in the composite. Also, there could be other effects like the absorption of the heat of hydration from the cement reaction by the aggregates resulting in lower thermal stresses that cause micro-cracking in the system. Some of these factors are probably neither fully investigated nor appropriately quantified to discuss and delineate their effects. The idea of looking at models to predict the characteristics of the composites is to ensure a reasonably reliable first assessment of the strength of the resulting composite and to ascertain its suitability. In most modeling practices, the resulting product is fine-tuned through verification and later modulation of the components if need be to achieve the level of accuracy desired. In the present context, traditional experience over the past almost hundred years in defining the strength characteristics of concrete and the design of philosophies proposed by the various national and international recommendations are revisited. It is with this that the analytical formulations have been attempted. These are later verified through experimental data available in the literature so that the mathematical model proposed is a most effective solution. Apart from what was said, the characteristics of the primary cementitious material, the cement itself, needs a better understanding in terms of its strength characteristics. In fact, earlier research efforts toward an understanding could show a way forward toward explaining some of the anomalies in terms of the water cement ratio to strength relationships from the various organizations that were seen in the previous chapter.

4.3 Unification Attempts

Any effort toward an understanding of the strength characteristics of a concrete mixture is primarily influenced by the strength characteristics of the cementitious binder. The appropriate starting point for such an understanding is basically looking at the characteristics and the development of ordinary Portland cement as it is primarily called. Since the first patenting efforts of Joseph Aspdin from Leeds in England in 1824 into what was then as already known hydraulic cement, there have been several efforts toward an appropriate and effective utilization of the same. Concrete, a mixture of sand and gravel or crushed rock (aggregates) bound by the hydrated paste of cement and water, has become probably the most important and ubiquitous material of construction over the past couple of hundred years. Its primary success lies in the fact that in its infancy of production, it results in a cohesive plastic mass which can be cast into an appropriately proportioned mould of the required size and shape. Later the hydrated cementitious compounds resulting in the heard stone-like material called concrete will exhibit the compressive strength as required and with reinforced tensile steel will be able to resist the applied loads in moments.

It is indeed a tribute to the untiring efforts of several research workers in the early 1900s that the very low strength concrete of those times has now reached levels that could compete in several significant ways with the most often advocated alternative (metallic) material, steel, in every aspect imaginable. In fact, the early prehistoric practices of rammed earth or the Byzantine and Roman practices of rammed floors and other construction practices have changed significantly with the introduction of reinforcement into the concrete practice. Over the years, the need for flexibility of the concrete mass to pass through the reinforcement cage and appropriately cover the reinforcement pushed the semidry mixtures of those times to be modified into flexible matrices of different consistencies.

In this scenario, probably the first and most important contribution to the technology of concrete materials is the water cement ratio relation that was presented by Duff Abrams in 1924, exactly a hundred years later. Even though there have been other reports presenting such relations earlier by Lyse and Ferret, it is a fact that the mathematical expression based on then available data on concrete mixture proportions as was presented by Abrams is the most accepted and appreciated. This indeed was the starting point to have a clear definition of the strength of concrete, which invariably is also related to several other mechanical parameters and even the durability aspects of concrete over the years.

One major factor that could influence the design of the concrete mixture in particular is basically the characteristics of the cement itself. Of these, probably the most important is the strength of cement. A look at the strength of cement over the last hundred years clearly shows that there have been significant improvements, primary owing to the fact that the vertical shaft kilns have given way to rotary kilns, and even the very long rotary kilns required during the wet process production have changed to substantially shorter ones with the introduction of preheater towers with the precalcinator. The recent developments in the grinding processes coupled with an understanding of the clinker microstructure modulation methods have added significantly to these developments. A clear exposition of the improvements in strength of cements over the years starting from the beginning of 1900s to almost the end of the century was presented by Neville (2013). While there are several factors that go into the making of cement—in terms of uniformity through the stacker-reclaimers, the finer raw meal grinding, more effective precalcination, the improved combustion of the more finely ground coal as fuel, as well as the use of grinding aids to improve the crystal structure in the clinker to name a few, the effects of each modulation and their combined effects are difficult to be exactly predicted.

However, it is to be recognized that the significant changes that have taken place in more recent years with the better understanding of the chemical composition reflected in the consequent effects of improved strength and strength gain rate with age. Table 4.1 presents a summary of these improvements over the last 50 years in the American cements scenario. Similar observations can be made with reference to the cements produced in Europe and to a certain extent even in India. The specific inconsistencies and other associated parameters that are to be explicitly recognized in terms of the Indian cements scenario is probably not appropriate at this stage; it will be discussed at a later stage while presenting the recommended design methodologies in the Indian context.

The main factors that probably led to the development of cements with increasing strength characteristics appear to be a significant increase in the C_3S content (from a value of around 50% to about 57%) and a corresponding decrease in the C_2S content (from a value of around 23% to about 15%), however retaining the total calcium silicates at levels just above 70% (Table 4.1). The improvements in the grinding capability over the years, both in terms of the intrinsic clinker crystal structures and the improved mechanical machinery, have made it possible to obtain significantly higher fineness, which is also reflected in the data presented in Table 4.1. One should also understand that the values presented in table were the average values from across the different companies for type cement alone as reported by the Portland Cement Association of the United States (PCA, 1996; Clifton and Mathey, 1971; Tennis, 1999, 2005). Needless to say that though, as can be expected from such a diverging group of companies and systems at different locations, there is a significant variation (spread) in the values reported for each of the parameters, the average values as reported by PCA appear to clearly point out that the above factors have led to the developments in the cements produced.

TABLE 4.1

Chemical and Phase Compositions; and Fineness of ASTM Type I Cement Over the Years

Year	SiO_2	Al_2O_3	Fe_2O_3	CaO	LoI	C_3S	C_2S	C_3A	C_4AF	Blaine Fineness (m^2/kg)
	Average (%)									
1950	21.4	5.7	2.7	63.9	1.3	51	23	10	8	332
1994	20.5	5.4	2.6	63.9	1.4	54	18	10	8	369
1998	20.7	5.1	2.6	64.0	1.3	56	17	9	8	381
2004	20.2	5.1	2.7	63.2	1.5	57	15	9	8	384

Source: PCA, *Concrete Technology Today*, 17, 1–3, 1996; Clifton, J.R. and Mathey, R.G., Interrelations between cement and concrete properties, Part 6. Compilation of data from laboratory, National Bureau of Standards, Building Science Series 36, Washington, DC, pp. 118, 1971; Tennis, P.D. and Bhatty, J.I., *Concrete Technology Today*, 26 1–3, 2005; Tennis, P.D., *Concrete Technology Today*, 2, 1–4, 1999.

Also, the actual compressive strength values and the strength gain rate as observed in the American context from the same data is presented in Figure 4.2. Even in this case the values that are being presented in the graph are essentially average values. The original publications clearly show that there is a wide variation (spread) in the strength values also at all ages. It can even be seen from them that there have been cases where clearly the cements with present-day characteristics were available, if only even in limited cases, from almost the late 1950s and early 1960s. One significant observation from Figure 4.2 is that there is no major variation of the average strength values at all ages from the early 1990s. This probably goes to prove that the understanding of the cement and cement manufacturing concepts in terms of both the chemical compositions and physical characteristics of concrete have attained reasonable levels, and that further improvements in technology in terms of the strength and performance characteristics of the cements will need inputs from other resources like the supplementary cementitious materials, which is clearly reflected in the new classification of cements that is being advocated presently.

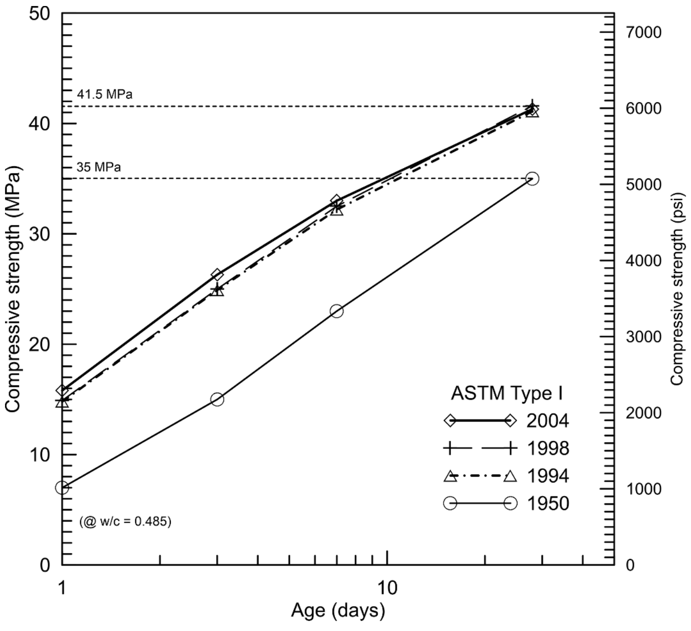

FIGURE 4.2
Improvements in strength of ASTM Type I cement over the years. (After PCA, *Concrete Technology Today*, 17, 1–3, 1996; Clifton, J.R. and Mathey, R.G., Interrelations between cement and concrete properties, Part 6. Compilation of data from laboratory, National Bureau of Standards, Building Science Series 36, Washington, DC, pp. 118, 1971; Tennis, P.D. and Bhatty, J.I., *Concrete Technology Today*, 26, 1–3, 2005; Tennis, P.D., *Concrete Technology Today*, 2, 1–4, 1999.)

Similar to the improvements in cement strengths in the American scenario, over the years the characteristics and compositions of the cements produced in Germany have also undergone consistent and probably very methodical improvements, both in terms of the cements themselves and also the concrete compositions that are associated with it. These have been discussed in the enormous amount of literature published through the aegis of the Association of German Cement Works (Verein Deutscher Zementwerke e. V) and other journals concerning cement and concrete. Incidentally, while tracing the historical development of the building materials, the concrete cement pocketbook (VDZ, 2002) discusses pictorially the development of the compressive strengths of normal concrete, which has been transformed into the graphical representation presented in Figure 4.3. The figure clearly delineates the various modifications, improvements as well as advancements in the compressive strength of concretes used for structural applications. While not much needs be read into the equation depicting the strength gain over the years, the possibility of even normal concretes (concretes containing mineral and chemical admixtures along with improved cements) is making further strides.

It is important to note that the 28-day compressive strength of concrete is the one that is specified as a quality requirement, though it is well established

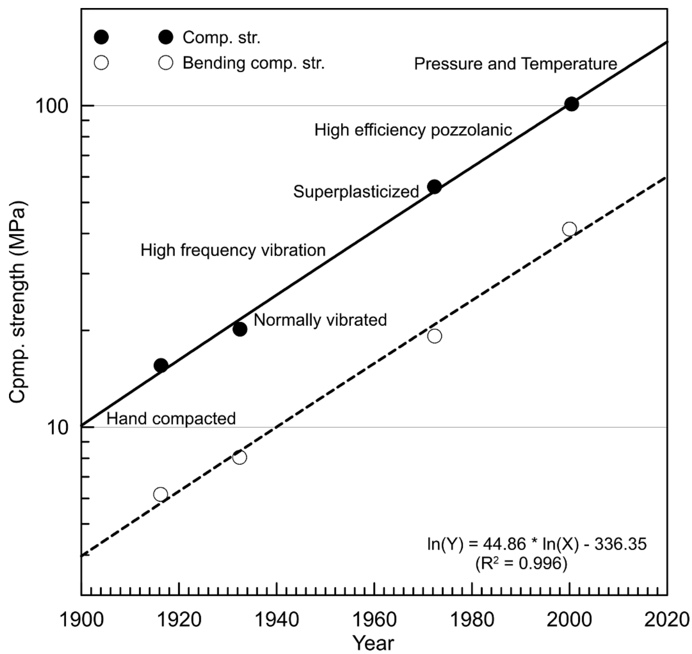

FIGURE 4.3
Developments in the compressive strengths of normal concrete. (After VDZ, Zement-Taschenbuch 2002, Verein Deutscher Zementwerke e. V. Düsseldorf, p. 792, 2002.)

that apart from the water cement ratio controls strength, two other specific factors, compaction and curing, influence the same. In this context it was observed that over the years there has been a significant improvement in both the chemical and physical characteristics of the cements that are being produced in both the American and British context (PCA, 1996; Clifton and Mathey, 1971; Tennis, 1999, 2005; Pomeroy, 1986). It was observed by Pomeroy (1986) that the ordinary Portland cement strength increased from about 35 MPa to almost 45 MPa, almost 25% improvement, during the period from 1960 to 1980 in the United Kingdom. At this stage one should also remember the British regulations for establishing the strength of cement uses a water cement ratio 0.6, which should not be directly compared the strength of American cements that are established with a water cement ratio of 0.485. Pomeroy (1986) are also tabulated the effects of the changes in the cement strength from the 50s to the projected 90s in terms of the concrete strengths at the different water cement ratios ranging from 0.40 to 0.80. The values at the water cement ratio of 0.6 were suggested to be for the concretes used for the British compliance requirements. While Pomeroy was looking at the possible changes that have taken place over the years in terms of the water cement ratio required for a particular strength, it is felt more appropriate to have a graphical representation of the water cement ratio to strength relationships for the concretes over the years as reported by him (Figure 4.4).

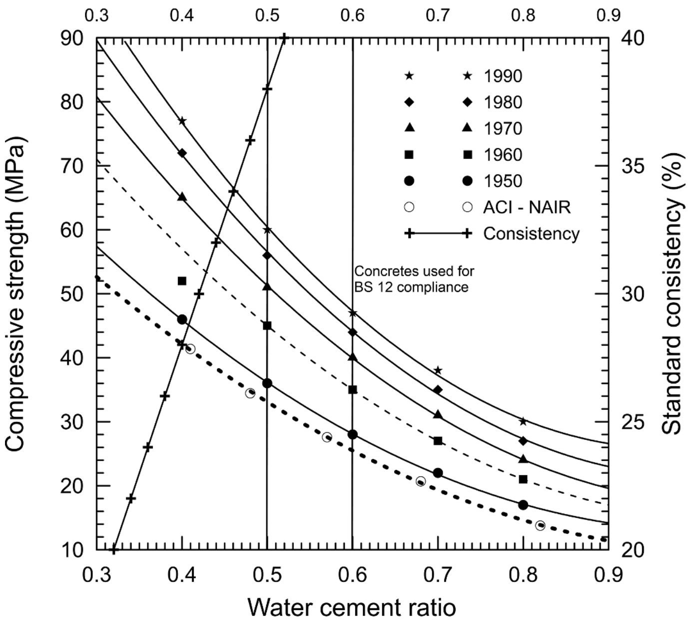

FIGURE 4.4
Variation of concrete compressive strength over the years. (After Pomeroy, C.D., *ICE Proceedings on Improvement of Concrete Durability*, Thomas Telford, London, UK, 1986.)

While the information discussed earlier regarding the strength of cement in both the American and British scenarios is in fact available in their published literature, no specific effort is made to bring it into the national recommendations, either in the code on cements or concrete. The only effort in the British recommendations is that the recommended water cement ratio to strength relationship in the concrete mixture design is chosen based on the concrete's strength to water cement ratio of 0.50. It is also surprising that the British for the strength of cement can be assessed through a 1:3 mortar mix at the water cement ratio of 0.40 or alternatively through strength of concrete at the water cement ratio of 0.60. The American recommendations present individual water cement ratio strength relationships for the different concrete compositions directly. For the cement strength itself, the compressive strength of 1:2.75 mortar and the water cement ratio 0.485 is prescribed in the American recommendations. Even the compaction procedures recommended are totally different between these two codes. A comprehensive overview of the characteristics of the ordinary Portland cement as delineated in the various national recommendations is presented in Table 4.2.

Apart from what could be seen in Table 4.2 regarding the specifications for the ordinary Portland cement by the different national standards, one has to also appreciate that the characteristics of the standard sand that is recommended is also varying apart from the cement to sand ratios. It is important to note that the grading distributions can also have a significant influence on the strength of mortar itself. Thus an appropriate comparison between the strength characteristics of the different cements in relation to the various national standards is difficult not only because of the water cement ratio to strength variations specified but also due to the differences in the grading of the sand as well as the varying sand cement ratios adopted by each one individually (Table 4.3).

4.3.1 Effect of Cement Strength on Water Cement Ratio

In a sharp contrast to the American and British recommendations regarding the strength of cements discussed earlier, the German recommendations have specific and scientific basis strength to water cement ratio relations for the cements of the different strength grades. In principle, experimental investigations on cements of various strengths have shown that the water cement ratio to the concrete strength to cement strength ratio relationship can be represented by a single curve (Walz, 1970, 1971). Considering the results of about 828 investigations into the various concretes at the different water cement ratios, Walz observed that the variations in the strength ratio are well within the ±5% fraction of the expected mean value as can be seen in Figure 4.3. The mean curve along with the ±5% fraction limits as presented in the figure is normally referred to as the Walz roll curve. From this roll curve one can always arrive at the water cement ratio strength relationships for concretes consisting cements of different strengths as can be seen in Figure 4.5 by considering the strength at

TABLE 4.2

Recommendations for the Requirements of Ordinary Portland Cements

Characteristic (parameter)	**ASTM C150**	**BS BS 12**		**EN/DIN EN 196/197 (DIN 1161)**			**BIS IS 4031**	
Cement grade	—	—		**32.5N (Z35)**	**42.5N (Z45)**	**52.5N (Z55)**	**C43**	**C53**
Physical and Setting Characteristics								
Fineness, Blaine (m^2/kg)	280	275		(220)			225	
Soundness				<10%				
LoI				<5%				
Insoluble residue				<5%				
SO_3 & Cl^-				<3.5 & & <0.1				
Vicat initial set	>45	>45		>75	>60	>45	30	
Vicat final set	<480	<600		(<720)			600	
Strength Characteristics								
Material	Mortar	Mortar	Concrete	Mortar			Mortar	
Proportions	1:2.75	1:3		1:3			1:3	
Size (cube, mm)	50	70.7	100	40 mm cube (of broken flexural)			70.7	
w/c ratio	0.485	0.40	0.60	0.50			Varies with consistency ***(0.30–0.35)***[a]	
Compaction	Tamping	Vibration		Jolting			Vibration 12,000 rpm	
Curing	24 hr moist 20°C later						24 hr moist 27°C later	
Loading rate				2400 ± 200 N/s				
2 day (MPa)	—	—	—	—	>10	>20		
3 day (MPa)	12.4	>25	>15	—	—	—	23	27
7 day (MPa)	19.3	—	—	>16	—	—	33	37
28 day (MPa)	27.6	47–67	34–52	32.5–52.5	42.5–62.5	52.5–	43	53

[a] Generally for the reported consistency values 26–32 in recent times.

0.50 water cement ratio as the representative strength of the cement (Walz and Dahms, 1965). One critical observation is that the strengths at the lower water cement ratios (below about 0.40) appear to be lower, which can be attributed to the inadequate compaction, associated with such low water cement ratio concretes. As a matter of fact, taking the water cement ratio to strength relationships over the years as presented by Pomeroy (Figure 4.4) was also reworked as a roll curve (by dividing each strength at any water cement ratio with the strength at the water cement ratio of 0.50 in that curve) to see the credibility of the Walz theory. It is a matter of surprise that both the roll curves of Walz and

TABLE 4.3
Sand Characteristics for Cement Testing

Parameter	ASTM ASTM C 778	BS BS 4550	DIN DIN 1164	EN EN 196-1	BIS IS 650
Sieve Size (μm)	**% Passing**				
2000			100	100	100
1600				93	
1200	100				
1000			66.7	66	66.7
850		100			
600	98	10			
500			33.3	33	33.3
425	70				
300	25				
150	2			13	
80	0	0	0	1	0

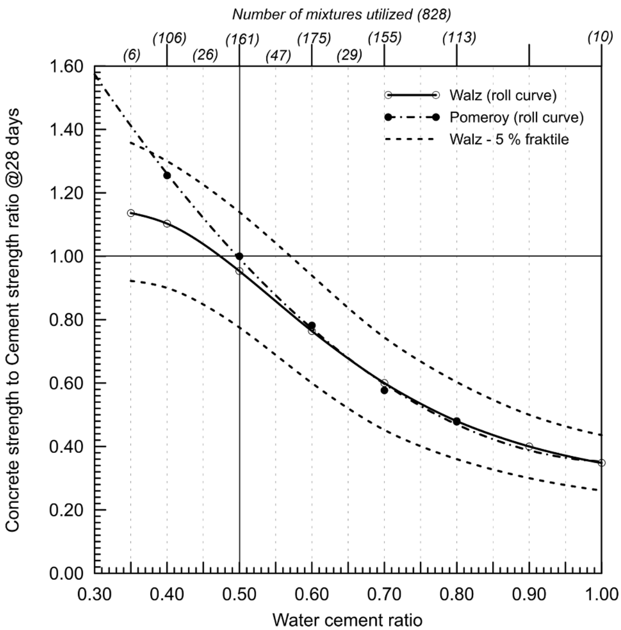

FIGURE 4.5
Roll curve for water cement ratio to strength relation. (Walz, K., Beziehung zwischen Wasserzementwert, Normfestigekeit des Zements (DIN 1164, Juni 1970) und Betondruckfestigkeit, Beton, pp. 499–503, 1970; Walz, K., Herstellung von beton nach DIN 1045, Betontechnologische arbeitsunterlagen, Beton-Verlag GmbH, Dusseldorf, Germany, p. 89, 1971; Pomeroy, C.D., *ICE Proceedings on Improvement of Concrete Durability*, Thomas Telford, London, UK, 1986.)

Pomeroy almost coincided with each other. The reverse S curve portion (falling portion) presented by Walz also got corrected and the relationship is of a continuous nature as can be expected in theory.

The advantages of using the roll curve presented by Walz and Dahms (1965) can be seen in Figure 4.6 clearly. Apart from this one specific aspect, it can be seen that the curves all have a reversal in the curvature, which is typical of the effect of inadequate compaction of the concretes at the lower water cement ratios. This indeed is reflected in the fact that the proposed cement strength value in each curve is attained at a water cement ratio of 0.485. In fact the value of 1.0 for the ratio of concrete strength to cement strength in Figure 4.6 was indeed the same water cement ratio from which roll curves have all been derived. It can also be seen from Figure 4.5 that the curve representing a similar roll curve from Pomeroy results, which falls on the Walz curve yet without the expected reductions in strength due to inadequate compaction leading to a reversal of the curvature, showing that a value of 1.0 for the ratio of concrete strength to cement strength was indeed 0.50. Incidentally, the fact that this cement strength in the American standard is determined at the water cement ratio of 0.485, for which there is no

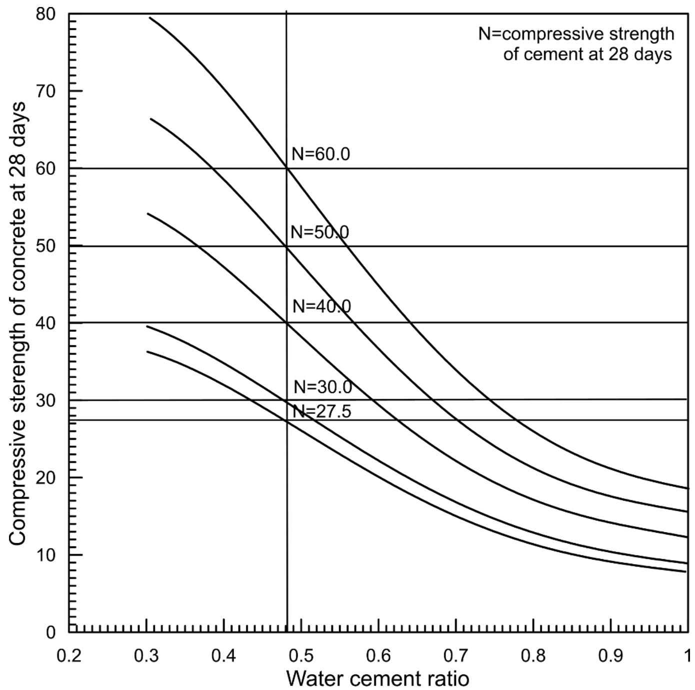

FIGURE 4.6
Concrete water cement ratio to strength relations with cements of different strengths. (After Walz, K. and Dahms, J., Erläuterungen zu den Richtlinien für Beton im Grubenausbau, Beton, pp. 347–352, 1965.)

major exploration or justification available in the literature other than that seen above is a matter of intrigue. Even the fact that, while the water cement ratio is in general presented invariably to the first two digits only in almost all the recommendations including that by the Americans, the adoption of the third digit only for the strength of cement appears to be, to say the least, unusual. As a corollary to the discussions above, it is presumed from henceforth in all the various modulations attempted for the water cement ratio to strength relationships of concrete at 28 days, a division by the probable cement strength used in those concretes as represented by the strength of concrete and 0.50 water cement ratio is reasonably acceptable.

It is also known that the strength of the cements has reasonably improved over the years, and some of these effects could have necessitated a change in the type of assessment as discussed earlier. For this reason, the available literature for extending this particular philosophy was once again look at and the effectiveness of the propositions by Walz in the 60s was well confirmed, even if only it was found to be more conservative than ever, by the findings of Hanke and Siebei (1995) as shown in Figure 4.7. It was stated by Hanke that this general philosophy developed for the so-called three material

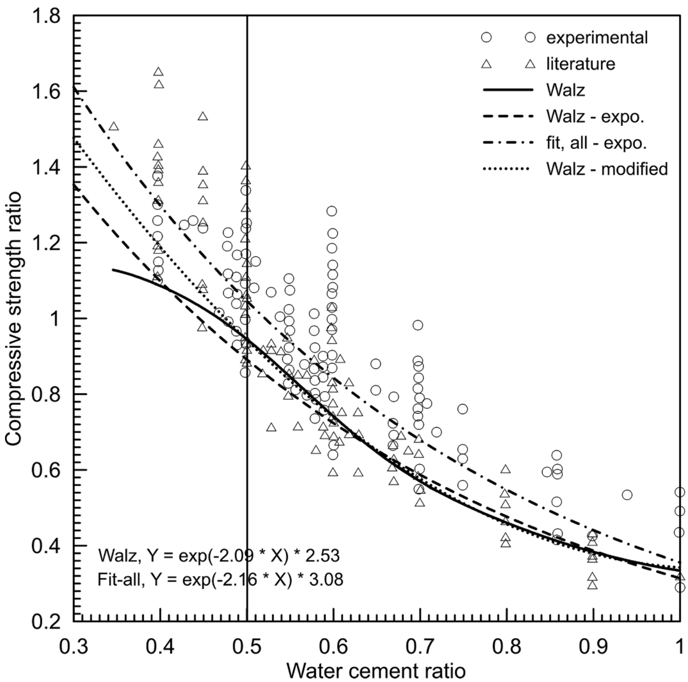

FIGURE 4.7
Extended basis for water cement ratio to strength relation roll curve. (After Walz, K., Beziehung zwischen Wasserzementwert, Normfestigekeit des Zements (DIN 1164, Juni 1970) und Betondruckfestigkeit, Beton, pp. 499–503, 1970; Hanke, V. and Siebei, E., Erweiterte Grundlagen für die Betonzusammensetzung (Extended basis for concrete composition), Beton, pp. 412–418, 1995.)

composition system of cement, aggregate and water could be comfortably extended to depict the properties of a five material composition system of concretes containing both additives and admixtures as is the practice today.

It can be see that Figure 4.7 presents the concrete strength to cement strength ratio variation with the water cement ratio along with the original Walz curve. The simple correction possible to remove the strength reversal effect at the lower water cement ratios was also presented as a modified Walz curve along with an exponential relationship for the available data. It can be seen that even this curve is a part of the other two and also underestimates the strengths, suggesting that the curve proposed as the best fit of all the data is still highly conservative. Maybe one should also recognize the fact that the cementitious systems, containing the more modern cements with improved chemical and physical characteristics augmented with the use of mineral and chemical admixtures support an extension of this particular philosophy as presented by Hanke (1995).

Apart from looking at the effectiveness of the Walz roll curve, Hanke and Siebei (1995) also look at the relationship between compressive strength of concrete and cement and the water cement ratio of 0.50. The results of his experiments with different cements, including the slag cements, indicate that the 7-day and 28-day strengths of both cement and concrete at the water cement ratio 0.50 appear to be nearly the same. These two factors could go a long way in understanding the strength characteristics of the different cements at any age and at any water cement ratio theoretically.

4.3.2 Efforts on the Unification of Strength to Water Cement Ratio Relationships

The fact is that the water cement ratio to strength relationships could be adequately related to the strength of cement in concretes which are adequately mature (represented by the 28 day strength of cements as well as concretes) appears to be in order. It is also a fact that there are several situations wherein the strength of concrete both at the early ages (necessary for applications like transfer of prestress or for slip forming or even for demolding, etc.) and maybe even at the later ages (particularly for applications in situations where the expected loading is only to be realized far later as in dams and roads, etc.) has to be adequately predicted. Efforts have been made in this direction for a very long time, and probably the earliest of all could be traced back to the report by Lyse (1931, 1933) in which instead of the water to cement ratio he suggested the use of cement to water ratio for obtaining a linear relationship with strength. In fact there have been several others who advocated this, and some of them even tried to propose it as their own finding. It is obvious that this proposal was given by Lyse while showing that the Abrams water cement ratio to strength relationship could be approximated to a straight-line and more importantly that these relationships at the various concrete ages could all be represented by such approximate linear relationships.

In one of the later efforts, Dewar (1999) suggested the possibility of linearizing the water cement ratio strength relationships itself by presenting the strength in the logarithmic scale. In extending the possibility of this approach, Dewar suggested that the relationship will indeed be a bilinear one, with the relationship at the lower water cement ratios being a much flatter one compared to that of the higher water cement ratios. The point of inflection probably could not be specifically defined. This suggestion was seen to be in almost all cases—with the variations in cement content aggregate size of content. However, with age, the strength characteristics of concrete at the lower water cement ratios appear to be merging at the theoretical water cement ratio limit of 0.00. In the broader sense, the possibility of a bilinear relationship for concretes of much wider spectrum of water cement ratios is well accepted both by Dewar (1999) and also Popovics (1998). A typical representation of this can be seen by simply presenting the revised relationships given in Figure 4.8, which apparently shows that the relationships deviate from the water cement ratio 0.50 and also that being roll curves these are parallel to one another for the different cement strengths.

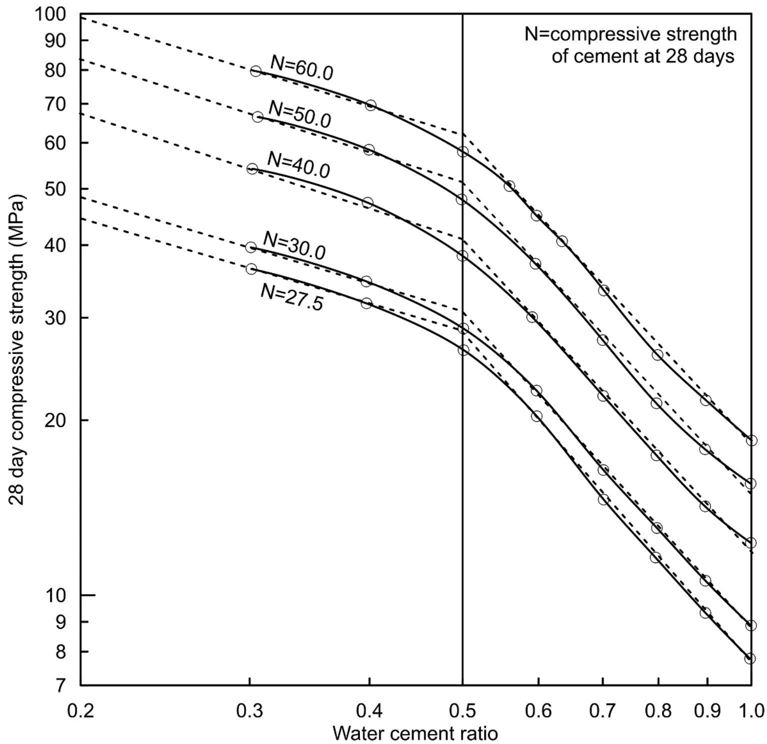

FIGURE 4.8
Apparent bi-linearity in the water cement ratio to strength relations. (After Walz, K. and Dahms, J., Erläuterungen zu den Richtlinien für Beton im Grubenausbau, Beton, pp. 347–352, 1965.)

Probably, a very comprehensive effort toward the linearization of the water cement ratio to strength relationships was reported by Popovics (1998). In his efforts to understand the compressive strength versus water cement ratio relationships at the various ages (3 to 91 days), he presented the results of an earlier investigation from Kaplan (1960) in a bi-linear perspective. To have a reasonable clarity on the strengths and the lower water cement ratios in particular, he experimented with presenting the strength in the logarithmic scale initially, as was done by Dewar (1999). He also tried to observe if by looking at the relationships with the water cement ratio in the logarithmic scale there could be better clarity. While both these efforts appear to present reasonably linear solutions, there still appear to be some inconsistencies. In trying to spread the data in the lower water cement ratios regions wider, looking for even more clarity, the same data is now presented with both the strength and the water cement ratio axes in the logarithmic scale (Figure 4.9). It is obvious that the bilinear relationship is still a reality, but the conformance of the data to be linear segments appears to be much better defined. The inflection point also appears to be located at the water cement ratio of 0.50 in the present case. However, with the different sets of results of the strength variations with age, this point could vary a little from this.

Apart from the earlier discussions, one can offhand think of several other formulae for the strength to water cement ratio relations from the earliest

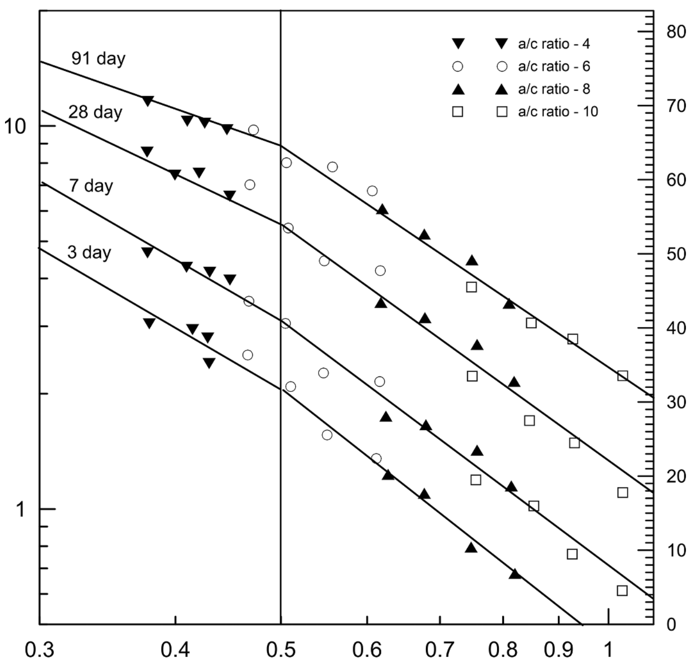

FIGURE 4.9
Bi-linearity in water cement ratio to strength relations with age. (After Popovics, S., *Strength and Related Properties of Concrete A Quantitative Approach*, John Wiley & Sons, New York, p. 552, 1998.)

of times, even before the most acclaimed Abrams relation. There are also efforts directed toward delineating the water content requirements as well as the methodology for aggregate proportioning requirements through methods like specific surface characteristics and packing density methodologies. It may not be possible to discuss all these at length at this point, but some of these will be looked at while looking for the appropriate recommendations to arrive at a suitable methodology for the concrete mixture design of specified strength or of any other characteristics.

4.4 Further Necessities for Unification

It is also true that some of the earlier enunciated parameters and relationships are being moderated, modeled and augmented to accommodate other parameters of importance. There are also several other newer relationships that are coming into existence, be it from the direct mathematical approaches that enforce a reasonable prediction of a specific dataset or otherwise directed toward the concrete mixture design of a specific type from time to time. At this stage, the basic parameters that influence and dictate the strength characteristics of normal concretes have been broadly discussed. Even so, it is necessary to recognize that there are gaps in information particularly in relation to the aggregates and the grading distributions. This is one parameter that has a significant influence on primarily the performance and also the economy of the concrete mixture designed. This aspect of the concrete mixture design will be dealt with briefly in the later chapters while discussing performance. Apart from this, the concrete mixtures of the present day invariably have several minor or not so minor constituents to improve the green and/or the hardened state characteristics. Looking at the possible effects of these additives and modifiers, it is possible to broadly discuss them in terms of their action and effects. The first of these categories is the chemical modifiers, followed by the fine fillers and lastly the mineral admixtures. Some of the broad aspects of their need and actions in formulating the concretes for specific applications are discussed in the following sections.

4.5 Effect of Aggregate Characteristics

Aggregate as already stated occupy over a third of the total volume and if appropriately graded could influence both the green and hardened characteristics significantly. In fact the effect of the process of ensuring appropriate gradation to have a loosening effect has not yet been either fully investigated or appreciated. In a comprehensive way it is enough to say that by ensuring an effective loosening of the material, two specific aspects of the concrete behavior can be addressed. Firstly, it will allow the aggregate components themselves to be of a free flowing composition, facilitating the highest possible slump even without the support from the matrix phase. This helps in optimizing the matrix component to its minimum, resulting in the highest economy. The second aspect is that there is absolutely no danger of the composite segregating, primarily owing to the distribution of the aggregates due to the continuous presence of the next lower grade to support the larger particles of the grade above. While a large number of opinions and methodologies have been reported on the packing characteristics of concrete aggregates, no specific explanation or attribute is reported for the resultant aggregate mixture. Even the discussions on loosening effects concentrate on explaining the effect conceptually in terms of two size fractions without a definite discussion regarding the possibility of extending that throughout the concrete aggregate gradation. One can presume that this is implicit, but explicitly recognizing it will go a long way in ensuring that the effect is fully and systematically enforced.

In this context a different perspective is to understand the efficacy of the combined grading of aggregates. In the earlier concrete mixture design methodologies, the practice was to define generally the grading characteristics of the aggregates, and more often the combined grading. Over the years the practice of defining coarse and fine aggregate proportions separately has come into existence. In practical terms, the smaller sizes in the course aggregate and the larger surface of the fine aggregate are generally missing due to the commercial practices and methods for combining the aggregates to conform to certain regulations have come into existence. Even so, from practical considerations, provisions are only made for combining two different course aggregate sizes, and the rest is expected to be taken care of by the fine aggregate even in the most acclaimed practices of the ready mixed concrete. The possible problems associated with this approach should indeed be obvious, but a more detailed discussion on this particular aspect will be taken up in later chapters.

4.6 Effect of Chemical Admixtures

The use of chemical admixtures, in particular the superplasticizers, is almost taken for granted in most constructions to be able to not only moderate concrete but also to facilitate its transport to sites farther away yet ensuring a satisfactory mixture on arrival. The possibility of using superplasticizers in conjunction with other construction chemicals is also a common practice many a time to modulate these concrete compositions further, maybe sometimes even at site. Most of these chemical admixtures, which are invariably water-soluble or in some cases could be suspensions in water even, while influencing the concrete properties as desired, will also infuse additional quantities of water into the existing concrete mixture inadvertently. In most cases, from the considerations of economy, it is prudent to limit the requirements of these chemical admixtures to about 2%–2.5%. However, there have been reports wherein the superplasticizers in particular have been too far in excess of this, which may cause difficulties in terms of the mixture stability even if the economic considerations are given a go. Also, while using these chemical admixtures at the lower water cement ratios in particular, even this small amount of additional water associated with chemical admixtures, including superplasticizers, will certainly be critical and could lower the compressive strength of the matrix. In simple terms, these being mostly solutions, the actual water associated with the admixtures could be simply treated as the additional water, which could be marginally on the safer side. Finally it is important to emphasize that the quantity of any chemical admixture used in making concretes of specific qualities need not necessarily go beyond the 2% as already discussed for each individual admixture.

4.7 Effect of Mineral Admixtures

The use of pozzolanic mineral admixtures like volcanic ash to improve the characteristics of the lime mortars and concretes of yesteryears is a very well-known fact. With the advancements in cement and concrete technology, efforts toward utilization of industrial wastes like fly ash and silica fume gained prominence, not only because of their effectiveness as pozzolanic materials but also due to the fact that the performance characteristics could be specifically improved through an appropriate utilization of these materials. These could be broadly classified into the industrial waste materials and the naturally occurring materials like calcined clays. But to look at them in terms of their pozzolanic reactivity is probably more appropriate. The lower efficiency pozzolanic materials like fly ash, GGBS and maybe even rice husk ash (RHA) could probably be the most appropriate materials for augmenting the cementitious components of concretes of lower strength grades (maybe up to about 30 MPa). This aspect is a specific help in ensuring a reasonable amount of powder content to make the paste phase in the matrix more pliable and spread itself to cover the aggregate matrix appropriately. This aspect is not directly advocated as the advantage for these materials generally. It is also possible that they can be used in smaller quantities to produce medium strength concretes (in the range of 40 to 60 MPa). At the same time, the higher end pozzolanic materials like silica fume and metakaolin can be gainfully employed in concretes of very high strength and performance (in the range of 80 to 120 MPa). Some of these materials can enhance the performance characteristics specifically if appropriately utilized, and the advantages and limitations of these materials should be understood better.

4.8 Effect of Fine Fillers

While it is always possible to use the lower end pozzolanic materials like fly ash as mineral extenders to cement, it is obvious that it is not a material available in the cement manufacturing system itself generally. Incidentally, the international standards on cement allow the use of about 5% other available materials as a part of the cement itself. Invariably the two materials that are on hand are the kiln dust and limestone powder which are available as a part of the processing. One of the first factors that come to mind is that the limestone powder itself has a very small amount of pozzolanic reactivity due to the amorphous sites that could represent in the very fine powder. There has been quite an amount of interest in using this as a cement extender or filler to ensure the required amount of fines to address the filler effect part of the concrete mixture. It is possible that one could use other fine materials like silica dust from rock crushing or even powdered glass available from industrial waste for this purpose. While there is definite and specific information regarding the possible uses of some of these non-pozzolanic fine powders as fillers, a comprehensive view on their potential and cement and concrete composites is probably not yet presented in literature with clarity. Some of these aspects, along with their applicability and utilization potential, need a better and focused presentation.

4.9 Efficacy of the Unification Aspects

Notwithstanding the fact that there have been several efforts to date to model the design methodology appropriately for normally vibrated concretes in specific, the need for an approach that could encompass and yet recognize effects of the various additional constituents that came into existence over the years into the concrete mix design is obviously pertinent. An effort toward this requires a specific and comprehensive understanding of the effects of these additional constituents on the basic mix design parameters that are probably defining it reasonably over the years for normal concretes. Efforts to date have invariably been focused primarily to consider each of these variations as entirely new and significantly different cementitious composites requiring a completely different design philosophy to accommodate the specific characteristics and influences of these materials. However, it is only appropriate to look at the characteristics and the influence of the additional materials on the concrete behavior with a view to modify the relationships while keeping the fundamental tenets of the design parameters and the overall philosophy unchanged from that of the normally vibrated concretes. This approach is not in any case uncommon, and there have been efforts by several researchers and nation bodies in this direction. The broad and overarching principles of such attempts to accommodate the newer materials for specific modifications have to be understood correctly.

During this assessment of the variability of the cement characteristics over such a wide spectrum, it is probably not really inappropriate to take a step back from the scientific and more understandable physical and chemical characteristics as they changed over the years, but look at the more managerial, administrative and commercial aspects that drive the demand and supply chain. Knowing the highly commercial nature of advertisement and dissemination of technical know-how (having certainty given credence to the patenting and intellectual property rights aspects adequately), one can see that obviously a certain small segment of the industry is always trying to excel while the majority who are the regulatory and recommendatory bodies try to enforce a significantly lower bar for the product in general. It is often said that this is to accommodate the smaller players who probably do not have the wherewithal for all the research and development and the upgradation of their facilities within the meager resources available. But it is obvious that there are different grades or classes into which they can be categorized appropriately without compromising on the quality requirements. This aspect is more often than not openly voiced for materials like aggregates, which are locally produced and could have a significant variation though there are excellent benefits of these characteristics and requirements being adequately ensured.

Mathematical modeling of the concrete mixture design procedure, even to the limited extent of normal concretes, is still a matter of debate. In simple terms, it means that the model should be able to present the constituent components given the requirements of strength and probably even durability without having to go through all the experimental investigations associated with it. This helps in reducing the time and effort associated with the design process and may probably even facilitate looking at several alternatives before finally deciding on the concrete mixture to be adopted. Another way is to understand the design of normal concrete mixtures well and later incorporate appropriately the procedures and methodologies to accommodate other components like chemical and mineral admixtures. This is a much broader perspective of the unification aspect. It is indeed possible to put in mathematical terms of the methodology adopted in the design once it is available. It is a totally different picture if the one tries to find the common axioms that define the various processes. Apart from all these things, a more global approach could be to fix the fundamental aspects as best as one could and work around that methodology to modify suitably either to impart a specific property or to accommodate a specific additional constituent.

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5

American Recommendations

5.1 Introduction

The role of concrete as the primary engine of economic development, particularly through its application in the transport infrastructure of highways and bridges, ports and harbors, airports etc., apart from the built space for habitation is well understood. It has had several different avenues for its developments necessitating modifications for adapting to the construction facility and the local requirements of a region in its own way. This is but natural as the largest inert ingredient in the system, the aggregate filler component, is to be necessarily local to ensure a reasonably viable and economic solution. In the light of such a constraint, its development and regulatory recommendations from the various national bodies have always been home-grown over the past couple of hundred years in particular, yet recognizing and also relying on the overall concepts and perceptions of its origin, science and technology. Most early thoughts of modern cement and concrete and its development have probably started with the concepts and constructions of the bygone era of the Romans or even earlier. In a way, one can clearly see that the European thought and developmental paths in principle are largely at variance to the exported and home-grown concepts of the American continent, which one can say are the two largest influencers on the world of concrete in their own specific ways and perceptions. Maybe it is relevant to appreciate the significance of each of these and their offshoots particularly in Europe like in Britain, Germany, France and Russia, to have a clear picture of the concrete design and developmental aspects.

The ubiquitous nature of concrete can be very easily seen from its application in the various, essentially diverse, fields in the engineering construction scenario of the built space environment. This obviously enforces and ensures that there are several players looking at the various facets of concrete in its multitude of variations conceivable through their own respective utilization potentials, coming up with documents reflecting their own perspective. In the broad sense, one can say that this approach presents only a myopic view of a specific segment in the entire panorama of concrete as a material in its all-encompassing perspective of being a cementitious composite.

Having said this, one can always look at its brighter side that such a specific and directed view of its utilization potential for particular types of applications will firstly support the industry professionals associated with such activities leading to a direct growth of the industry. This apart, it is obvious that such a focused approach could effectively address the needs and expeditiously redress constraints through appropriate modifications, yet keeping in mind the broader material science perspective of the concrete and even other cementitious compositions of polymeric nature also in the background.

5.2 Historical Background

In a way, the diverse and urgent need for facilities in a fast-growing and expeditiously expanding industrial scenario of the last century, with the vastly varying geographic complexities of the North American continent, particularly the United States, is probably the best example. In particular, one can see that each of the organizations charged with the responsibility of the construction needs of highways, bridges and dams had to look more closely at the specific requirements of such constructions. These requirements have led to the different regulatory bodies like the Bureau of Reclamation (USBR), the Transportation Research Board (TRB), the Federal Highway Administration (FHWA) of the U.S. Department of Transportation and its various associates from the different states. At the same time, the primary cement industry in its own perspective had to look at its requirements and its extended need to support the industry using products through an organization such as the Portland Cement Association (PCA). The backbone of any industrial activity is obviously the research and development support that it gets from both the academic institutions (universities) and research laboratories (like the NRC, NSF, and NIST) that are actually charged with the responsibility of addressing many of the needs by the industry. There are also professional associations linked to such activities with member groups trying to present a regulatory framework such as the American Concrete Institute (ACI), American Society for Civil Engineers (ASCE) and American Society for Testing and Materials (ASTM). Apart from these, several individual user groups with a considerable presence, all looking to support and promote the appropriate use of concrete in their individual but diverse spheres, also present documents for individual use of products and processes. They are also active in formulating norms specific to the particular industry and some of these are the ones like National Ready Mixed Concrete Association (NRMCA), Precast/Prestressed Concrete Institute (PCI) and Nuclear Regulatory Commission (NRC) that have a more specific role, apart from the several private research units from the various industries that work to promote the growth of the industry. However, as a matter of abundant caution one should be aware that the industry concepts always highlight and even actively promote only the few characteristics that are obviously of their interest, while unobtrusively not presenting or possibly obscuring the other and more effective alternatives as well as limitations. It is in the interests of the concrete user community that the present report explains the relevant facts in their entirety, with the appropriate background reported in literature to the extent possible.

In the American context, a host of highly professional organizations address the needs of the construction industry overall. Some of the more prominent and active amongst these organizations that are often looked upon as the forerunners in such activity could be listed as ASCE, ASTM, ACI, PCA, NIST, TRB, etc. It is only appropriate if not imperative that one looks at the reports and recommendations from these major institutions to have an idea of the American thought toward the application of concrete in the creation of the different constructed facilities. It is also important to note that most of these organizations have been forerunners and pioneers in their efforts to the popularization through the appropriate regulations for ensuring adequate performance of the constructed facility, and naturally have had not only a national presence but also an international recognition. It is enough to say that they are taken to be not just as recommendations alone but also as the most appropriate practices even in addressing the legal commitments in the industry all over the world. This not only puts a lot of focus on these organizations which have a very broad audience in membership, and naturally a balanced approach to most specific needs of the industry for which the regulations are generally addressed. While it is the effort at this point to look at this complex scenario in its proper perspective, it is to be fundamentally accepted that one cannot reflect on the complexity as well as the breadth and depth of the information that is available even just looking at the American scenario. Naturally, the present effort is to appropriately highlight some of the major recommendations, their consequences and limitations in a broad perspective to have clarity toward the fundamental aspects of concrete mixture designs overall. It is obvious that such an effort can only be meaningful only if it can be related suitably to the basic background of the fundamentals in the development of cement and concrete composites to help understand these regulations in their proper perspective along with the probable limitations or boundaries of their applicability.

It is important to note that as was already seen in the previous chapters, one of the most prominent and probably the most important axiom in the design of concrete mixtures ever came from the work of Abrams (1919). Though there have been efforts toward relating the strength to the concrete constituents in general, it is obvious that the water cement ratio to strength relationship proposed by him paved the way for a better understanding of the design of concrete for a specific strength, which is the basic structural design parameter. This is probably not only a milestone in the American thought regarding concrete mix design, but could easily be termed as the earliest milestone in concrete mix design procedures of later years. One can say that though there are better explanations or even relationships in terms of the void or air content, the density, the porosity and permeability to explain the strength and more importantly the performance characteristics of concrete, for the operator on the site the physical clarity of the water cement ratio in ensuring the required strength has always been the cornerstone. One can also say that this is also the starting point for a mathematical modeling of the concrete mixture designs, or by extension the methodology for an appropriate understanding of all the cementitious compositions in general.

5.3 The "PCA" Approach

As was the case with the development of cements with the various characteristics, efforts toward an appropriate set of formulations to effectively produce concretes of acceptable strength and quality were indeed afoot long before the mathematical relationships as being used in the present context came into existence. With the background that the strength of concrete is indeed related to the water cement ratio, a few simple formulations for concrete mixtures suitable for different applications came into existence in the form of reports. One such early effort was the report entitled "Proportioning Concrete Mixtures and Mixing and Placing Concrete" by the Portland Cement Association (PCA, 1916). The report envisages presenting a set of arbitrary volumetric proportions for both mortars and concretes suitable for use in the specific "Classes of Construction" activity resulting in "Concrete for Permanence."

A few of the statements made in this report (PCA, 1916) probably need a special mention, particularly due to their significance that they are more than relevant and that we probably need to appreciate the significance of these even today. In a way many in recent times appear to echo these but seem to present these as the newer axioms of concrete mixture design for performance or permanence as advocated almost a century earlier.

- "Proportioning of materials must be such that the cement will coat every particle of sand, and the sand-cement mortar will coat every pebble or particle of broken stone and be slightly in excess of what is actually required to fill the air spaces or voids in the mass of pebbles."
- "In other words, the amount of sand used should slightly exceed the volume of air spaces in the pebbles or broken stone, while the quantity of cement used should slightly exceed the voids or air spaces in the sand."
- "There are a number of ways to determine the volume of air spaces in a given bulk of sand and pebbles or broken stone, so that the

materials to be used for any concrete mixture can be accurately proportioned to reduce air spaces to a minimum."

- "For most classes of construction, the correct amount of water is that which will make a concrete of quaky or jelly-like consistency."

The fact that a richer mix of 1:2:3 volumetric proportions is proposed for roof slabs and constructions subjected to water pressure, while a slightly leaner mix of 1:2:4 is suggested for reinforced concrete walls, floors, beams, columns and other concrete members designed in combination with steel reinforcement is probably noteworthy. The publication also contains a table presenting the quantities of materials required for the various mixtures of mortar and concrete, outlining not only the quantities of materials but also the resulting yield of the mixture. The water content necessary to produce concrete of the required consistency is to be determined during the mixing operation. The other aspects like mixing, placing and compaction of concrete mixtures were also broadly discussed. This is probably one of the starting points for introducing the table on "Mixes for small jobs," where time and personnel are not available to determine proportions in accordance with the recommended procedure as reflected in the ACI 211.1 (1991).

Over the past hundred years, there have been several revisions of this document, which indeed trace the advancements and the understanding of concrete over the years due to the consistent research efforts of the several individuals and organizations in the American scene. Maybe it is only appropriate to have a trace of this century-long journey to understand more clearly the efforts of PCA in ensuring "Concrete for Permanence" as originally envisaged.

Incidentally, apart from the continuous and steady improvements in the quality of cements produced in the later years, efforts were underway to have a fundamental understanding of the concrete strength gain aspect. The concept of water cement ratio to strength relationship was introduced (in the form of "water-US gallons per sack of cement" to the compressive strength at 28 days relation) in the later revised title "Design and Control of Concrete Mixtures" (Third edition, PCA, 1929), which continues to be titled the same even today. Subsequently the aspects of mixing, curing and temperature effects were also introduced, apart from presenting the water cement ratio to strength relationships at 1,3, 7, and 28 days through Portland Cement Association laboratory testing. The possible variations of these relations due to the effects of temperature were also evaluated theoretically and presented (PCA, 1929). The specifications for plain and reinforced concrete through what was termed as "water cement ratio method" were introduced based on the ACI committee recommendations. In brief, a general treatment of the factors essential for the economic production of concretes of proper strength and durability were discussed, underlining the importance of the selection of materials and proper workability.

Continuing with the improvements of these specifications, over the years the publication “Design and Control of Concrete Mixtures” has become a permanent feature year after year from the Portland Cement Association, a beacon of information for concrete lovers. A later report (Tenth edition, PCA, 1952) has indeed suggested a possible band for the water cement ratio to strength relationships at the various ages (1, 3, 7, and 28 days) for concretes containing both the ordinary Portland cement (Type I) as well as the high early strength Portland cements (Type III). These bands present the possible variations in strength essentially due to the variety of materials used by the different laboratories, even though all of them comply with the requirements of the ASTM. It is also to be observed that the relationships were still presented in terms of the volume of water (U.S. gallons per sack of cement), essentially continuing with the volumetric proportions as originally envisaged by Abrams (1919) in his first water cement ratio to strength relationship reported. Apart from this, several aspects of the production, processing, placing and curing of concretes and their variations have been a part of the discussion in the publication.

The scope of the publication (“Design and Control of Concrete Mixtures”) has only grown over the years, presenting information based on their research efforts for the production of concretes containing various admixtures for different applications. One of the more recent editions of this (Thirteenth edition, PCA, 1994) contains typical age to strength relationships for both air-entrained and non-air-entrained concrete based on 150 × 300 mm (6 × 12 in.) cylinders using ordinary Portland cement (Type I), moist cured at 21°C (70°F). It is felt appropriate to critically analyze some of these relations, at least for the non-air-entrained concretes, so that these could be discussed in relation to the others that are proposed by the different recommendatory bodies or research publications in the later parts of this effort.

The variation of strength f_c (in MPa) with water cement ratio at the various ages for the non-air-entrained concretes are all defined by different polynomials of the type (Figure 5.1)

$$f_c = a - b * X + c * pow(X,2) \tag{5.1}$$

where, a, b, and c are the above polynomial constants. The second order polynomial constructs (a, b, and c) have been evaluated and their variation with age is also presented in the same Figure 5.1. It is clear that essentially these constants vary in a log linear fashion with age as can be seen. Incidentally the 28 day strength variation with water cement ratio at 28 days was seen to be presented by the equation

$$f_{28} = 79 - 115 * X + 45 * pow(X,2) \tag{5.2}$$

Another important aspect that is probably most appropriate to mention is that this 28 day relationship presents that the concrete will exhibit a strength

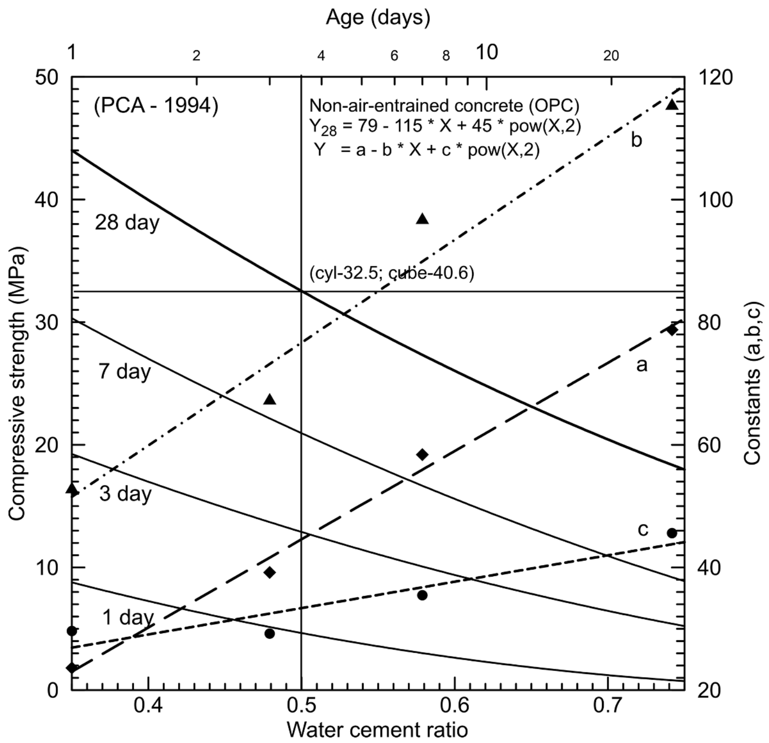

FIGURE 5.1
Strength to water cement ratio relationships with age for OPC. (After PCA, 1988/1994.)

of 32.5 MPa at the water cement ratio of 0.5. Incidentally, it was already seen that the strength of cement (established through a representative mortar specimen) and that of the concrete are essentially the same at a water cement ratio of 0.5. However, considering the fact that the strength values are established on cylinder specimens in the present context (assuming the strength ratio between the cylinder and cube to be 0.8 in this strength range), the probable approximate strength of the cement could be 40.6 MPa. This suggests that these cements may represent a 32.5 grade (with a strength range of 32.5–52.5) according to the Euro norms (EN 197-1, 2000). It is to be noted from the earlier discussions on the American cements in Chapter 2 that these American regulations appear to intentionally underestimate the strength of cement (maybe to accommodate the variations in cement production or more importantly to ensure a higher level of safety for the conventional normal concretes of lower strengths used by industry without a serious attempt for quality control). Considering this, it is possible that the cements produced are of a higher grade (maybe of the 42.5 MPa, as per Euro norms). However, the fact remains that such an approach will invariably lead to substantially higher cement contents, a material of the highest cost in the matrix, apart from the environmental and carbon footprint of the oft adopted and ubiquitous concretes for general-purpose applications. The effects of such practices and the need to address and redress the outcome due to them will be discussed probably more cohesively at a later stage after we look at the provisions by the various national and international bodies. Also the need for vigilance about this aspect due to its uneconomical and ineffective use of the high cost pyro-processed material like cement obviously requires serious attention from not only a national but also an international perspective of it being highest contributor for the greenhouse gases from the industry as already highlighted earlier in this chapter itself.

It can also be seen that the most recent editions of this "Design and Control of Concrete Mixtures" (Fourteenth, Fifteenth and Sixteenth editions, PCA, 2008, 2011, 2016) have been expanding the scope in terms of high-performance concepts continuously over the years. It is to be noted that they have not included any specific relationships of the above type between the water cement ratios to strength at the different ages for concretes containing any type of cement. However, the possible band of variation in the water cement ratio to compressive strength for non-air-entrained concretes was presented, based on the results of about 100 different concrete mixtures studied between 1985 and 1999 (Figure 5.2). It was suggested that for a precise relationship,

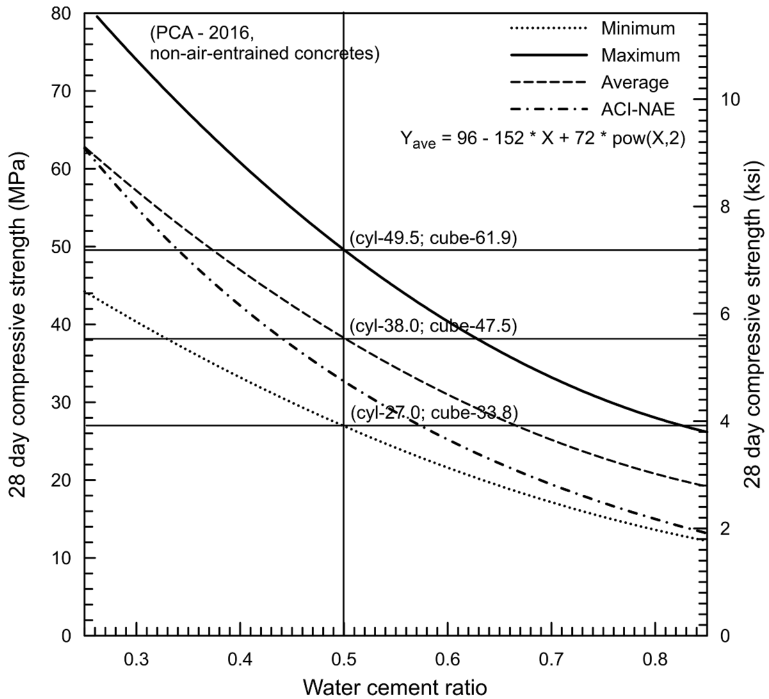

FIGURE 5.2
Range of 28 day strength variation with water cement ratio for OPC. (After PCA, 2015.)

data should be generated with the specific materials proposed to be used for the project under consideration. It is important to note that while this may be a possibility for an RMC plant, the idea of developing a complete relationship over the wide range required is not easy with just about 3–4 different mixes required for a particular project. A more important fact is that it will only be in the fitness of things to expect that the mix design practices from the several eminent organizations with significant asset base do suggest relationships that are more definitive with the appropriate variability factors associated with them. Such specifications are indeed a common practice in the DIN norms (DIN 1045, 1988) from the earliest of times the concrete mixture design methodologies existed. In the light of this thinking, the possible water cement ratio to strength relationship band suggested as a part of the recent editions of this publication is presently analyzed appropriately. In line with the thinking, the average water cement ratio to strength relationship for the band that was given was established resulting in the three curves of maximum, minimum and average as given in Figure 5.2. Similar to the earlier analysis of Figure 5.1, these curves suggest that the corresponding strength of cements (cylinder strengths of concrete at 0.5 water cement ratio) used in these investigations to be 27.0, 38.0, and 49.5 MPa at the minimum, average and maximum levels. Similar to the observations made earlier, the corresponding cements strengths that could be related to the strength of the corresponding cubes will be 33.75, 47.50, and 61.87 MPa respectively. It can then be assumed that the concretes representing the strength results close to the minimum of the band essentially may be at best the 32.5 MPa grade cements, while those around the average could be the 42.5 MPa grade cement. The upper quarter, those near the maximum of the band, could be the 52.5 MPa grade cements as per the euro norms for cements (EN 197-1, 2000). These observations invariably assume that all these concretes were made with aggregates having proper distribution and that they have an appropriate consistency for an effective compaction.

Similar to the 28 day strength relation in Figure 5.1, the strength to water cement ratio relation of the average curve from Figure 5.2 will be the following.

$$f_{ave} = 96 - 152 * X + 72 * pow(X,2) \tag{5.3}$$

It is also to be noted that all these recent PCA recommendations listed above invariably adopted in principle the methodology proposed by ACI 211.1 (1991) for the design of concrete mixtures. Naturally, as a part of its recommendations the ACI also presented the water cement ratio to strength relationships for the air entrained as well as the non-air-entrained normally vibrated concretes. This for the non-air-entrained concretes being discussed presently as can be seen lies in the lower half of the band (between the average and the minimum), with the strength values reaching the average curve at about 0.25 water cement ratio while almost touching the minimum level curve at the highest water cement ratio of 0.85 as can be seen (Figure 5.2).

In fact, the ACI recommendations for the design of concrete mixtures are quite comprehensive, specifying not just the water cement ratio for any particular strength but also suggesting required the water contents for a wide variation of slump levels as well as both the fine and coarse aggregate contents that are required for achieving an appropriate mixture of a desired consistency. The ACI recommendations are also available for the design of different types of concrete types (no slump, high strength, etc.) which are all presented and discussed explicitly and in detail in the later part of this chapter. The PCA recommendations of the recent times, as can be seen, also include many other important aspects relating to chemical admixtures and special concretes apart from a broad overview on the hot and cold weather concreting as well as the quality control aspects.

5.4 The "USBR" Contribution

Incidentally, the "Concrete Manual" of the U.S. Department of Interior's Bureau of Reclamation (USBR) also has a long history of existence (like the PCA publication that existed from 1916 as discussed earlier) with the first "Concrete Manual" appearing as a tentative edition in 1936 presenting its own recommendations for the design of concrete mixtures. The primary activity being the conservation of natural resource of the United States, the USBR is indeed the authority for the construction and management of the several large and small dams, along with their upkeep, and naturally did a pioneering work on not just concrete mixes for such huge structures but also contributed substantially to an understanding of its performance, like the sulfate attack and alkali silica reactivity aspects in particular. The several editions of the Concrete Manual contain the complete essence of concrete making in terms of the materials, design, compaction and curing broadly apart from an outline regarding maintenance and repair as well as a general overview of the different types of concretes. This was also adopted as a reference document in other countries, and an Indian edition was published in 1965 (USBR, 1965). In the present context, the seventh and the eighth editions of the same are being generally discussed to have an idea of the changes that happened in the concrete thinking during the 1960s to the early 2000s (USBR, 1975). In general, the USBR recommendations, after presenting the effects of parameters like temperature and air on the characteristics of the concrete, go on to provide the effects of the different types of cements generally. What is important to note is that it is followed by explicit recommendations on the grading of sand and coarse aggregates and more particularly explains the effectiveness of the combined grading curve (though not explicitly). In its following chapters on concrete mixes, the Concrete Manual presents the mix design procedure for obtaining concretes of specific strength in detail.

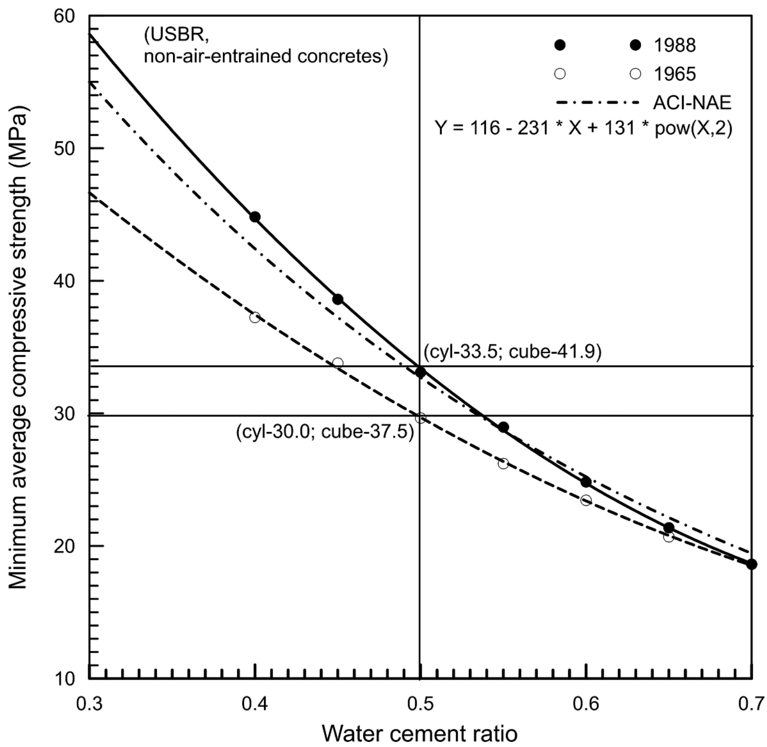

FIGURE 5.3
Comparison of the water cement ratio strength relationships over the years. (After USBR, 1965; USBR, 1988.)

The significant improvements in the cements produced on the concreting practices that followed can be seen from the fact that the water cement ratio to strength relationships have changed from 1965 to 1975/1988 even in the Concrete Manual (Figure 5.3). It can be seen from Figure 5.3 (as was observed in Figures 5.1 and 5.2) that the cements strengths have certainly improved from 32.5 grade to about 42.5 grade from the 60s to 90s. The water cement ratio to strength relationship in the USBR eighth edition (1988) was seen to be depicted by the equation:

$$f_c = 116 - 231 * X + 131 * pow(X,2) \tag{5.4}$$

It may not be out of place here itself to state that the latest water cement ratio to strength relationship in the eighth edition of 1988 as can be seen is very close to that presented by the ACI recommendations for the non-air-entrained concretes, which will be discussed in detail in the later part of this chapter. At the same time the fact that the concrete manual refers the strength presented to be the "minimum average compressive strength" is also noteworthy, suggesting that there is certainly enough scope for the values to be revised upwards, given the fact that the present day cements are certainly better in terms of composition, quality and consistency. In addition, the American Concrete Institute presents recommendations for the design of a number of other types of concrete mixtures which are all specified appropriately, for ensuring the ease of adoption in the industry. The complete provisions of the recommendations of ACI for the various types of concretes and the modulations possible with regard to the provisions therein are presented in the subsequent sections.

The mix design methodology presented by USBR (1988) was also slightly modified in terms of the water content required for the different aggregate sizes with the introduction of water reducing admixtures from the earlier 1975 provisions. The changes required in slump, if any, are accommodated by adjusting the values in water and aggregate contents broadly. The mixes and calculation procedure which initially proposed the calculation of coarse aggregate content first and calculating the remaining quantity containing all the other constituents was changed to the calculation of total aggregate corresponding design and then deducting the sand content to arrive at the coarse aggregate content. Also the importance given to the combined aggregate grading curve is certainly noteworthy as it ensures the presence of the intermediaries between sand and coarse aggregate appropriately. A simple relook at the variation of the different constituents like—water content sand and coarse aggregate volumes as well as the air content for concretes containing the different maximum size of coarse aggregates were also prescribed considering a slump of about 75–100 mm to ensure adequate compactability. The graphical representation of these presented in Figure 5.4 clearly shows that the variation of the quantities suggested appear to be varying a log linear fashion with the maximum size of coarse aggregate in concrete. However, for coarse aggregates below 20 mm and those about 80 mm, this linear variation could be not so accurate as can be seen from Figure 5.4. The corresponding relationships for the variation of the concrete constituents with maximum size of coarse aggregate as can be derived from Figure 5.4 are presented below.

$$\text{Recommended air content, } (\%) = -1.60 * \ln(X) + 10.56 \tag{5.5}$$

$$\begin{aligned}&\text{Sand vol. } (\%\ \text{TA})\\&(\%\ \text{of total aggregate by solid volume}) = -10.10 * \ln(X) + 71.88\end{aligned} \tag{5.6}$$

$$\begin{aligned}&\text{CA vol } (\%)\\&(\%\ \text{dry-rodded unit weight of coarse}\\&\text{aggregate per unit volume of concrete}) = 13.70 * \ln(X) + 21.15\end{aligned} \tag{5.7}$$

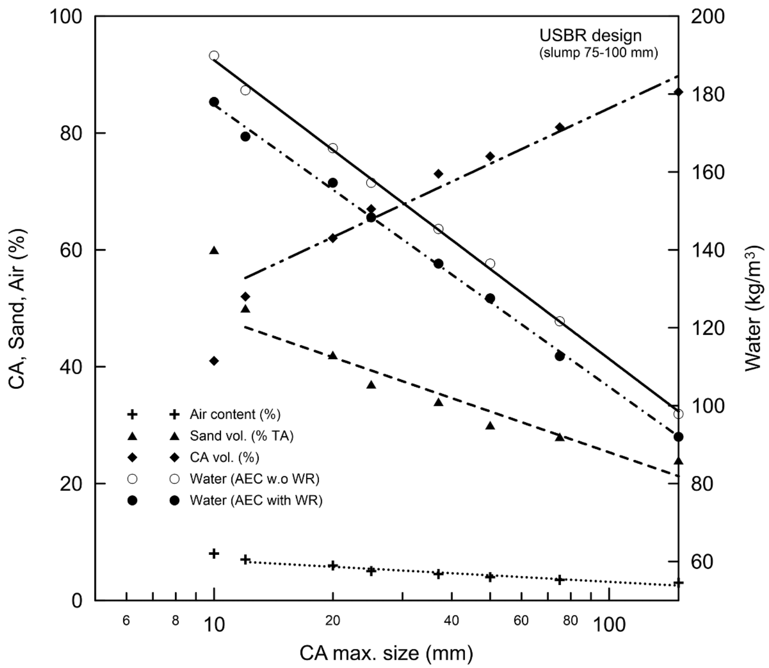

FIGURE 5.4
Variation of the concrete constituents with coarse aggregates size. (After USBR, 1988.)

$$\text{Water (AEC with WR)} \\ \text{(average water content of air entrained} \\ \text{concrete with WRA — kg/m}^3) = -31.45 * \ln(X) + 249.66 \tag{5.8}$$

$$\text{Water (AEC w.o WR)} \\ \text{(average water content of} \\ \text{air entrained concrete — kg/m}^3) = -33.30 * \ln(X) + 265.39 \tag{5.9}$$

where X is the value of the maximum size of the coarse aggregate in mm. It may be noted that these values were established from concretes containing natural sand (FM–2.75) exhibiting about 75–100 mm slump.

The USBR recommendations also provide suitable adjustments for variations in the conditions like increase or decrease in F.M. of sand, slump, air content, water cement ratio and sand content. The Concrete Manual also presents a table of "Concrete mixes for small jobs" suggesting a mix which can be replaced appropriately to account for an undersanded or oversanded condition for concretes with 12–50 mm maximum size of the coarse aggregate.

At this stage the next remaining major contribution with the substantial history of research and development to the concrete mixture design methodology could be said to American Concrete Institute (ACI) recommendations. It should also be recognized that the idea of looking closely at the recommendations from the various contributors to the science and technology of cement and concrete composites is essentially to bring them to a common platform and project each of them in their proper perspective. In doing so, efforts are being made to collate and correlate the viewpoints of each of these approaches and to finally suggest the way forward, wherever possible. In particular, the idea of trying to arrive at the strength of cements through the strength of cement or concrete at the water cement ratio of 0.5 as discussed in several earlier occasions is essentially to ensure that the results can be correlated on the international platform. It is to be understood and recognized that such an attempt is neither new nor inappropriate as can be seen from two distinctly different reports utilizing a very similar philosophy decades apart. The first of these factors is the assessment of the very same American cements in comparison to the then available norms for cements in Germany (Walz, 1963). The second one is the evaluation of the available Indian cements in contrast to the international recommendations by an apex body at the request of the Cement Manufacturers Association in India (ECRA, 2012).

5.5 The "ACI" Recommendations

The rapid industrialization and a subsequent thrust toward urbanization have brought with it the need for a significant urgency toward growth in the infrastructure requirements in the American context almost suddenly. Concrete being the choice material for such mega structures, the bodies charged with the task have been making concreted efforts to arrive at the most appropriate solutions as could be seen from the earlier discussions. In this scenario, while there have been several different methods for selecting proportions of hydraulic cement concretes that were proposed over the years, the construction industry in close collaboration with the research and developmental efforts of the academic community founded the American Concrete Institute (ACI) in 1904. Charged with the objectives of putting together the most appropriate technical standards based on the latest scientific and technical resources and ensuring its appropriate distribution through dissemination and certification, ACI stands alone today with several chapters and a thriving member community of several committed individuals drawn from almost every corner of the world. To put it simply, it is important to have an appropriate understanding of the present-day concepts and methodologies of concrete mix design. Naturally it is essential to look for some universally accepted practices for selecting proportions of concrete. Amongst these it can easily be seen that the "Standard practice for selecting the proportions for normal, heavyweight, and mass concrete" (ACI 211.1) is one that is simple and holistic in many ways for the design of concrete mixtures. The fact that a very large group of individuals associated with research and development as well as practicing professionals participate on a continuous basis to ensure an appropriate recommendation suitable for specific applications naturally makes it most user-friendly. This may probably be one of the reasons that the recommendations for the various types of concretes required for different applications (normal, lightweight, no slump and high strength concretes) are presented individually through four different sets of the recommendations (ACI 211.1–ACI 211.4). It is obvious that this approach was preferred exclusively to address the specific needs of the industry in particular and to address the intricacies of making a concrete of the specific variety in question. However, it is obvious that the overall philosophy and the conceptual methodology in ensuring an appropriate mix of a particular type of concrete were all essentially the same. In view of this, if one has an in-depth understanding of the fundamental concepts that are involved in the making of the normal concretes as discussed in ACI 211.1 (1991), it may be possible to see the implications of the various modifications and changes that were attempted to arrive at the other types of concretes discussed under the remaining three sets of recommendations (ACI 211.2–ACI 211.4).

The choice of the methodology for selecting the proportions of hydraulic cement concrete mixtures according to the American recommendations is in fact an obvious one for several reasons. Firstly it is the simplest of all the available methodologies, particularly because of the reason that it tries to look at each type of concretes—normal, lightweight, no-slump, and high strength concretes—separately and tries to specify the relevant procedures for each one of them through specific and different guidelines. This eliminates the need for a comprehensive understanding of the entire gamut of parameters that actually influences the design and performance of concretes in their entirety. This means that a certain amount of the broader picture is not always so obvious to the designer, which could make the resulting concrete not necessarily an optimum solution for a specific situation. Even so, one can always say that the guidelines do result in concretes that are more user-friendly and are effectively much less sensitive to the variations in constituents within the general limits of acceptability. It can also be said that the methodology is better orchestrated in terms of both the theory and the design steps that are needed to arrive at a concrete of a specific strength. However, some of the aforementioned limitations can easily be addressed through minor modifications. These could effectively ensure that the specific needs like incorporating chemical and/or mineral admixtures that are the order of the day are taken care of. Some of these aspects in particular will be discussed toward the end of this chapter and also later in some of the proposed broader outlines presented in the ensuing chapters.

It is well recognized by the ACI 211.1 (1991) that the selection of concrete proportions needs to be a compromise between the construction and structural requirements like strength, consistency required for the construction method, performance over its lifetime that are all obligatory in the specification for the project and the overall economy in the materials and processes put together. While it is absolutely essential to ensure the required strength and performance of concrete for any specific application, it is almost too obvious that these guidelines place a special emphasis on ease of placement and aesthetics of the resulting concretes, particularly being the concretes for general-purpose applications, keeping in mind their use by even contractors with limited specialized knowledge and without the appropriately skilled manpower that are essential for the more demanding construction scenarios. It is thus a fundamental question of how much of a compromise should it be between the economics and adaptability. It may be prudent at this stage to actually ascertain not just the cost involved in the compromise itself, but to have a holistic assessment in terms of the savings in cement which is to be taken as the additional installed production capacity and more importantly its effect on the carbon footprint and greenhouse gases to which cement is one of the primary contributors. Looking at this perspective, there is an urgent need to reassess our thinking and search for reasonable avenues to alleviate the need for a significant compromise at levels beyond what can be reasonably achieved. One should also think and detail well in advance specific recommendations and limitations that could apply to each domain of the concrete construction activity to ensure the effective performance over the entire life of the structural facility. This fact can be more easily understood during the later discussions wherein one can see a definite shift toward the use of marginally higher water contents during the later revisions of these recommendations, which apparently are more helpful in ensuring the required workability needed for a higher ease in placement that automatically ensures a better compaction resulting in a better appearance.

The ease of placement and compaction in the present context (termed as placeability) is in fact not just the workability or consistency as we understand but was ascribed to encompass factors like moldability, cohesiveness and compactability that ensure the capacity of the concretes to be placed, consolidated and finished without any problems of segregation and bleeding. In effect the consistency in terms of slump is its capacity to easily flow during placement (ACI 211.1, 1991). The durability or the inadequacies in serviceability against temperature effects or the chemical actions was in fact only vaguely suggested to be remedied through the introduction of pozzolanic materials like fly ash, GGBS and silica fume. However, the use of water cementitious materials ratio as a factor in such a scenario was broadly recognized. The effects of heat of hydration in large pours where temperature differentials could induce significant thermal gradients and associated thermal cracking was also recognized as these recommendations encompass the mass concrete requirements as well.

5.6 The Proportioning of Normal Concretes

The recommended procedure for the selection of mix proportions by ACI 211.1 (1991), essentially for normal concretes (NC), can be described through the following simplified steps. At the very outset the characteristics of the constituents as may be required later were all ascertained through the appropriate tests or from the information made available by the suppliers. The desired characteristics of the concrete for the particular application as given by the job specification are also recorded. These could be the maximum water cement ratio, minimum cement content, and air content required for the particular environment; the maximum size of aggregate based on the minimum dimension of the structural member; slump to ensure the compactability as well as the design strength of concrete for the structural components. The characteristics of the cementitious materials need special attention and have to be tested for conformity to the required standards at different stages of construction. It is to be recognized that the recommended mix design procedure is applicable only for well consolidated concretes through appropriate compaction practices. It is obvious that the compaction and curing are adequately taken care of to ensure the required strength and performance of the concrete.

5.6.1 Slump Requirements

The recommendations presented broad guidelines regarding the preferable slump for the various structural components, though these may be generally available through the job requirement specifications already available. In brief, recommended slumps for substructure and slabs or pavements which are in general of a smaller thickness and for mass concrete were specified to be ranging from 25 to 75 mm. For reinforced concrete members of substantial depths that means walls and columns are expected to range between 25 and 100 mm, which would be increased by 25 mm for methods of consolidation other than vibration or when chemical admixtures are used. Care should be taken to ensure that such an increase in slump does not lead to segregation and/or bleeding.

5.6.2 Maximum Size of Coarse Aggregate

Recognizing the fact that the largest possible maximum size of coarse aggregates (CA) in a well graded material will have lesser voids, it is proposed that the maximum size of coarse aggregate should be limited to the minimum of the following—1/5 of the smallest thickness of a member, or 1/3 death of a slab, or 3/4 the clear spacing between reinforcement in general. It is also recognized that for higher strength concretes, reduced nominal maximum size of the aggregates is preferable.

5.6.3 Water and Air Contents

Having ensured that the nominal maximum size of the course aggregate is chosen appropriately, Table 5.1 presents the details regarding the approximate mixing water and air content requirements for achieving the proposed slump values. It can be seen that Table 5.1 presents not only the water and air content requirements for the different maximum sizes of aggregate as given by ACI 211.1 (1991) but also the recommendations of the same body earlier in 1977 (ACI 211.1, 1977). It is felt that the marginal increase of about 2–5 kg water contents in the latest 1991 recommendations is probably to accommodate the variations in cement strength and construction quality. However, the experience with several mixes both in field and laboratory appears to show that the water contents proposed in the 1977 recommendations are perfectly adequate for most construction scenarios even in developing countries like India. In view of this, the reasons for increasing these water contents (that result in an increase in the cement content directly) cannot be understood and is certainly unnecessary.

The effect of the addition of finer cementitious materials on the water content requirements can in fact only be judged based on the initial cement content values and probably also the fineness of the mineral additives that are being utilized. Notwithstanding the fact that such a critical assessment of the wetting water requirements of the finer cementitious compositions in the concrete mix which are yet to be finalized at this particular stage is not available (at least apparently), it was obvious that the values given in Table 5.1 were generally found to be a perfectly balanced requirement for ensuring the relevant slump values with most aggregate gradations in the realms of normal concrete used for general-purpose construction. The use of chemical and mineral admixtures for improving the green and hardened state characteristics or consistency and durability are not being discussed at this particular stage. The required modifications and the way to handle these will be discussed in some of the later chapters wherein the requirements as well as the effects can be properly explained. Table 5.1 also contains distinctly different water requirements for air-entrained and non-air-entrained concretes clearly recognizing the fluidizing effect of air entrainment. It also presents the recommendations toward the use of air entrainment in the system for addressing the effects of environmental degradation due to the different exposure conditions. This is quite understandable as the minute air bubbles with their thin walls all around break up the continuity of the pour system in the concrete mass, thus ensuring that the environmental ingress is reduced to a very large extent. It also helps in providing the cushion required for the expansion and contraction effects due to the thermal cycling that could take place.

The slump values for concrete containing aggregate larger than 40 mm are based on slump tests made after removal of particles larger than 40 mm by wet screening. It may also be said that the slump test is indeed not an appropriate representation of the consistency of concrete having

TABLE 5.1

Water and Air Contents for Different Slumps

	Water Content (kg/m^3) for Different Maximum Sizes of CA (mm)							
	Non-Air-Entrained (NAE)							
Slump (mm)	9.5 (*10*)	12.5	19 (*20*)	25	37.5 (*40*)	50	75 (*70*)	150
25–50	207 (*205*)	199 (*200*)	190 (*185*)	179 (*180*)	166 (*160*)	154 (*155*)	130 (*145*)	113 (*125*)
75–100	228 (*225*)	216 (*215*)	205 (*200*)	193 (*195*)	181 (*175*)	169 (*170*)	145 (*160*)	124 (*140*)
150–175	243 (*240*)	228 (*230*)	216 (*210*)	202 (*205*)	190 (*185*)	178 (*180*)	160 (*170*)	NA
>175	*(Only with HRWR with aggregates below 25 mm. Liquid admixture is to be included as mixing water.)*							
Entrapped Air (%)	3	2.5	2	1.5	1	0.5	0.3	0.2
	Air-Entrained (AE)							
25–50	181 (*180*)	175 (*175*)	168 (*165*)	160 (*160*)	150 (*145*)	142 (*140*)	122 (*135*)	107 (*120*)
75–100	202 (*200*)	193 (*190*)	184 (*180*)	175 (*175*)	165 (*160*)	157 (*155*)	133 (*150*)	119 (*135*)
150–175	216 (*215*)	205 (*205*)	197 (*190*)	184 (*185*)	174 (*170*)	166 (*165*)	154 (*160*)	
>175	*(Only with HRWR with aggregates below 25 mm. Liquid admixture is to be included as mixing water.)*							
Exposure	**Air content (%)**							
Mild	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Extreme	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0
(Extreme)[a]	(*8*)	(*7*)	(*6*)	(*5*)	(*4.5*)	(*4*)	(*3.5*)	(*3*)

Source: ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete, 211.1-91*, American Concrete Institute, Farmington Hills, Michigan, 1991, p. 38.

[a] The values given in brackets in italics belong to ACI 211.1-77.

aggregate larger than 40 mm. This is obvious from the fact that the size of the largest aggregate particle should be limited to about a fifth of the minimum mould dimension, which will actually limit that to about 25 mm approximately. This is in line with the fact that the strengths reported are based on 152 × 305 mm cylinders of concretes containing 19–25 mm nominal maximum size aggregate only, as reported later. Considering the fact that the largest diameter is 200 mm at the bottom of the slump cone, maybe it was felt that this could be extended to the possible maximum of 40 mm, though a maximum of 25 mm or even 20 mm is certainly more appropriate.

While it is not explicitly stated that the wetting water requirements of the finer constituents of concrete dictate the amount of water needed for the different slump regimes, one can understand in a broader sense that even the maximum size of the aggregate and the grading distributions do finally decide the cementitious materials in the system and the water requirement values reported in the Table 5.1, which were recommended based on the past experience. These recommendations probably balance both the cementitious materials and the water content in the concrete mixture for any given strength; given the fact that the wetting water requirements of the coarse aggregate are really not a matter for great concern, understanding of the water requirements as we do today. In a way these observations are amply reflected in the statements that "the quantities of mixing water are for cement factors of trial batches at 20°C–25°C using 75 or 150 mm normal maximum size aggregate" and that "they are the average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine" as given in the appended comments on the table. The comments also contain a few other observations, namely that rounded coarse aggregate will generally require 18 kg less water for non-air-entrained and 15 kg less for air-entrained concretes. The observation that water-reducing chemical admixtures could reduce mixing water requirement by about 5% certainly needs an amendment as the present day high range water reducers (HRWRs) can easily reduce the water contents by well over 15%, with the poly carboxylic esters based superplasticizers capable of achieving even higher reductions.

The recommendations recognizing that superplasticizers or high range water reducing admixtures (HRWRs) (as liquid admixtures) should be treated as a part of the mixing water are indeed sensible and commendable. The fact is that liquid plasticizers, with their normal 40% solution concentration, have a lot water and will affect the strength adversely at higher dosages and particularly in concretes of higher strengths, though it is often forgotten universally in the present-day context. It may also thus be appropriate to have a recommendation prescribing range for the percentage of HRWR. The experience of the author with concretes in both field and the laboratory and with the considerations of economy and effectiveness show that this could be set as 0.5%–2.5% for most situations. Requirements below 0.5% could easily be managed through small adjustments in water content itself, while in case of requirements of over 2.5% it is probably the water in the superplasticizers that is primarily driving the plasticizing effect rather than the effect of the plasticizer itself. Also in very low strength concretes, the need for minimum fines content (not minimum cement content) is a factor that should be addressed appropriately in this context of water reduction possibilities.

It can be seen that the water requirements at different slump levels were continuously increasing with a decreasing maximum aggregate size. To have a definitive mathematical understanding of these variations, the water content requirements at the different aggregate sizes for different slumps were all plotted in Figure 5.5. It is obvious that the values could be related through a polynomial in general. A close observation appears to show that the variation is essentially trilinear, with the actual water requirements becoming steeper primarily at the 75 and 25 mm maximum course aggregate sizes as can be seen. Assuming that the relation is mainly continuous, the typical variation of the water requirements of concretes at the different maximum course aggregate sizes for a 100 mm slump in the case of the non-air-entrained concretes ($W_{100\text{-nae}}$) appears to suggest the relationship presented below.

$$W_{100\text{-nae}} = -38.17 * \ln(X) + 315 \tag{5.10}$$

where X is the aggregate size in mm.

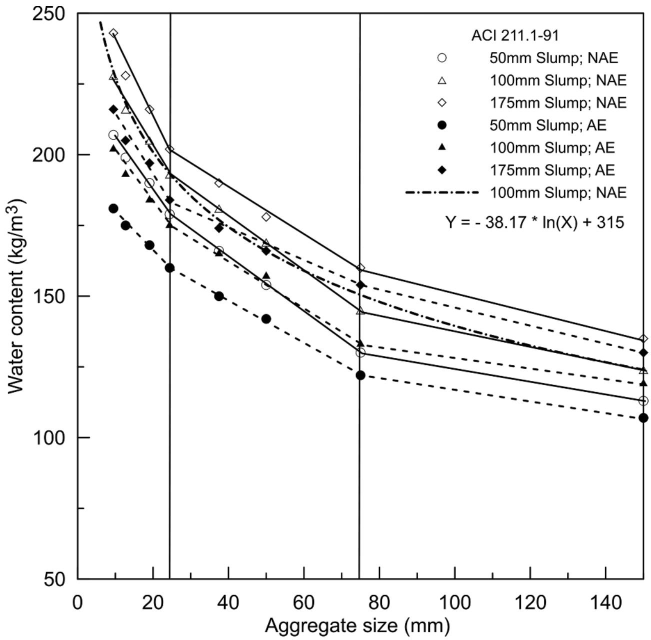

FIGURE 5.5
Mixing water requirement at different slumps in normal concrete.

It is possible to arrive at similar relationships for each of the slump values of both air-entrained as well as non-air-entrained concretes presented in ACI 211.1 (1991). A more detailed discussion on these variations and a more comprehensive assessment of all these factors are relegated to the later parts of this particular chapter.

The air contents recommended for the different concretes subject to the various exposure conditions have been looked at critically to arrive at possible relationships. While doing so the entire air contents possible in the normal non-air-entrained concretes have also been taken into consideration. Figure 5.6 presents these variations as described in the ACI 211.1 (1991), which shows a reasonable linearity of the recommendations. Barring the value recommended for air-entrained concretes under moderate exposure, which was duly adjusted to the same slope, all the others (almost until the 75 mm maximum aggregate size) appear to follow the relationship:

$$\text{Air content} = -1.4\ \ln(X) + a \tag{5.11}$$

where "X" is the maximum size aggregate in millimeters and "a" is a constant, defined in brackets in the graph itself.

It is obvious from Figure 5.6 that the recommended air contents vary almost linearly with the logarithm of the maximum aggregate size, and after

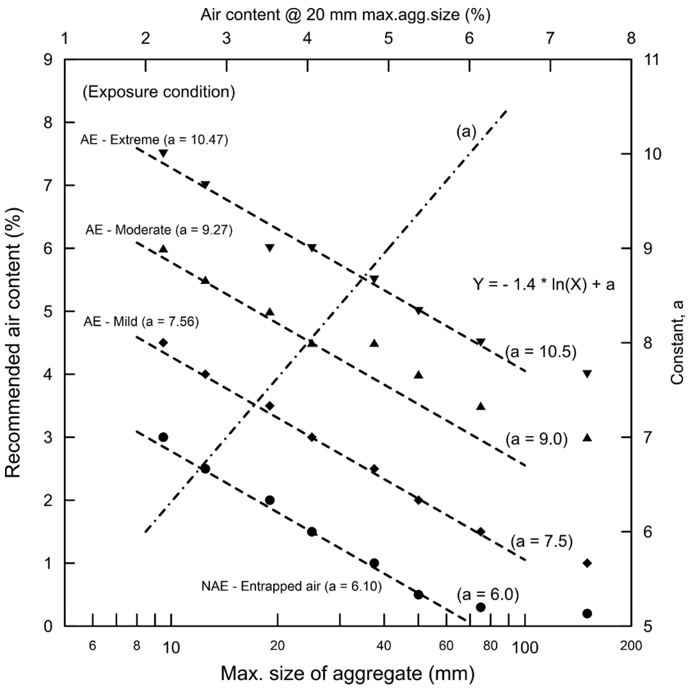

FIGURE 5.6
Variation of air content maximum size of aggregate. (After ACI 211.1.)

close relook at these variations it is suggested that constant "a" may be chosen as 6.0 of the entrapped air content of the non-air-entrained concretes. The same could easily be seen effectively to be 7.5, 9.0, and 10.5 for the mild, moderate and extreme exposure conditions respectively. This obviously, as can be seen, will result in gradual and equal variation in steps from the air content in normal concrete to that finally the air-entrained concretes proposal for use in extreme environmental conditions. Also the variation of this constant had a linear relation with the relative air content recommended for the 20 mm maximum size aggregate, the values for which will be certainly based on the largest data base being the most used concrete aggregate.

5.6.4 Selection of the Water-Cement Ratio or Water Cementitious Materials Ratio

It was emphasized that the requirements of water cement ratio or water cementitious materials ratio (w/c or w/(c+p)) is chosen not just based on the strength requirements but also the requirements of durability. The need for generating a specific relationship for the constituents being used is highly recommended, particularly as the rate of strength gain could be different for various supplementary cementitious materials. However, in their absence, the values given a table therein, which was in fact termed as approximate and relatively conservative for concretes containing Type I Portland cement, could be used. The strengths reported here are based on 152 × 305 mm cylinders of concretes containing 19 to 25 mm nominal maximum size aggregate that are moist cured at 23°C ± 1.7°C for 28 days.

It is also surprising that the ACI 211.1 (1991) marginally reduced the water cement ratios for the corresponding strengths from the earlier same recommendations of ACI 211.1 (1977), a recommendation that cannot be easily explained considering the fact that the cement strength has been increasing over time due to the advancements in technology in cement production and efficient grinding techniques (Figure 5.7). Maybe it is only appropriate at this stage to specifically look at the tabulated water cement ratios for the given strengths and arrive at the possible mathematical relationships. Figure 5.7 presents the variation of the compressive strength with the water cement ratio for both air-entrained and non-air-entrained concretes as recommended by ACI 211.1 (1991). These could be written as

$$f_c = \exp\left(-2.63 * X\right) * 122 \tag{5.12}$$

for the non-air-entrained concretes, and

$$f_c = \exp\left(-2.73 * X\right) * 103 \tag{5.13}$$

for the air-entrained concretes, where X is the water cement ratio.

There are a couple of important factors that need to be discussed at this stage for an appropriate understanding of the above recommendations of

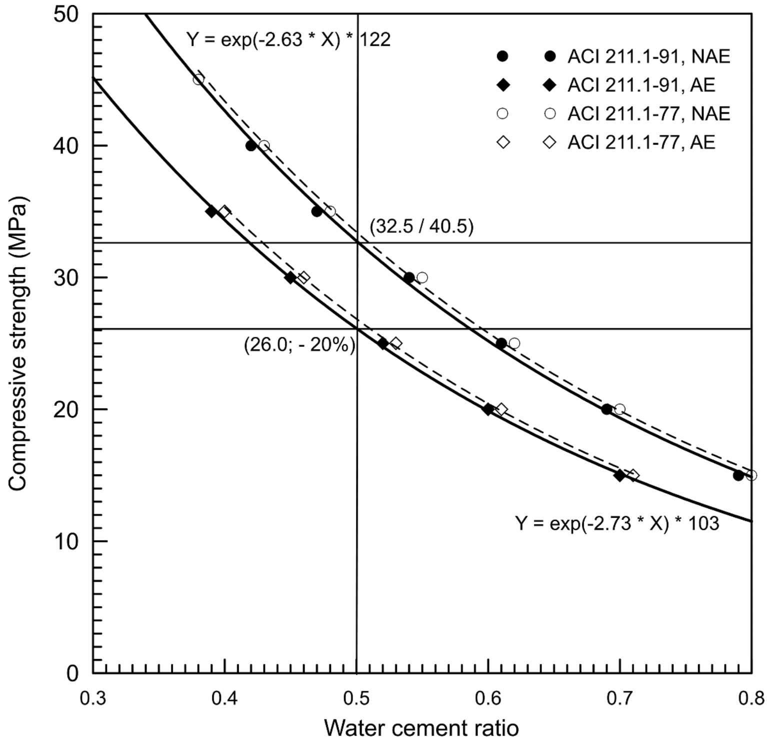

FIGURE 5.7
Strength to water cementitious materials ratio relation for normal concretes.

the ACI 211.1 (1991) in particular and also the general philosophy of the ACI recommendations. The first of these stem from the fact that the strength of cement, as represented by the strength of concrete at a water cement ratio of 0.50 (as already discussed and that the cement characteristics in Chapter 2), appears to be the 32.5 cylinder strength (approximately 40.5 cube strength in relation to the international norms conforming to the 32.5 grade cement nearly). In fact the ACI does not relate in any way the strength of cement and the strength of concrete. It appears that maybe to relate itself to the specific user industry for the particular concrete type, it has chosen to specify individual concrete strength to water cement ratio relationships as a matter of practice. While the effectiveness of this approach is never in doubt as they are specific to the regime in which they are operative, the broader scientific concepts are probably never emphasized or elucidated.

The second aspect that should be of interest is the fact that air entrainment as recognized by ACI 212 (2010) results in the reduction of about 5% strengths for every 1% of the entrained air, and the rate of reduction of strength increases with increasing air content. However, air entrainment improves the workability, enabling small reduction in the water content

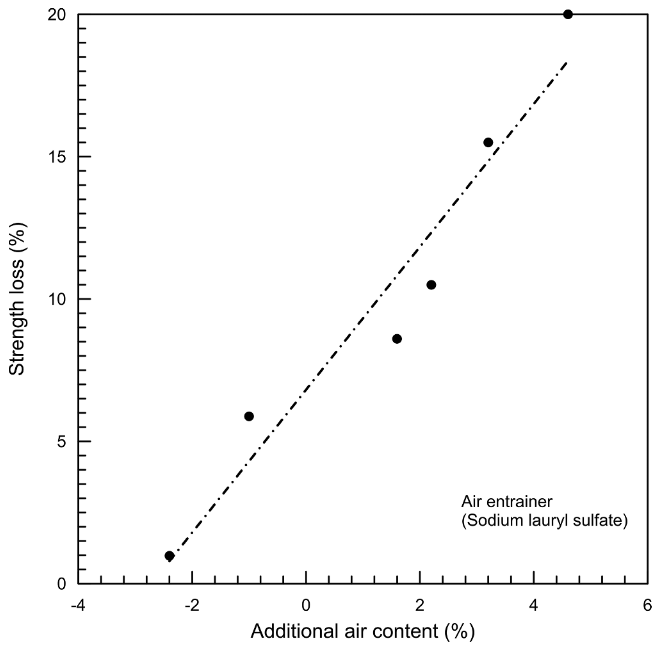

FIGURE 5.8
Typical effect of air entrainment on the strength loss characteristics.

that could partially offset such strength reduction. The effectiveness of air entrainment is reflected in the fact that it improves the freeze thaw durability and may also have some effect on the chloride diffusion due to the interceding air bubbles breaking up the continuity of the capillary pores (Powers, 1968). However, it should be emphasized that the strength loss varies from 2% to 6% depending on the concrete mix and its constituents like cement content, aggregate size and admixtures. Figure 5.8 presents the results of an investigation in the laboratory (Ranga Raju, 1992) showing that the strength reduction due to the air entrainment effects of sodium lauryl sulfate in a few typical concretes (of about 50 MPa strength) was approximately 2.5% for every 1% increase in air entrainment.

In this context it is to be recognized that the ACI recommendations for strength to water cement ratio relationship for air entrained concretes are essentially for normal concretes of the moderate exposure class containing about 4.5%–5% entrained air compared to about 1.5%–2% on concretes without any air entrainment. The 20% reduction in strengths suggested appears to corroborate well with the expected strength reduction of about 5% for every 1% increase in entrained air. Thus it appears that one could arrive at the strength to water cement ratio relationship for air entrained concretes (containing any specific amount of additional air entrainment over and above that of the normal concrete) from the strength to water cement ratio relationship for normal concretes itself. Extending this argument a little beyond the air entrained concretes, maybe it is possible and even arrives at the strength to water cement ratio relationships for lightweight aggregate concretes (containing porous aggregates) by establishing the total porosity of the air contents involved.

It is proposed that while using pozzolanic materials like fly ash, GGBS, and silica fume, the water cementitious materials ratio by weight instead of the water cement ratio should be considered, of course with the pozzolanic materials being limited to the following percentages.

Class F fly ash—15%–25%

Class C fly ash—15%–35%

Natural pozzolans—10%–20%

Ground granulated blast-furnace slag—25%–70%

Silica fume—5%–15%

The recommendations also provide a detailed explanation of how the cementitious materials are to be distributed in terms of the specific gravities of the cementitious constituents, though a lot of it could have been avoided to ensure that the recommendations are more concise and focused as recommendations should be. It can be seen that the recommendations look at the need for restricting the maximum permissible water to the cement or the cementitious materials ratio to ensure the requirements of durability through a very broad outline. This is attempted by restricting the maximum water cement ratio to 0.45 for thin sections with reinforcement cover of less than 25 mm in environments continuously that are frequently exposed to freezing and thawing, to 0.40 for structures exposed to sea water or sulfates, and to 0.50 and 0.45 for all other structures. The use of sulfate resistant cement is also advocated with an acceptable increase in the water cementitious materials ratio by 0.05.

A couple of observations on the above could be probably in order to put things in perspective. Firstly, the water cement ratio to strength relationship is well defined, given the cement and the specific constituent's distribution, with of course possible variations due to the inherent effects of minor changes in constituents and quality of production. Naturally a highly conservative approach specifically for normal concretes with Type I cement as is proposed appears to be unnecessary. This could be further amplified later while discussing the recommendations for other types of concretes including high strength concretes (ACI 211.2–ACI 211.4). Such an approach will only result in much higher cement content in the most commonly used concretes for most general-purpose applications. The fact that this probably is neither in the interests of the national economy nor will help in reducing the carbon footprint associated with the cement concrete constructions should be a matter of serious concern to all. The possibility of a reasonable water cement ratio strength relationship that could sufficiently represent the type I cements in the American context is probably a more apt approach, and the same will be looked for while discussing the recommendations of the different concretes later in this chapter.

It is also to be remembered that the pozzolanic efficiency of the individual materials like fly ash, GGBS and silica fume at the varying percentages are not reflected in these proposed recommendations. One of the alternatives is to presume that replacement of the cement contents resulting from the water cement ratio to strength relationships (given already the water content for a specific slump required) will not alter significantly the strength characteristics, naturally ensuring that the proportions are calculated in accordance with the revised absolute volumes. Even so, one should remember that it should be specified explicitly the allowable percentage levels for either addition or replacement of the individual pozzolanic materials. This would mean that the efficiency of the allowable replacement materials will be equal to that of the cement that is being utilized. Another approach would be to directly prescribe a specific value for the cementitious efficiencies of these materials within the narrow band of allowable replacements facilitating the designer to calculate the quantities appropriately. This practice is already available in a few other national recommendations. In fact the recommendations clearly state that the water cementitious materials ratio to strength relationship could be established while using such supplementary cementitious materials at the desired allowable percentage. A broad outline on the efficiency factors for the different pozzolans and their appropriate utilization in establishing the strength to water cementitious materials ratio relationship will be detailed in a later chapter. It may be appropriate to state that the limitations on minimum cement content if any, particularly in such cases, can be regulated by ensuring that the values prescribed are the actual cement contents in specific and not for the total or the effective cementitious materials contents established through the pozzolanic efficiency factors discussed later.

5.6.5 Calculating the Cement Content

Knowing the water content required for an effective consistency (in terms of the slump required) to ensure appropriate compaction of the concrete mass in the specific member type and the water cementitious materials ratio from the strength requirements (maybe even moderated by the durability criteria if required), it is now possible to establish the cement content. It is also possible to look at the cementitious materials contents compositions in a coherent fashion considering the type of pozzolan if adopted, and modulate marginally the required water content to ensure that the cementitious materials are not too far in excess while using an appropriate superplasticizer if required.

In fact even the proportioning of the cement and the supplementary cementitious materials can also be modulated at this stage to effectively arrive at the minimum cement content needed from both the strength and durability criteria. It appears that there is a certain ambiguity in some national norms, and the ACI 211.1 recommendation that wherever the specifications were to include a specific minimum limit on the cement content in addition to the requirements of strength and durability, the mixture must be based on the criterion that leads to the larger amount of cement, even while recognizing that the chemical and mineral admixtures, will affect the properties of both the fresh and hardened concretes. Even so, it is not obvious if the requirement of the minimum cement content is effectively satisfied, since the minimum cement content requirement appears to be a job specification and not as required by the environmental considerations, as it should be. It will only be apt to recommend the minimum cement contents for the various environmental conditions, like the maximum water cement ratios prescribed for specific structural or environmental conditions, maybe even in a more comprehensive and clearer form in this recommendation itself or indicate the requirement that it should conform to the recommendations made a certain other specification. A broad outline of this form of a recommendation will be attempted at a later stage in the ensuing chapters.

5.6.6 Appraisal of the Coarse Aggregate Content

It is accepted that for equal workability, the volume of course aggregate depends not only on the maximum size of the coarse aggregate and the fineness modulus of the fine aggregate which will actually supplement the minimum fines needed for an appropriate flow. In view of this the volume of dry rodded coarse aggregate per unit volume of concrete at the different fineness moduli of the fine aggregate was given in a tabular form by the ACI 211.1 (1991). The table presents the volume of coarse aggregates required per unit volume of concrete for the various nominal maximum sizes of aggregates at the varying fineness moduli of the fine aggregate. A graphical representation of the table is presented below showing that the variation of the volume of coarse aggregate with fineness modulus are all linear and have the same slope, with only constant varying with the aggregate size (Figure 5.9). Both these aspects are presented in Figure 5.9.

This is essentially based on the experience on concretes with enough cementitious materials content being present so that the mortar fractions will be able to ensure an appropriate consistency and given water content adopted. In this case the interfacial friction between the various course aggregate particles of different sizes is alleviated through the mortar fractions that are introduced in the system. A specific alternative in certain of the other design methodologies is the use of a continuous gradation of the combined coarse and fine aggregates. Each of these methods have their own proponents, but given the fact that the present approach will not totally ensure an appropriate distribution in the course aggregate, given the accepted variation in the different size proportions as specified in the code itself, it may be more appropriate to look at this aspect more closely. It is also to be

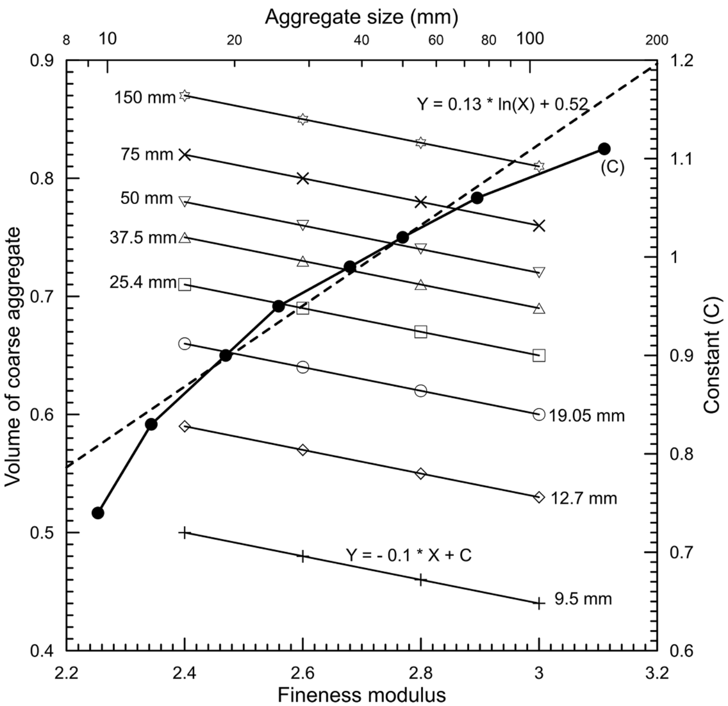

FIGURE 5.9
Coarse aggregate volume and slope constant for each maximum size.

recognized that the fractions between the lower end of the coarse aggregate grading and the upper end of the fine aggregate (in the size range of 6–2 mm generally) are invariably absent in most cases necessitating much higher proportion of the fine aggregates in general, which will consequently increase both the water and cementitious materials requirements for coating the larger surface area thus generated. These values can be increased or decreased by about 10% approximately to ensure the higher or lower workabilities that may be required for the pavement applications on the one side all for ensuring comparable concretes on the other end.

5.6.7 Evaluation of Fine Aggregate Content

Presently all the constituents of the concrete mixture other than the only remaining fine aggregate have been estimated. It is only appropriate to use absolute volumes of all the other materials to arrive at the volume of fine aggregate required.

Alternatively, an approximate method can be adopted by simply looking at a table of the first estimate of weight of fresh concrete given in ACI 211.1 (1991) for the purpose. Though as reported the values of these first estimates of the mass of fresh concrete are computed for concretes of what is called the median richness (330 kg/m^3 cement) and for a slump of about 75–100 mm, with aggregates of specific gravity 2.7. A correction of about 8 kg for each 20 kg difference in cement content is suggested, but it is only appropriate to state that the absolute volume method is indeed more apt. Apart from this the fact that the supplementary cementitious materials utilized could also influence these values should also be recognized. However, the values proposed in the recommendations are also presented graphically in Figure 5.10, if one prefers to use it to have a rough estimate or to check the appropriateness of a reported mix. The corresponding mathematical equations for the variations of the fresh concrete mass with maximum size of the aggregate are also given in Figure 5.10. It may be noted that in arriving at the relationships of the first estimates of concrete mass at the different nominal maximum size of aggregates, other than that at the 150 mm size, were found to be almost linearly related to log of the aggregate size considered.

The corrections for the additional moisture content in aggregates should also be undertaken at this stage. This has significance particularly for the fine aggregate portions (sand) more importantly. The absorbed water in the case of construction and demolition wastes or even certain light weight aggregates can also be assessed and accounted for if appropriately addressed.

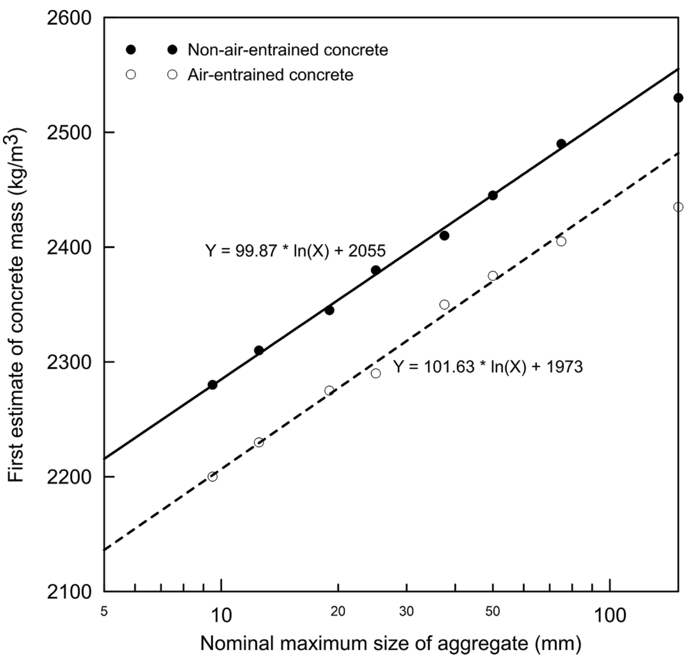

FIGURE 5.10
Estimate of the mass of fresh concrete.

TABLE 5.2

Appropriate Major Conversion Factors

			Conversion Factors	
Measure	**FPS Unit**	**SI Unit**	**FPS–SI**	**SI–FPS**
Length	in	mm	25.40	0.03937
Volume	ft^3	m^3	0.02832	35.31
	yd^3	m^3	0.7646	1.3079
Mass	lb	kg	0.4536	2.2046
Stress	psi	MPa	6.895×10^{-2}	14.5033
Density	lb/ft^3	kg/m^3	16.02	0.0624
	lb/yd^3	kg/m^3	0.5933	1.6855
Temperature	F	C	(F–32)/1.8	(C × 1.8) + 32

As is customary in the American context ACI 211.1 (1991), the associated and appurtenant documents primarily use the "FPS" units, though in recent times the SI units are also encouraged. However, to be more globally applicable, most of the information given herein as well as equations associated with the mathematical modeling have all been framed to represent the variations in SI units. To facilitate an easier transportation to the "FPS" units, ACI 211.1 (1991) presents the conversion between the two systems, which is slightly modified and presented here for convenience (Table 5.2).

Finally, it is at this stage that the recommendations of ACI 211.1 suggest the need for a set of laboratory tests on the characteristics of the cementitious materials and the aggregate characteristics to ensure their appropriateness, which in fact is many a time given a convenient go by leading to erroneous results. Maybe it is only appropriate to reiterate the fact that the cement and the supplementary cementitious materials should comply with the recommendations and that the appropriateness of the grading of aggregates is to be ensured to realize the expected strength and performance of the concretes designed. Specific attention should be drawn to the statement that the undesirable coarse aggregate grading should be corrected by removing the larger size fractions not designed for and supplementing the deficient sizes. The idea of trial mixes to ensure minor adjustments (in the requirements of water and fines in particular on the experience of the author) may be relevant only at this stage for ensuring the most appropriate mix. Apart from all this, the recommendations also present a table containing "concrete mixes for small jobs" for different maximum size of the aggregate proposed for the construction. They suggest a very simple method, in which the mix B type is chosen initially, adding just enough water to produce workable concrete mix. Any correction required could simply be achieved by changing to mix A type if the concrete appears to be under-sanded or mix C type if it appears to be over-sanded. It is important to note that the inclusion of this "concrete mixes for small jobs" obviously means that a structural concretes must be essentially designed for the constituents and job requirements envisaged, and should also be continuously monitored through appropriate quality assurance and control measures.

The above paragraphs clearly delineate the various recommendations and their implications as specified by ACI 211.1 (1991) for selecting proportions for normal concretes. These are based on the experience of the several researchers involved in the formulations as well as the knowledge of the experimental investigations on the concrete compositions reported by several others in the published literature. Also, the earlier paragraphs explain a brief outline of the methodology and actual principles in the design of normal concretes as directed by the ACI recommendations (ACI 211.1, 1991). The recommendations available in the form of tables mostly have been depicted and discussed through a set of graphs that present the actual variations in the recommendations as can be seen in the earlier paragraphs. Another way of comprehensively presenting the interrelationships between the various parameters as proposed by these recommendations could be through the overall graphical representations like the ones presented in Figures 5.11 and 5.12, for the non-air-entrained and air-entrained concretes respectively. These are essentially not a direct graphical representation of the various tables as was attempted by the ACI 211.3 (2002) recommendations revised from ACI 211.3 (1997). It can be seen that these are simple and direct translation of the values given in the recommendations to present a possibility of arriving at the recommended

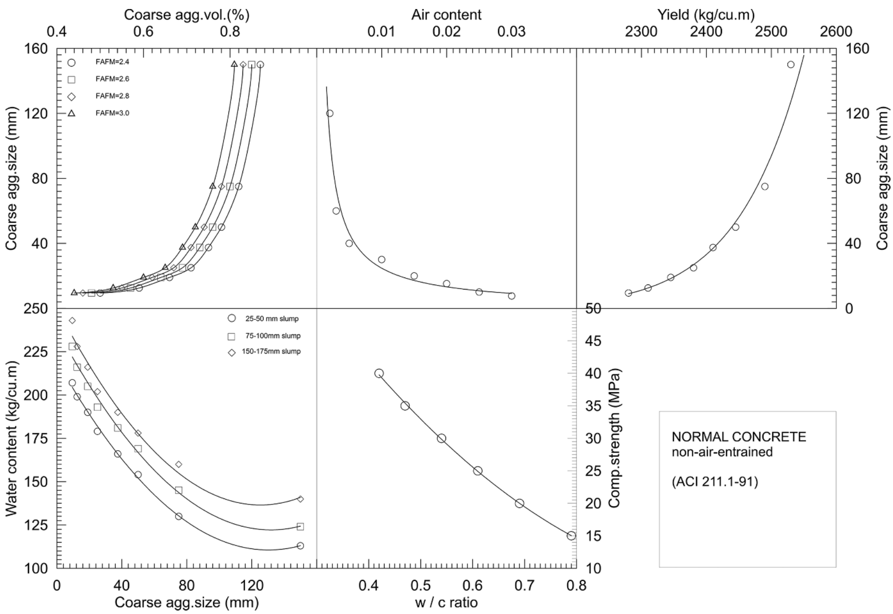

FIGURE 5.11
Recommendations for non-air-entrained concrete mix design. (After ACI 211.1, 1991.)

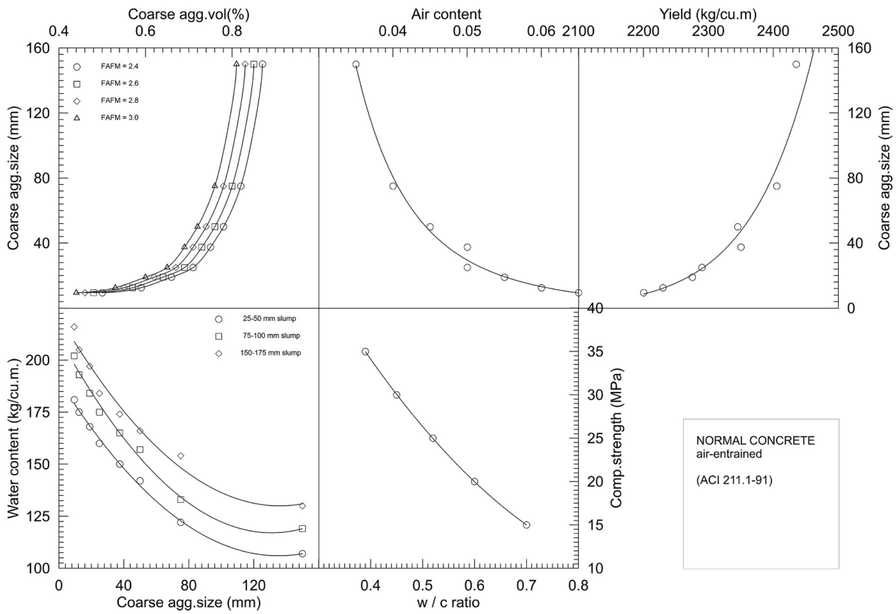

FIGURE 5.12
Recommendations for air-entrained concrete mix design. (After ACI 211.1, 1991.)

values for the various parameters by ACI 211.1, which are required for the mixture proportioning as proposed by these recommendations.

These graphical representations have also been utilized to arrive at the appropriate mathematical equations for the different parameters proposed in the ACI recommendations as was presented already. These mathematical relationships could be used directly for the design of any required normal concrete mixture of a particular strength. Incidentally, while looking at these recommendations, an effort was made to identify specific areas (like the use of chemical and mineral admixtures) that probably need a better formulation to ensure their efficient and appropriate use in practice; the specific aspects of such a possibility are discussed later.

Another way to orchestrate mathematical modeling of a design process is to put together an appropriate set of nomograms that could directly lead to an appropriate design from the initial job specifications if possible. Naturally it was felt essential to look at the recommendations more closely and understand the effects on the constituent materials on the panorama of the resulting concrete mixture proportions itself. Such an approach to figuratively present relations of the constituent materials in terms of the different strengths with a specified set of constituent material characteristics like the maximum size aggregate, the slump that is needed to be realized for a particular application will present a greater insight into the recommendations itself, and more often will also permit the comparison of the constituent proportions at the different alternatives available from these mixture design recommendations. A typical such nomogram presenting the constituent quantities directly for a representative non-air-entrained concrete with an expected slump of 75–100 mm containing different nominal maximum size of the aggregates (9.5, 19, and 50 mm) and different fineness moduli of the sands (2.4–3.0) is presented in Figure 5.13. Incidentally, there have been several individual mixture proportions designed and investigated in detail for

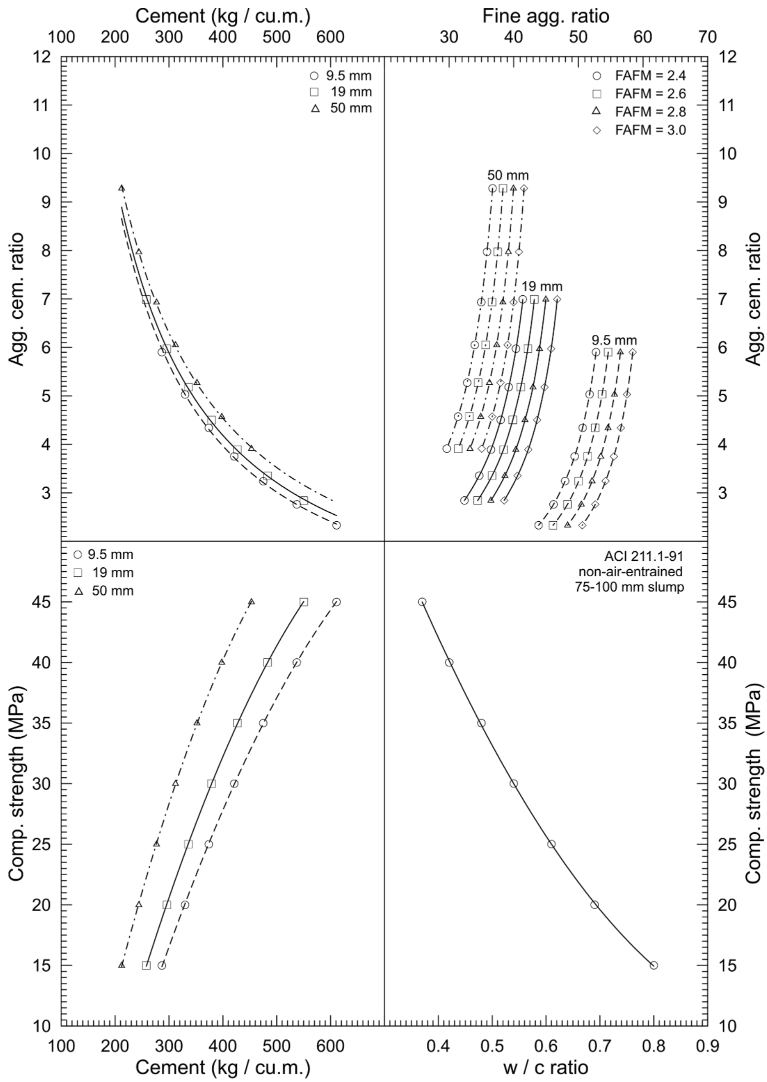

FIGURE 5.13
Typical nomogram for non-air-entrained concrete. (After ACI 211.1, 1991.)

the mechanical, durability and performance characteristics of various types of concretes with several different materials and admixtures for the various applications in the laboratory over the past four decades.

However, to be pragmatic with the computational effort involved in attempting individual concrete mixture details, a computer program was written in a Fortran compiler for arriving at the mixture details in the nomogram. In fact it is to be emphasized that the computations were done based on such computer programs written specifically for the purpose of arriving at the mixture ingredients for all concrete compositions defined by ACI 211.1–211.4 as well as the other codal provisions like British, German/Euro and Indian standards. There were several versions of these from time to time over the past thirty to forty years or even more. Some of these started with basic language and then graduated to Fortran compilers. A typical set of results from a similar effort was presented way back in 1992 (Ganesh Babu, 1993). To be totally transparent and communicative to the different segments of concrete researchers and users, a typical program listing for the design of the different concrete mixtures in accordance with the ACI 211.1 is appended herein (Appendix PROG-ACI-NCNA-5). It is also to be recognized that there have been several different formats available over the past; it is felt essential that this program be utilized after correcting for a necessary syntax appropriate to the present day compilers if need be.

Though the "Appendix PROG-ACI-NCNA-5'" presented at the end of this chapter contains this with the necessary details indicating the concrete mixture design that was attempted, it may be prudent to be explicit with some of the limitations that may be appropriate to mention. As already stated, the program is written for obtaining concrete mixture proportions for normal concretes as per ACI 211.1 (1991). The tabular form for the water cement ratio to strength relationship was incorporated as an equation, while the water contents were defined directly. The coarse aggregate contents were defined as the equations for each particular maximum size of the aggregates. The air contents and exposure conditions were also taken into account. Finally, the yield values were estimated. The program logically follows the steps associated with ACI 211.1 explicitly. Similar programs were also written for the other types of concretes like no slump and high strength of ACI as well as other codal provisions as already stated, but are not being presented to be concise and not to be repetitive. However, the nomograms resulting from each of these programs are appended to the appropriate locations, to facilitate a direct and quick look at the concrete mixture proportions required. One important aspect is that the bulk density of the coarse aggregate was taken to be 1600 kg/m^3, while the specific gravity of both fine and coarse aggregates was taken to be 2.6 for the calculations in arriving at the nomograms. The program, however, has provisions to appropriately change these values as required. One important observation probably is that the variations in the quantities of fine and coarse aggregates due to variations in the bulk density and specific gravities of aggregates is almost insignificant, and one can comfortably assume that there is no significant effect on the resulting strengths of concrete for all practical purposes. Even so, one can go ahead and make simple calculations to find any necessary changes even from the nomograms while reading out the corresponding constituent proportion.

5.6.8 Proportioning of Heavyweight Concrete

The fact that is not given prominence in presenting the recommendations of ACI 211.1 (1991) by many is that it also contains recommendations for heavyweight and mass concretes, which in itself suggests that there is an acceptable commonalty in not only the design philosophy but also in the defining parameters and even their values. A more comprehensive presentation of the same will be presented toward the end of this chapter. The recommendations present that concretes of acceptable consistency with different densities (ranging between the 2350 for normal concrete to the 5600 kg/m^3 using heavier aggregates such as Barites or iron ores like Hematite and Magnetite or even iron or steel shot and pellets) can be put together with the same mix design methodology. The variation of the possible density of concretes with the different specific gravity of the aggregate as opined by ACI is depicted in Figure 5.14. Incidentally, this could serve as a general guideline in attempting

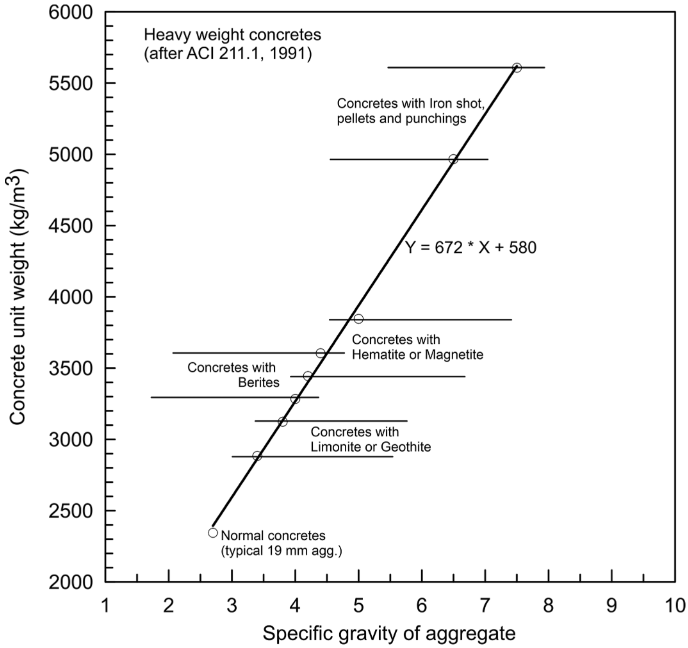

FIGURE 5.14
Variation of the density of concrete with the specific gravity of the aggregate.

to realize the concrete of a specific density for any application, particularly in the nuclear industry.

Experience in the laboratory while designing the concretes required for the top shield of the prototype fast breeder reactor at Kalpakkam near Chennai showed that concretes of very high flexibility, which are able to flow into all the confined spaces of the top shield steel shell, could easily be achieved through a similar approach. However, a few critical aspects for ensuring such highly flexible concretes which have a flowing consistency may have to be realized for ensuring such concretes, though the heavier aggregates used will be helpful in aiding the flow.

- One of the first aspects is to understand and account for the very fine dust associated with both the Hematite coarse and fine aggregates. While this could supplement the additional fines required for an appropriate flow, one should realize that it also necessitates a reasonable quantity of additional water for wetting such fine powders.
- It is also necessary to ensure an appropriate grading of the aggregates, particularly the availability of the lower-end sizes in the coarse aggregate. A better alternative is to ensure an appropriate combined grading of the coarse and fine aggregates. The reasons and the appropriateness of such an alternative will be discussed under the relevant topics in the later chapters.
- The fine aggregates should also be made up of the same Hematite aggregate used for the coarse aggregate. The need for this is certainly obvious from the fact that much lighter fine aggregates will not be able to support and keep the heavier course aggregates, particularly the larger sizes, in suspension and could promote segregation.
- The additional water requirements due to the increased fines should be appropriately accounted for in calculating the water cement ratio strength relationships utilized for the design. The aspects relating to the water cement ratio to strength relations and the recommendations in the different national and international standards will also be discussed under the relevant topics in the later chapters.
- In the case of nuclear concretes for containment purposes, though there is no apparent reason for not using lower-end pozzolanic admixtures like fly ash and GGBS and the chemical admixtures like superplasticizers in combination or otherwise, the various authorities do not approve their use for want of documented studies on the performance these concretes in such applications.

It is also possible to realize heavyweight preplaced-aggregate concrete of a type similar to normal weight preplaced-aggregate concrete by choosing the appropriate grading limits for fine and coarse aggregates as prescribed in ACI 304 (1989). However, it is obvious that these recommendations given for the design on normal concretes are indeed applicable for heavyweight concretes as well. Even so, it may only be appropriate to accept enumerating and explaining that the intricacies of ensuring cohesive mixtures at the different fluidity levels with the wider variation in densities as in normal concretes is still a difficult proposition in a short report like this and the same was not also attempted by the ACI 211.1 (1991) recommendations.

5.6.9 Proportioning of Mass Concrete

The primary aim of looking at the proportioning of mass concrete mixtures is to ensure an appropriate mix of cementitious materials, along with the chemical admixtures if necessary, to arrive at a set of cementitious composites that will not result in the significant variation in temperatures (temperature differentials) between the surface and the core concrete of the element under consideration. Particularly the use of pozzolanic admixtures which help in generating lower heat at early ages is recommended. The recommendations presented information regarding adiabatic temperature rise with time for the different cements (Type I–Type IV) along with the total heat of hydration for the cements in a concrete mass containing approximately 225 kg/m^3 of cement.

An important observation is that the characteristics depend essentially on the fineness of cement as well as the different compounds (Bogues compounds) associated with the cements. Some of these aspects were already discussed in detail in the earlier chapter on cements. It is also to be noted that the appropriate way of combining cement of the different pozzolanic admixtures (fly ash, diatomite or slag, which are all slightly larger than that allowed for normal concretes) is probably a matter for specific consideration and will be appropriately discussed at a later stage in this work. One of the simple and possible explanations for recommending pozzolanic of mineral fines larger than normal concrete could be attributed to the possible enhanced pozzolanic hydration effects at the higher internal temperatures in such mass concrete members. The use of even simple mineral fines with limited pozzolanic effect is also a possibility and will also be discussed in the later chapters. Apart from these aspects, the recommendations in this part primarily appear to be similar to those that are discussed under normal concrete composites, with only the appropriate changes for concretes of lower strengths. It is probably simpler to extend the relation for water cement ratio to strength to accommodate the lower strength concretes, while extending the discussions on cementitious compositions to include the effects of the higher quantities pozzolanic or mineral admixtures in the earlier part itself to be comprehensive. In fact, the designer always has the basic liberty to extend the validity of the water cement ratio to strength relation (if not any theoretical relation by and large) to accommodate the design concretes of strength slightly lower or even higher than that presented in the recommendations without compromising on the quality. It is only in certain specific realms of materials science that the effects of singularities negate such a practice, the most prominent of these being semiconductors and superconductors. Also, in principle these mass concretes are effectively for the massive foundations of structures where the strength requirements are significantly lower and the strength gain rates could also be significantly larger, though the soil characteristics and the characteristics of the waters surrounding may impose significant and definite restrictions to ensure appropriate performance over the life of the structure.

The recommendations recognize that the mortar quantities were optimized for concretes containing aggregates up to a nominal maximum size of 37.5 mm. For mass concretes containing larger sized aggregates, it suggests that the Fuller and Thompson (Powers, 1968) parabolic gradation (with the corrections for the fines at the lower end) be adopted. In fact, the recommendations present tables of the combined grading curves for some of these larger sized aggregates, which could be used as a guideline when combining the different aggregates to ensure maximum density and minimum voids. A more detailed discussion regarding the methodology of arriving at an appropriate packing density for the highest possible strength is discussed in the later chapters.

5.7 Proportioning of Structural Lightweight Concrete

It is a well-known fact that in the design of structural facilities of large spans, the effects of dead weight dominates significantly, even compared to all other live loads put together. It is in these cases like long span bridges, large span industrial building frames, offshore and marine structures that any possible weight reduction will significantly lower the cost of construction. It is in this perspective that there are several efforts underway to alleviate the difficulties associated with dead weights, even if only in part, or even in the appurtenant facilities that is giving a large thrust to the development of higher performance lightweight concrete compositions.

Apart from this, the thrust toward increasing the efficiency of the building envelope in the fast paced urbanization and efforts toward the concept of energy efficient structures is leading the way toward development as well as modulation of the available material combinations to ensure specifically thermal barrier materials like lightweight concretes. The need for installation that was the primary requirement in colder regions that gave an impetus to the development of the lightweight concretes is now seen also to be a requirement for even the tropical regions. Essentially lightweight concretes obtained through the use of lightweight aggregates produced through either exfoliation or sintering appropriate mixtures of shales and clays and industrial wastes like fly ash and blast furnace slags etc, have assumed a lot of significance.

The main problems associated with the production of structural lightweight concrete naturally are all associated with the aggregate characteristics themselves and could be listed as:

- The significant absorption characteristics of the aggregate, which interferes with ensuring the specific water cement ratio required for the proposed strength,
- The difficulty of ensuring size and gradation of the aggregate as in normal concrete,
- The effects of variations in the density of lightweight aggregates during the project period,
- The possible and significant reductions in strength (density related).

In particular, the moisture content of a saturated surface dry aggregate can give out large quantities of water even with mild agitation (even without vibration) into the concrete, making it too fluid leading to significant losses in strength as well as in most cases segregation and bleeding. Alternatively, if the aggregate is not fully saturated, the absorption during mixing can lead to significantly faster stiffening effects and also larger shrinkage stresses due to the absorption of moisture from the surrounding concrete by the aggregates. The entire diligence in balancing these two aspects is the most important part in the production of structural lightweight concretes. One effective way of addressing this problem is to allow the draining of the saturated aggregates through mild agitation initially itself, so that the aggregate is not able to thrust any water available into the mix during the compaction efforts that will produce some agitation. Apart from all this, even minor variation in the density of the lightweight aggregates from batch to batch could lead to changes in both the final concrete yield and consequently density, apart from the strength itself.

A much broader aspect in terms of being more comprehensive is to recognize the fact that the associated difficulties relating to the very high moisture absorptions and their release even with minor agitation is very similar to the problems associated with the use of recycled concrete aggregates. In this particular case it is the significant absorptions of maybe the slightly lower strength matrix that was absorbing significant quantities of water, which is totally unstable in its pours, that gets released even while attempting to retrieve it after soaking that was seen to be the problem, which is similar to what happens in lightweight aggregates concretes as well. A recent investigation with recycled aggregate clearly showed that some of these concepts could be beneficially utilized to alleviate the problems associated with such concretes also.

Having understood that there is still a significant amount of moisture associated with the lightweight aggregate or the mortar that is sticking to the recycled aggregates, one can easily see its potential in promoting hydration at later ages, a concept that is the backbone of self-cured or internally cured concretes of the recent years. This moisture that is associated with these types of aggregates, if appropriately proportioned, could be a better choice than the superabsorbent polymers that are often advocated for this purpose. Indeed the use of lightweight aggregates for this purpose is already well recognized. Some of these concepts if appropriately modulated may also have applications in addressing the self-desiccation effects in very high strength concretes of very low water cement ratios using high end pozzolanic admixtures like silica fume and metakaolin etc.

Finally, a close look at the design methodology of the structural lightweight concretes also appears to show that the general steps associated with their design is essentially similar (if not same) as those for the design of normal concretes that was discussed earlier. It is possible thus to represent the various relationships associated with the water cement ratio to strength, the water content, etc. and arrive at specific relationships as was done earlier in the case of the normal concretes for the design of these concretes too. While it is a fact that these relationships have already been calculated and were available to the author, such a repetition of the various relations and equations was felt not justifiable as they would at best serve as additional information. Certainly they will be unique, but not in terms of the novelty in the concepts involved in such an approach. However, in the later part of this particular work an attempt is made to look at the possibility of a synergistic modulation of the concepts involved in the design of the different types of concrete mixture designs and present them coherently to be more universal and amalgamated.

In view of this, a comprehensive summary of all the parameters of design—like the water requirement at the different slumps, water cement or cementitious materials ratio to strength relationships and the volumes of dry rotted coarse aggregate per unit volume of workable concrete—proposed in the four ACI 211 recommendations which are considered basic (ACI 211.1, 1991; ACI 211.2, 1998; ACI 211.3, 1997; ACI 211 4, 1993) is attempted. These details are summarized in Tables 5.3 through 5.5 as can be seen. Though there have been a few modifications in the presentation of these basic four in recent years, the configuration of the overall concept and even the specific characteristic values tabulated for the different parameters (in some cases presented in the graphical form recently) have not varied in any way. Naturally, the recent attempts to make such modifications or even add additional sets of recommendations for a few specific concrete compositions could be seen to be essentially to clarify and promote a few newer forms of concrete composites (like Aggregate Suspension Mixture Proportioning, ACI 211.6T-14; Proportioning Concrete Mixtures with Ground Limestone and Other Mineral Fillers, 211.7R-15; apart from the several other exclusive

TABLE 5.3
Water Requirement for Concretes of Different Slumps (ACI)

				Water Content (kg/m³)																
				Normal Concrete (ACI 211.1-91)[b]					Light weight Concrete (ACI 211.2-98)			No-slump Concrete (ACI 211.3-97)					High Strength Concrete (ACI 211.4-93)			
Consistency[a]	**Slump (mm)**	**Vebe (sec)**	**RWC (%)**	**9.5**	**12.5**	**19**	**25**	**37.5**	**9.5**	**12.5**	**19**	**9.5**	**12.5**	**19**	**25**	**37.5**	**9.5**	**12.5**	**19**	**25**
Non-Air-Entrained																				
Extra Dry		32-18	**78**									178	169	***157***	148	139				
Very Stiff		18-10	**83**									187	187	***169***	157	148				
Stiff	0–25	10-5	**88**									199	193	***178***	169	157				
Stiff Plastic	25–50	5-3	**92**	207	199	***190***	179	166	208	199	***187***	208	199	***187***	178	163	184	175	***169***	166
	50–75			—	—	—	—	—	—	—	—						190	184	***175***	172
Plastic	**75–100**	**3-0**	**100**	**228**	**216**	***205***	**193**	**181**	**228**	**217**	***202***	**228**	**217**	***199***	**193**	**178**	**196**	**190**	***181***	**178**
	75–125			—	—	—	—	—	—	—	—									
Very Plastic	150–175	—	**106**	243	228	***216***	202	190	237	225	***208***	243	228	***214***	208	187				
	125–190			—	—	—	—	—	—	—	—									
Flowing[c]	190+																			
Air content (%), no HRWR in HSC				3	2.5	**2**	1.5	1	3	2.5	**2**	3	2.5	***2.0***	1.5	1.0	3	2.5	**2**	1.5

(*Continued*)

TABLE 5.3 (*Continued*)

Water Requirement for Concretes of Different Slumps (ACI)

				Water Content (kg/m³)																
				Normal Concrete (ACI 211.1-91)[b]					Light weight Concrete (ACI 211.2-98)			No-slump Concrete (ACI 211.3-97)					High Strength Concrete (ACI 211.4-93)			
Consistency[a]	**Slump (mm)**	**Vebe (sec)**	**RWC (%)**	**9.5**	**12.5**	**19**	**25**	**37.5**	**9.5**	**12.5**	**19**	**9.5**	**12.5**	**19**	**25**	**37.5**	**9.5**	**12.5**	**19**	**25**
Air-entrained																				
Extra Dry		32-18	**78**									157	148	***139***	133	125	*Air-entraining admixtures are seldom used in HSC, as they will reduce the strength significantly.*			
Very Stiff		18-10	**83**									169	157	***148***	139	133				
Stiff	0–25	10-5	**88**									178	169	***157***	148	139				
Stiff Plastic	25–50	5-3	**92**	181	175	***168***	160	150	181	175	***166***	187	175	***166***	157	148				
	25–75			—	—	—	—	—	—	—	—									
Plastic	**75–100**	**3-0**	**100**	**202**	**193**	***184***	**175**	**165**	**202**	**193**	***181***	**202**	**193**	***178***	**178**	**157**				
	75–125			—	—	—	—	—	—	—	—									
Very Plastic	150–175	—	**106**	216	205	***197***	184	174	211	199	***187***	217	208	***193***	187	169				
	125–190			—	—	—	—	—	—	—	—									
Flowing[c]	190+																			
Air content (%)[d] with HRWR in HSC				4.5	4.0	***3.5***	3.0	2.5	4.5	4.0	***4.0***	8.0	7.0	***6.0***	5.0	4.5				

[a] —The consistencies are from ACI 211.3R-97. The slumps 150–175 mm above are for 125–150 mm slump for lightweight concretes.

[b] —Water contents of aggregate sizes 50, 75, and 150 mm available for normal concretes were not presented.

[c] —Air content for mild exposure condition of normal and lightweight concretes was only presented.

[d] —*A higher fluid consistency called* ***"flowing"*** *was also defined in ACI 309-96 for concretes with* ***"slump above 190 mm."***

TABLE 5.4

Water Cementitious Materials Ratios for Concretes of Different Strengths (ACI)

		Normal Concrete (211.1-91)		Lightweight Concrete (211.2-98)		No-slump Concrete (211.3-97)				High Strength Concrete (211.4-93)							
										Without HRWR				With HRWR			
										Maximum Size of Agg. (mm)				Maximum Size of Agg. (mm)			
Comp. Str. (MPa)	**Age (days)**	**NAE**	**AE**	**NAE**	**AE**	**NAE**	**AE**	**Comp. Str. (MPa)**	**Age (days)**	**9.5**	**12.5**	**19**	**25**	**9.5**	**12.5**	**19**	**25**
14	28			0.82	0.74			**48**	28	0.42	0.41	0.40	0.39	0.50	0.48	0.45	0.43
15	28	0.79	0.70			0.80	0.71		56	0.46	0.45	0.44	0.43	0.55	0.52	0.48	0.46
20	28	0.69	0.60			0.70	0.61	**55**	28	0.35	0.34	0.33	0.33	0.44	0.42	0.40	0.38
21	28			0.68	0.59				56	0.38	0.37	0.36	0.35	0.48	0.45	0.42	0.40
25	28	0.61	0.52			0.62	0.53	**62**	28	0.30	0.29	0.29	0.28	0.38	0.36	0.35	0.34
28	28			0.57	0.48				56	0.33	0.32	0.31	0.30	0.42	0.39	0.37	0.36
30	28	0.54	0.45			0.55	0.46	**69**	28	0.26	0.26	0.25	0.25	0.33	0.32	0.31	0.30
34	28			0.48	0.40				56	0.29	0.28	0.27	0.26	0.37	0.35	0.33	0.32
35	28	0.47	0.39			0.48	0.40	**76**	28					0.30	0.29	0.27	0.27
40	28	0.42	–			0.43	0.34		56					0.33	0.31	0.29	0.29
41	28			0.41	–			**83**	28					0.27	0.26	0.25	0.25
45	28					0.38			56					0.30	0.28	0.27	0.26
50	28					0.33											
Str. @	**28**	**32.76**	**26.14**	**32.84**	**26.27**	**33.23**	**26.67**			**42.35**	**41.16**	**40.50**	**39.62**	**48.76**	**46.84**	**44.72**	**42.06**
0.5 w/c	**56**									**45.00**	**44.32**	**43.71**	**43.15**	**52.90**	**50.12**	**46.81**	**44.81**

The recommended replacement percentages of fly ash are 15%–25%for Class F and 20 %–35%for Class C.

TABLE 5.5

Volumes of Dry-Rodded Coarse Aggregate for Unit Volume of Workable (reinforced) Concretes (ACI)

	Volume of CA for Different FM of FA													
	Normal Concrete (ACI 211.1-91)				**Lightweight Concrete (ACI 211.2-98)**				**No-slump Concrete (ACI 211.3-97)**					**High strength Concrete (ACI 211.4-93)**
CA Size (mm)	**2.4**	**2.6**	**2.8**	**3.0**	**2.4**	**2.6**	**2.8**	**3.0**	**2.4**	**2.6**	**2.8**	**3.0**	**3.2**	**2.5–3.2**
9.5	0.50	0.48	0.46	0.44	0.58	0.56	0.54	0.52	0.5	0.48	0.46	0.44	0.42	0.65
12.5	0.59	0.57	0.55	0.53	0.67	0.65	0.63	0.61						0.68
15									0.59	0.57	0.55	0.53	0.51	
19	**0.66**	**0.64**	**0.62**	**0.60**	**0.74**	**0.72**	**0.70**	**0.68**	**0.66**	**0.64**	**0.62**	**0.60**	**0.58**	**0.72**
25	0.71	0.69	0.67	0.65					0.71	0.69	0.67	0.65	0.63	0.75
37.5	0.75	0.73	0.71	0.69										
40									0.76	0.74	0.72	0.70	0.68	
50	0.78	0.76	0.74	0.72										
75	0.82	0.80	0.78	0.76										
150	0.87	0.85	0.83	0.81										

explanatory guides that are a part of the ACI guidelines) even if they were to be very similar to the present ones under discussion. These modifications and extensions will only be discussed appropriately in the various segments as we go through. But for the purpose of a broad and coherent understanding of the various concrete mixture design specifications as proposed and promoted by the ACI, the present discussions will be more or less comprehensive and were felt sufficient.

Step 1—Slump requirements

Step 2—Maximum size of coarse aggregate

Step 3—Water and air contents

Step 4—Selection of the water cement ratio or water cementitious materials ratio

Step 5—Calculating the cement content

Step 6—Appraisal of the coarse aggregate content

Step 7—Evaluation of fine aggregate content

It can be seen from what was summarized in Tables 5.3 through 5.5 that both the major parameters of design as well as the steps involved in the actual design itself follow essentially the same general principles in all the ACI mixture design recommendations (ACI 211.1-91, ACI 211.2-98, ACI 211.3-97, ACI 211.4-93), though the individual values in the tables and graphs for each constituent design may vary. A closer look at these summary tables makes one to look for a method to amalgamate all these values to arrive at a unified and comprehensive methodology for the design of concrete mixtures of the different primary types presented by ACI 211 recommendations.

As can be seen from the earlier Figure 5.13 it is very difficult to accommodate all the different alternatives in one single nomogram. In view of this, the complete set of nomograms presenting the concrete constituents at the different strength levels for the non-air-entrained concretes have all been enclosed in Appendix NCNA-5 (Figures NCNA-5.1 through NCNA-5.9), while the same for the air-entrained concretes have been enclosed in Appendix NCA-5 (Figures NCA-5.1 through NCA-5.9) at the end of this chapter.

At this stage it may be appropriate to look at the recommendations for the other types of concretes in the ACI recommendations—both that are remaining in ACI 211.1 (1991) and also the others in ACI 211.2 (1998), ACI 211.3 (1997), and ACI 211.4 (1993). While doing so one should keep in mind the detailed discussions concerning the broad outline and the context in which the recommendations for the normal strength concrete mixture designs evolved as discussed in the previous paragraphs relate the others also been similar context. In fact, if one looks closely, the recommendations of ACI or the other types of concretes, be it lightweight, no slump or even high strength have all followed the same broad steps utilized for the design of normal concrete mixtures earlier and can be listed as the following.

- After establishing the slump and the maximum size of coarse aggregate required for the structural facility, the approximate water content required is established.
- The modifications required and the water content if any due to the chemical and finer pozzolanic admixtures along with the corrections for moisture content in aggregates are looked at.
- At this stage water cement ratio of the water cementitious materials ratio required for a given strength is established, which is not related if required for the structural or environmental conditions as desired.
- The quantities of cement as well as the finer pozzolanic admixtures are ascertained then.
- The regulations then prescribe the coarse aggregate per unit volume depending on the maximum size of coarse aggregates and the fineness modulus of the fine aggregate.
- Knowing all the remaining quantities in the mix at this stage, the quantity of the fine aggregate can be established through the absolute volume calculation.

It is imperative at this stage to recreate that all the remaining regulations primarily can be looked at in a similar format that follow the same steps for ease of understanding at least. This would also later facilitate establishing some coherent plan to look at the design philosophies of all these different types of concrete mixtures in unison and arrive at an appropriate set of guidelines that could depict the design of concrete mixtures in general. It is also to be remembered that in trying to arrive at a unified and cohesive set certain allowances must be made, well within reasonable limits of acceptability, as is always necessary. Notwithstanding this small compromising at any stage, the resulting framework could be seen to be as authentic as it ever can be.

5.8 Proportioning of No-Slump Concretes

The recommendations for the proportioning of no-slump concrete mixtures by ACI 211.3 (1997) was essentially seen as an extension to the earlier discussed normal concrete mixture proportioning methodology ACI 211.1 (1991). It is obvious that there is a definite need for concretes having almost 0–25 mm slump, having already enunciated the recommendations for selecting proportions of concrete mixtures from 25 to 175 mm earlier. It is also to be noted that while the normal concrete recommendations look at concretes containing 10–150 mm coarse aggregates (primarily to include and cater to the needs of mass concretes), the no slump concrete recommendations limit their purview to coarse aggregates ranging from 10 to 40 mm. Another notable factor is that the recommendations go well beyond the range of slumps defined by ACI 211.1 (1991), ranging from the "extremely dry" concrete (defined by the VB time of 18–32 seconds, as the slump is a defining characteristic is not possible) and the "very plastic" concrete having a slump in the range of 125–190 mm, which indeed encompasses a portion of the earlier regulations for the normal concrete.

At this stage one should have a clear view of the concrete consistency specifications, which evolved from the requirements of the various concrete applications in particular, and a comprehensive review of this is already available in ACI 309 (1996), the guide for consolidation of concrete. The recommendations of ACI 211.3 and the ACI 309 discuss and delineate the consistencies of concretes used for the various construction activities. Incidentally both the reports contain a broad picture of the relationships between the then available consistency measurement methodologies like—slump, VB time, compaction factor and an earlier Thaulow drop table test. Additionally ACI 211.3 presents the volume of water required for the different consistencies in concretes containing 10–40 mm maximum size coarse aggregates. In an effort to have a better understanding of the relationships between the relative volumes of water required for the various consistencies in terms of the various consistency characteristics, the average values of these consistency characteristics are compared with the relative water contents and presented in Figure 5.15.

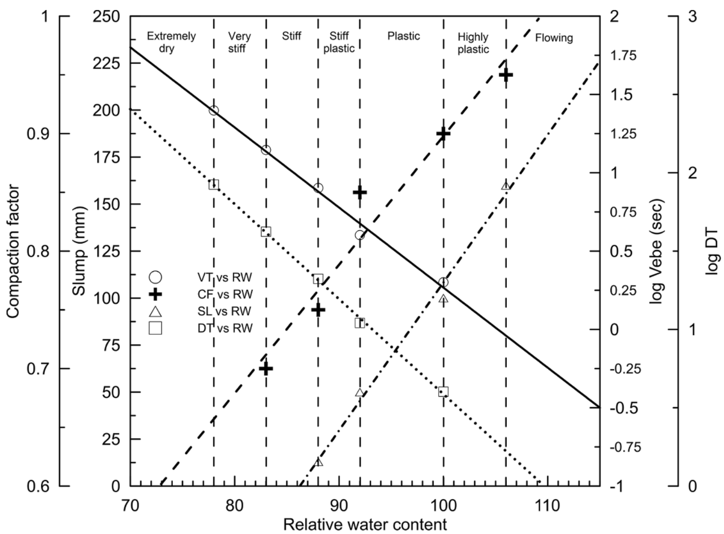

FIGURE 5.15
Correlations between relative water content and the different consistency characteristics. (After ACI 211.3, 1997 and ACI 309, 1996.)

The possible relationships between the relative water contents and the various consistency characteristics as an outcome of such a comparison are presented hereunder. Figure 5.15 could also help in having a broad understanding of the relationships between the different consistency parameters indirectly.

$$\log \mathrm{VT} = -0.051 * \mathrm{RWC} + 5.38 \ (\mathrm{R2} = 0.99) \tag{5.14}$$

$$\mathrm{Sl} = 7.87 * \mathrm{RWC} - 678.6 \ (\mathrm{R2} = 0.99) \tag{5.15}$$

$$\mathrm{CF} = 0.011 * \mathrm{RWC} - 0.197 \ (\mathrm{R2} = 0.95) \tag{5.16}$$

$$\log \mathrm{DT} = -0.0606 * \mathrm{RWC} + 6.65 (\mathrm{R2} = 0.99) \tag{5.17}$$

where "VT" is the VB time in seconds; "Sl" is the slump in mm; "CF" is the compaction factor; "DT" is the Thaulow drop table revolutions and "RWC" is the relative water content.

Apart from defining the relative water contents along with the actual water contents for different maximum sizes of coarse aggregates (from 10 to 40 mm), ACI 211.3 presents the water cementitious materials ratio to strength, the volume of course aggregate per unit volume of concrete at different consistencies. The general philosophy as well as the organization of the concrete mixture design methodology can be seen to be very similar to that followed in the recommendations for normal concretes (ACI 211.1, 1991). Though there are obvious clarifications required in the various stages to suit the needs of the recommendations for no slump concretes, there is not much discuss and delineate beyond what was already discussed in ACI 211.1. Figures 5.16 and 5.17 present an outline of the distribution of the no slump concrete constituents for of the six different consistency regimes. They are also organized in a way to be able to read out the essential details for arriving at the different constituent materials required and are broadly self-explanatory. In addition to the presentation of the current distribution of the constituents at the various consistencies of non-air-entrained no slump concretes, Figures 5.18 and 5.19 presents the same for the no slump air-entrained concretes defined in the ACI 211.3 (1997).

Apart from these, Appendices NSNA-5 and NSA-5 given at the end of this chapter present nomograms for the individual constituents of specific mixes no slump concretes, as was organized for the normal concretes earlier. In the intermediate analysis at this stage it looks very clear that the design philosophy as well as the methodology and steps to be followed in arriving at concretes of the different varieties like normal, lightweight and no slump concretes are all very similar and could be brought under a unified umbrella if appropriately attempted as can be seen later in this chapter. The importance of laboratory tests, particularly to ascertain the acceptability and conformance of individual constituents as prescribed in the code are very much

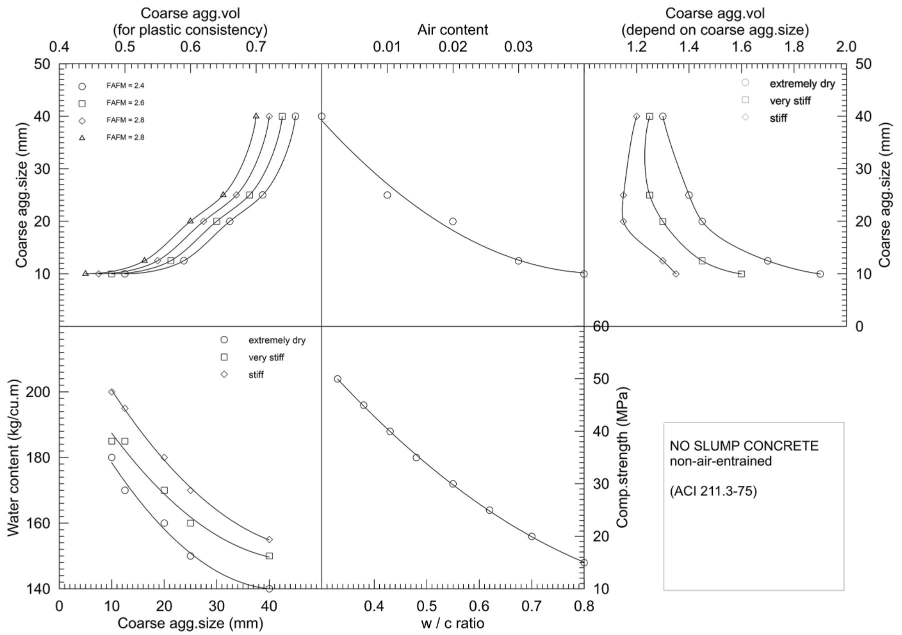

FIGURE 5.16
Recommendations for non-air-entrained no slump concrete mix design. (After ACI 211.3, 1997.)

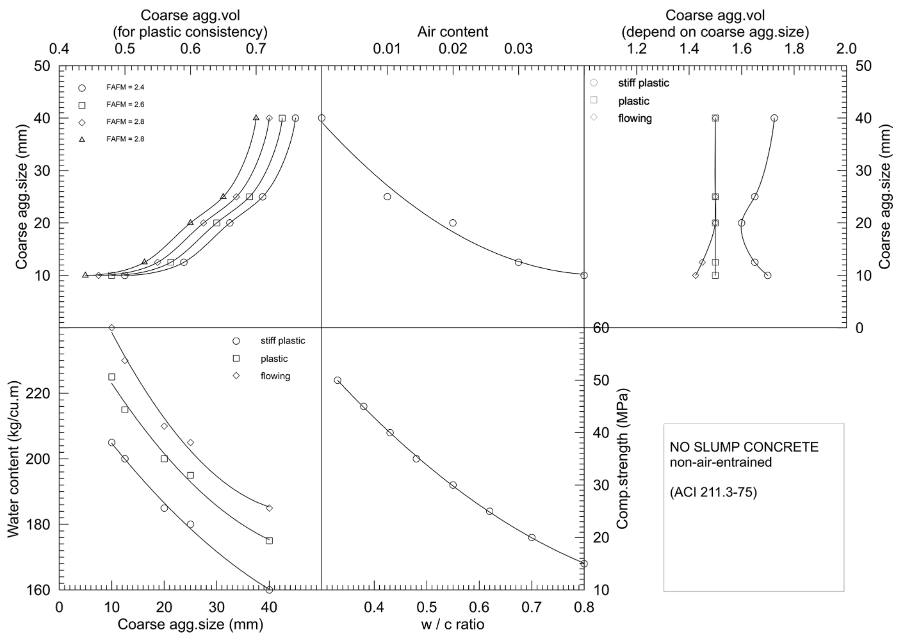

FIGURE 5.17
Recommendations for non-air-entrained no slump concrete mix design. (After ACI 211.3, 1997.)

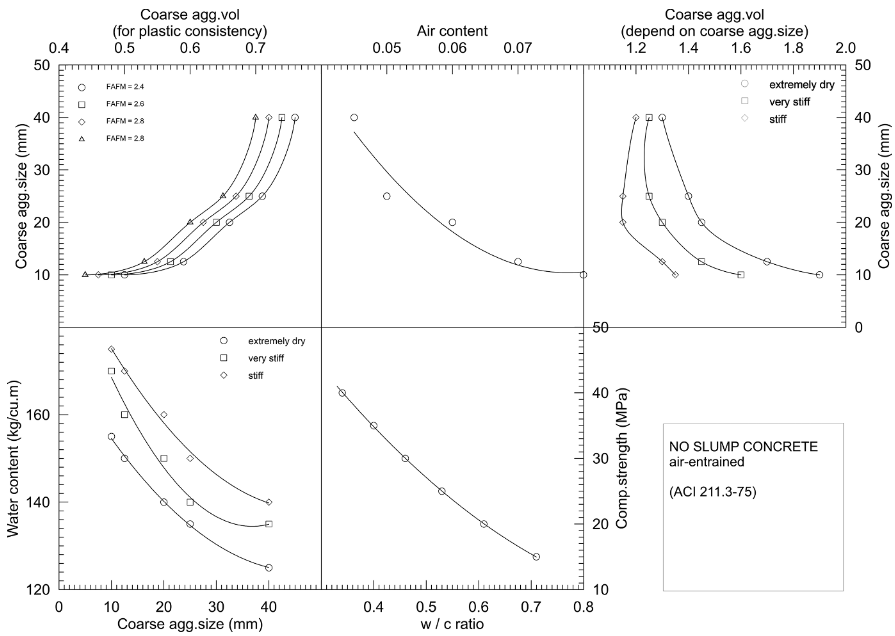

FIGURE 5.18
Recommendations for air-entrained no slump concrete mix design. (After ACI 211.3, 1997.)

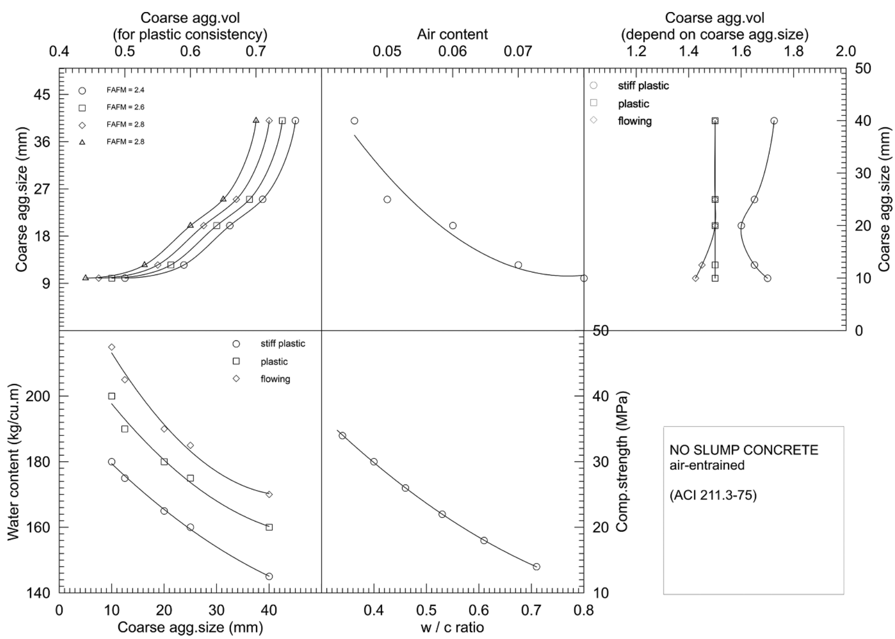

FIGURE 5.19
Recommendations for air-entrained no slump concrete mix design. (After ACI 211.3, 1997.)

essential to be able to arrive at the right combination of constituents for a specified concrete mixture need never be over stated as is reiterated in this code also. In particular the characteristics and the grading distributions of the aggregates which is essentially of a local origin have to be specifically addressed and taken into account.

5.8.1 Proportioning of Roller-Compacted and Other Moist Concrete Mixtures

It is easy to see that concrete applications like to roller compacted concrete or pressed concrete blocks require only a moist mix to be able to retain its shape immediately after compaction and removal of the component from the mould. At the other end of the spectrum are the flowing concretes and maybe even the more recent concrete varieties like the self-consolidating concretes with slump values well beyond 200 mm. Incidentally, for concretes of such high flexibility requiring no compaction effort presently the slump flow or the flow times through different constricted openings as defined by the various procedures. However, the consistency measurement methodologies hitherto proposed can in no way help to understand the compatibility of a moist mixture of the time required for the roller compaction. In fact the moisture content of the mixture should be very close to the optimum moisture content that is not normally determined in the case soils, so that it can support the roller adopted for compaction. Naturally for obvious reasons discussed a modified VB test apparatus (that essentially uses the vibro-compaction under pressure technique) or as advocated in some other literature the effect of the compaction effort through repeated drop weight technique used to assess the consistency and compatibility of the semidry or moist mixture used for the roller compacted concrete is most appropriate. It is not possible to dwell at length on the various characteristics and procedures, which will probably need a different and more focused discussion or even in limited justice to the topic. It is probably appropriate to suggest that two factors that are critical for durable and cohesive roller compacted concrete matrix or the mixtures of moist consistency like those for tiles and masonry blocks are the grading distributions of the aggregates (if not the grading distribution of the combined aggregates) and the quantity of the cementitious materials or the composite mortar matrix. The strength and strength gain rates are essentially governed by the efficiency of the mineral admixtures which can be modulated by percentage content and also the accelerated curing methods with higher temperatures. This part of the information is quite involved and needs specific and elaborate discussions and is not being attempted. Even so a broad outline of the possibilities can be gained from the aspects covered in the later chapters while discussing grading, efficiency of the different pozzolans and the accelerated curing on those cementitious materials. The pervious concrete mixture design is essentially a direct contrast in ensuring that there is an adequate quantity of mortar to bind the coarse aggregates that were chosen intentionally to be made up of grading with specific sizes missing to have the voids (not to have the highest packing density), while ensuring that the mortar is also limited to the minimum required for binding but not to fill the void deliberately created in the aggregate framework. One important aspect that is often not talked about is that, if appropriately formulated, such a mixture can also be roller compacted.

5.9 Proportioning of High Strength Concrete

The advancing frontiers of concrete construction in the recent past forced researchers to look for avenues of achieving higher strengths, and more importantly higher performance in concrete composites. Some of these developments actually owe their existence to the efforts that looked for concretes that could perform in a marine environment, the most severe natural environment. It also became obvious that such concretes are also necessary to combat the effects of both freeze thaw and deicing salts used in highway bridge structures. One of the first assumptions was to increase the strength of concrete, allowing for a discontinuous pore structure and lower pore volume possible through higher strengths. The fact that secondary pozzolanic reactions can address the need for higher strengths while reducing the peak temperatures of concrete due to the heat of hydration supported a relook into the effects of mineral admixtures. This was indeed supported by the use of chemical admixtures to address the need for a higher wetting water contents due to the increased fines in the system. In retrospect one can see that the ACI 211.4 (1993) address this requirement by suggesting a general restriction on maximum aggregate sizes, and the corresponding alterations to accommodate mineral admixtures like fly ash, ground granulated blast furnace slag or silica fume. The broad outline of the recommendations for such high strength concretes, essentially with fly ash as addressed by the ACI 211.4, is presented hereunder.

Having broadly underscored the governing principles of these recommendations, in spite of the need to address both chemical and mineral admixtures in one go, ACI 211.4 seams to essentially follow the same typical steps as was used in ACI 211.1 (1991). The modulations in the recommendations on the mixing water requirements for a specified maximum size of the coarse aggregate, the water cementitious materials ratios of a specified strength as well as the volume of course aggregate per unit for concrete are defined similarly. The only major changes appear to be in recommending:

- The limitations on the maximum size of coarse aggregates based on strengths above or below ~60 MPa, and
- In suggesting two distinctly different tables for the water cementitious materials ratios required for the different strengths with or without high range water reducing admixtures, HRWRs, broadly.

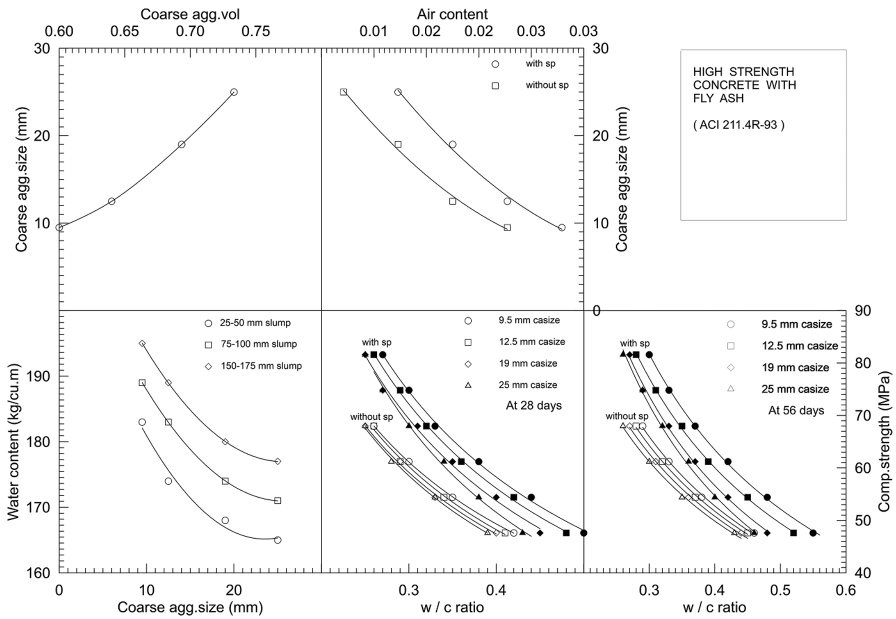

FIGURE 5.20
Recommendations for high strength concrete mix designs. (After ACI 211.4, 1993.)

The provisions also suggest a limit of 50%–25% class F fly ash while a limit of 20%–35% was placed on the class C fly ash. It was probably felt that there was insufficient information for making specific recommendations regarding the use of other high-end pozzolanic admixtures like silica fume, metakaolin or other calcined clays. Figure 5.20 presents the distribution of the constituents at the various consistencies of high strength concretes both with and without the addition of high range water reducing admixtures.

Similar to the nomograms presented for the earlier recommendations on normal and no slump concretes, Appendices HSN-5 and HSP-5 presented at the end of this chapter shows the distribution of the individual constituents for specific mixes of these high strength concretes as well. Finally, having looked at recommendations for all the different concrete mixture designs by the ACI one can see that the broad outline of the steps involved are essentially the same, while the numerical values of the individual parameters have obviously specific variations associated with the requirements. Having allies each of these concrete specifications and the resulting concrete mixtures in such depth, the possibility of arriving at some coherent methodology to have a set of unifying axioms that define the mathematical principles of all these different types of concretes was felt strongly. However, the fundamental axiom is that any such unifying methodology for any of the relationships, if at all possible, should not be simply arbitrary. Even an approach like the simple mathematical regression type (including the more modern fuzzy logic or neural network algorithms that could limit the universality of such an approach to the limited data analyzed) was not felt appropriate. The methodology thought to be most prudent is to fundamentally ensure that whatever tenets are used are completely verifiable and have a universal acceptability. The next part of this chapter presents essentially such an approach to have a simple yet fully reliable way to arrive at the various constituents for the different types of concretes.

5.10 A Panoramic Vision of the "ACI" Recommendations

The aforementioned parts of this chapter are given over to present a complete picture of the ACI recommendations—essentially in terms of the basic background, the actual recommendations and the philosophy of its formulation along with the mathematical relationships that could define such formulations. In a way it is probably the easiest part of this work, but to put it into a coherent and unified perspective through acceptable axioms that are verifiable is the most difficult part that is to be attempted now. It can be noted that the major thrust of the axioms being used come from several different absolutely authentic international sources that in fact include the ACI recommendations discussed earlier. This entire process is attempted in three specific steps (that are the cornerstones for the design of concrete mixtures according to the ACI 211.1–4). The complete data corresponding to the three major parameters dealing the specific aspects that define the design of concrete mixtures according to the ACI has already been presented in the Tables 5.3 through 5.5 earlier. The present steps discuss the specific amalgamation aspects that are being attempted along with the authenticity of the assumptions and the acceptability of the accuracy of the resulting representations for these specific parameters.

5.10.1 Amalgamation of the Water Content Requirements

During the discussions on the ACI recommendations for normal concretes, the design was seen to be seven one and a water content process, and steps 1 and 2 are essentially prescriptive depending upon the structural parameters like methodology of construction and member dimensions (prescribing the slump in maximum size of coarse aggregate). The next step involves the recommendation regarding the required water content for the specific slump which is presented in Table 5.3. In attempting the specific numerical recommendations for the various concrete compositions of different types, the following methodology was adopted.

- The first one is the recognition of the fact that the experience of several individual practitioners and researchers of the American scenario in making the most common concrete mixture—the normal concrete with 20 mm aggregates without any mineral or chemical admixtures at a comfortable slump level of about 100 mm—could be taken as a benchmark as it should have formed the basic cornerstone for making these recommendations for the other alternatives.

- In principle it is to be expected that the water contents defined for the various concretes containing 20 maximum size aggregates at a 100 mm slump (which is also the base for the relative water content assessments by the same ACI) are being considered as the base for all assessments.

As the first step let us attempt to understand the water contents proposed for the various maximum aggregate sizes at 100 mm slump in all the four ACI 211 recommendations which are considered basic (ACI 211.1, 1991; ACI 211 2, 1998; ACI 211 3, 1997; ACI 211 4, 1993). It can be seen from Figure 5.21 that values for the normal, lightweight and no slump concretes follow a log linear relationship, while the high strength concretes alone were far below (varying from about 15% for the 10 mm aggregates to about 10% of the 25 mm). This could probably be attributed to the possible reduction in the water content due to factors like the effect of lower sized aggregates, the higher fines content as well as the proposed use of water reducers. The suggested

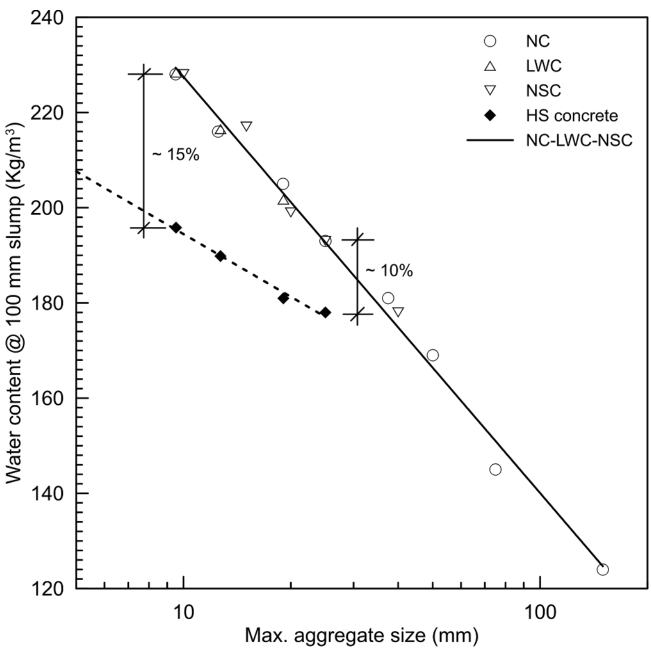

FIGURE 5.21
Variation of the proposed water contents for different maximum aggregate sizes at 100 mm slump. (After ACI 211.1–4.)

percentages of reduction in water contents also fits well with the accepted understanding of the effect of water reducers in general.

A further evaluation of the variation of water contents for the different size of aggregates as proposed by all the four ACI recommendations (ACI 211.1–4) for having a greater insight was attempted by looking at the variation profiles as the ratios of water contents relative to the water contents recommended for the 19 mm aggregate. The variation as can be seen from Figure 5.22 indicates that there is a log linear relationship given below for the water content ratios relative to 19 mm at different maximum aggregate sizes even considering all the four major ACI recommendations (ACI 211.1–4).

$$Y = 1.52 - 0.176 * \ln(X) \tag{5.18}$$

where Y is the water content ratio and X is the maximum aggregate size.

Considering the fact that the data concerning aggregates larger than 75 mm maximum size will be considerably limited, the relationship of the variation of water content ratio with the aggregate sizes below 75 mm was also attempted as shown in Figure 5.22. It is clear that even limiting the maximum size of aggregates of the more commonly used aggregate sizes of

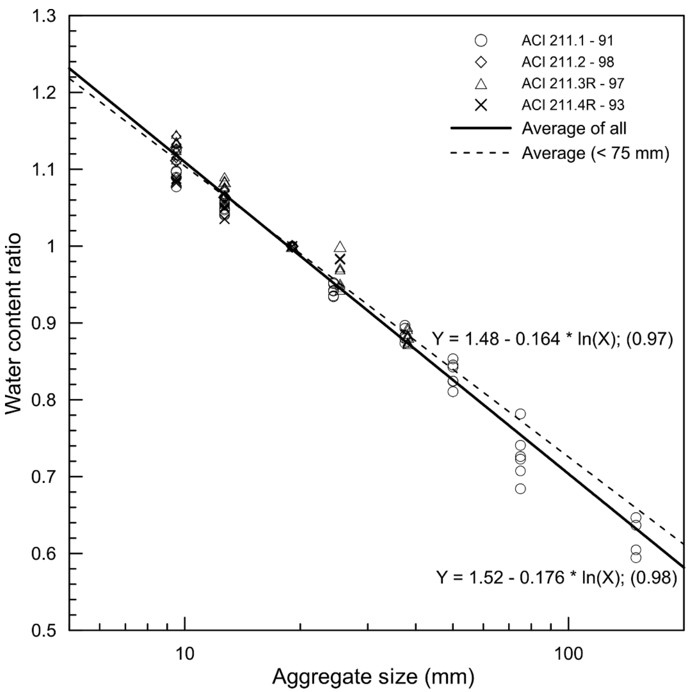

FIGURE 5.22
Variation of the proposed water contents for different maximum aggregate sizes relative to 19 mm. (After ACI 211.1–4.)

concrete on which sufficient data will be available for an appropriate confidence, the relationship did not appear to change significantly.

A look at the variation of the water content ratios keeping the water content at 100 mm slump as the base also shows that the water content ratio variation with slump appears to present a linear relationship as can be seen in Figure 5.23 for all the recommendations of ACI 211.1–4. This shows that it is possible to redefine the water content requirements in terms of either the water contents recommended for the 19 mm aggregates or alternatively in terms of the water content recommended for the slump of 100 mm. This appears to show that in reasonably designed concretes with appropriate aggregate distributions containing reasonable quantities of cementitious materials, the water demand for an appropriate consistency (wetting water requirements for the specific consistency) of similar relationships for all concrete types like—normal, lightweight, no slump as well as the high strength concretes as perceived by the ACI recommendations.

While it is possible to feel that the above solution for specifying water contents at the different consistencies of concretes containing different maximum size aggregates is reasonably acceptable, probably there is still room

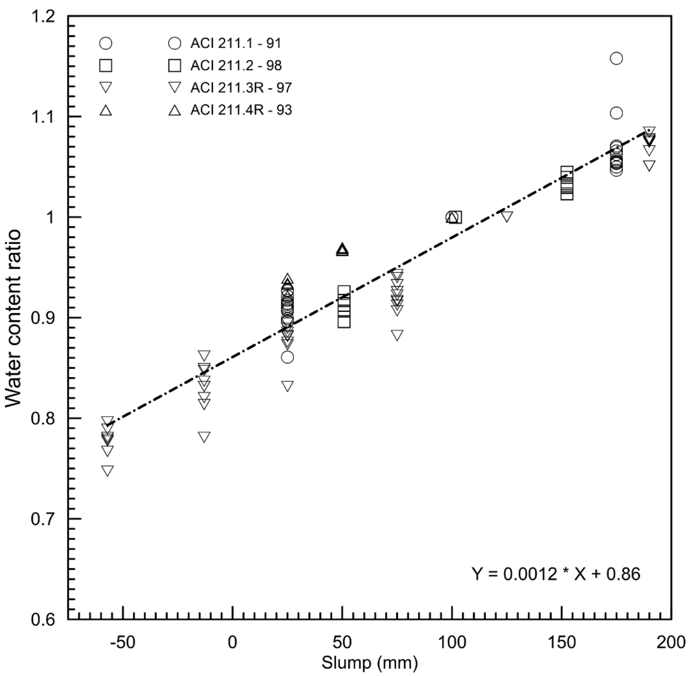

FIGURE 5.23
Variation of the proposed water contents for different maximum aggregate sizes relative to 19 mm. (After ACI 211.1–4.)

for minor readjustments to ensure that the relationships as well as the base values enunciated are more compliant with the modern materials and production, placement, consolidation and curing to achieve the highest performance possible.

5.10.2 Amalgamation of the Water Cementitious Materials to Strength Ratios

The primary design parameter for structural performance, safety and integrity, is the strength of concrete. In specific though a lot of research was done to look at this parameter from the first established relationship of Abrams (1919), the simplicity and the broad acceptability of the water cementitious materials ratio to strength relationship was never in doubt. Step 4 of the ACI recommendations deals with the selection of the water cement ratio or water cementitious materials ratio for a given strength, which includes the effect of the possible variations due to the materials and construction practices through the probability and standard deviation. The fact that the ACI recommendations suggests individual relationships is probably to address the specific requirements of each particular type of concretes, generally associated with a few specific industries that are involved in making such concretes and have also developed the corresponding knowledge to set the required specifications.

Broadly, it is important to understand and probably effectively prescribe a specific water cement ratio to strength relationship for at least the normal concretes that are conventionally produced for the majority of the application in vogue presently. It is also necessary to recognize that the construction scenario of the present day world has changed significantly from those of even a few years back (from say a decade ago) and more often than not for most construction applications, in housing as well as in industrial and transport infrastructure applications, the use of higher strength concretes has become quite common. The impact of chemical admixtures, particularly the superplasticizers, has also become a norm, probably more from the standpoint of ease of placement and compaction rather than the economy it offers.

In this context it is clear to see that ACI 211.1–ACI 211.4 present recommendations for the normal, lightweight, no slump and high strength concretes, a total of as many as 22 different water cement ratio to strength relationships. These are aimed at effectively representing the variations in air content for the first three categories (through the first six) and the later 16 relationships just to take care of the varying aggregate sizes with and without the high range water reducing admixture while including primarily fly ash for the high strength concrete combinations. This, in its own perspective, is the best way to deal with the effect of the variations in the constituent material characteristics, without burdening the construction industry. However, it may not be really appropriate to keep the industry so highly shielded from the basic facets of science and engineering that effectively are the reason for these variations. It will also certainly not be in the interests of the growth of the industry and be an active partner to the scientific innovations that keep growing. Also looking at the complete literature on concrete technology and concrete mixture design recommendations from the different nation bodies, this approach appears to be a little too lengthy and maybe not necessarily that effective. In any case it is important to look at the major parameters that define and enforce variations in the water cement ratio strength relationships of concrete composites, specifically before attempting to enshrine recommendations. Some of these aspects will be absolutely clear as we proceed to look at the various other national conditions and the background information that constituted a basis for such recommendations. Even in those cases where the parameters that mandate the recognition of the various water cement ratio to strength relationships, the need for effective experimental evaluations based semi-empirical methodologies is of course recognized and utilized as can be seen. Maybe it is possible to look at the complete picture that is available in the present context of the ACI recommendations once again and appropriately choose the possible alternatives that could pave the way for a holistic approach and the best way possible going forward. The idea is not to choose just any or a few specific relationships from the recommendations, but to look at what they represent and how they probably are the appropriate representatives of the present state of the art. In any cases, these have also got to be compatible and compare with the philosophy and methodologies that are adopted by a host of other international standards and practices.

In the light of what was discussed above, to start with the water cement ratio to strength relationship of the normal concrete without air entrainment could probably be the first choice for representing the broader picture. The marginally modified relationship in this context was seen to be the following earlier.

$$f_c = \exp\left(-2.60 * X\right) * 120 \tag{5.19}$$

for the non-air-entrained concretes, and

$$f_c = \exp\left(-2.70 * X\right) * 100 \tag{5.20}$$

for the air-entrained concretes, where X is the water cement ratio.

While the above relationship (Equation 5.19) is indeed probably the most utilized for several constructions in the American context, particularly for structures that do not require very high strength, it is obvious from an earlier discussion that it is certainly predicting much lower strengths compared to the British and Euro norms (Figure 3.2 in Chapter 3). In fact one possible explanation for such a recommendation is to ensure that the possible variations of the cement strengths from the various manufacturers at different times is difficult to be addressed otherwise and also that the industry practice of using different construction techniques may also have to be accounted for.

Even so one should understand that the American recommendations (ACI 211.5–96) and the other contractual obligations necessitate a fairly rigorous check on the quality of the concrete supplied finally. That apart, one has to understand that in the present context the choice of an appropriate water cement ratio to strength relationship in the American context could be to ensure and even enforce a better quality standard, particularly given the fact that the use of both superplasticizers and some form of mineral admixtures (be it the fly ash, GGBS or any other suitable) are indeed recommended. To be more explicit and clear, the actual water cement ratio to strength relationships as suggested by all the ACI recommendations (ACI 211.1–4) was already presented in the Table 5.4. Figure 5.24 depicts the actual distribution of the relationships for all these concretes for an essential comparison.

Naturally, the first and probably the most acceptable relationship in this context would be to utilize the proposed water cement ratio to strength relationship given by ACI 211.4, for high strength concretes with high range water reducing admixtures containing 20 mm maximum size aggregate. The relationship actually proposed is the following (Figure 5.24).

$$f_c = \exp(-2.60 * X) * 155 \tag{5.21}$$

where X is the water cementitious materials ratio.

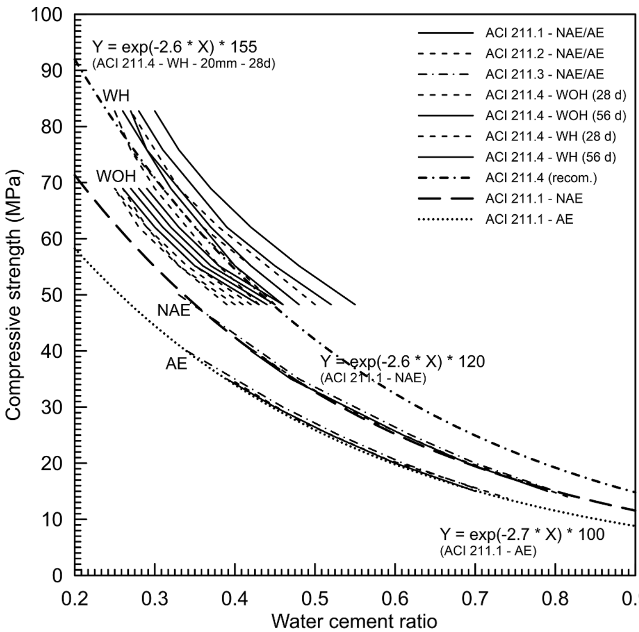

FIGURE 5.24
Strength to water cementitious materials ratio relation for different types of concretes. (After ACI 211.1–4.)

Some of the important considerations for considering this particular relationship to be a reasonable representative of the American concrete scenario is that it presupposes a proper compaction of the concrete mass (through the possible utilization of superplasticizers if required) and also a minimum amount of cementitious materials content in the system (through the use of the lower end pozzolanic mineral admixtures like fly ash if required) even for the lower strengths as already discussed above. The experience gained in the laboratory on such concretes compositions designed according to the ACI recommendations invariably goes to prove that it is eminently possible even with some of the cements produced in India, as can be seen in the later discussions pertaining to the unified approach in Chapter 7. It may not be out of place to say that this specific relationship is also compared with the provisions existing in other national recommendations to see if it has a reasonable compatibility as discussed later. At this stage an effort was made to arrive at a method to unify the several different water cement ratio strength relations through some already known principles from literature.

- This second fact for such a unifying attempt is of a European origin, which was discussed as a part of the cement strength characteristics showing that the concrete strength and cement strength are the same at the water cement ratio of 0.5 as originally proposed by Walz (1971).

In fact it was already seen earlier during the discussions on cement strength characteristics that the water cement ratio to strength relationships of cements of different strengths in the erstwhile DIN 1045 specifications were actually through the roll curves generated by Walz, 1971, which were obtained from the relationship between the ratio of the concrete strength to cement strength to the corresponding water cement ratio as almost unique, based on a very large data set. Extending the same philosophy to be reasonably applicable to any set of water cement ratio to strength relationships, the above curves depicting the water cement ratio to strength relationships of the different types of concretes, normal, lightweight, no slump and the different high strength concrete compositions presented in the ACI recommendations (ACI 211.1–4) were all rationalized by dividing with the strength at a water cement ratio of 0.5 for each of them. It can be seen from Figure 5.25 that this effort indeed resulted in ensuring that the entire set of the 22 relationships of the ACI recommendations (ACI 211.1–4) actually coalesce and reasonably merge together.

It is clear from Figure 5.25 that the idea is not indeed without merit and the entire set of 22 relationships recommended by the ACI (ACI 211.1–4) appear to coalesce and reasonably merge together to result in the relationship below, which is very close to the water cement ratio to strength relationship given by ACI 211.4, for high strength concretes with high range

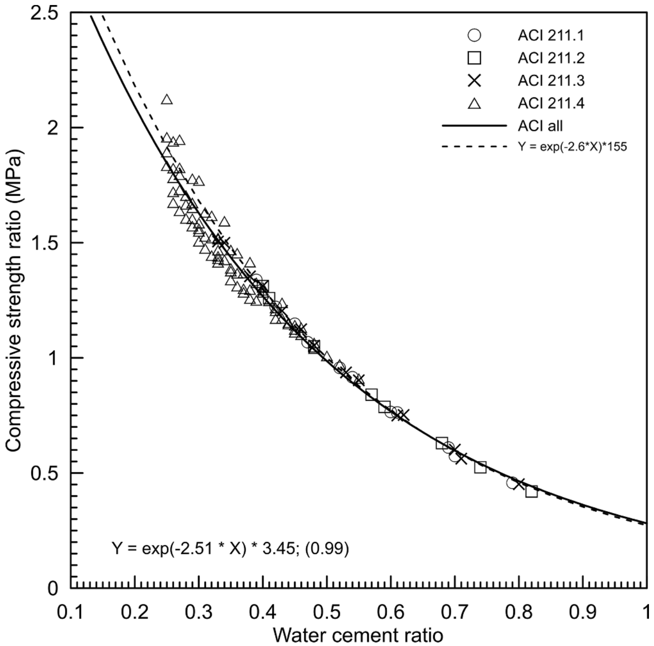

FIGURE 5.25
Unified strength to water cementitious materials ratio relation for all types of concretes. (After ACI 211.1–4.)

water reducing admixtures containing 20 mm maximum size aggregate (after the required modification by dividing with its strength at 0.50 water cement ratio).

$$(f_c)_{\text{ratio}} = \exp(-2.51 * X) * 3.45 \tag{5.22}$$

where X is the water cement ratio.

It was also observed that this effort resulted in a remarkable coherence with a regression coefficient of 0.99. It is to be noted that but for the additional 56 day strength results of the high strength concretes that contain fly ash as a part of the cementitious constituents (at 30%), the relationships were basically for the strength of concretes at 28 days. Apart from this it is expected that even in these high strength concretes containing fly ash, the relationships being considered were actually for strengths at 28 and 56 days, which are not the strengths at very early ages to reflect the effect of age significantly. These facts can easily be seen to be borne out by the coherence in the results as presented in the figure above. Also, the actual strengths values of the different concretes at the water cement ratio of 0.50 from the recommendations of ACI 211.1–ACI 211.4 are all given in bold type as can be seen in Table 5.4 for ready reference. Given these values and the unified relationship obtained, it is now possible to define the water cement ratio strength relationships of any specific concrete composites as desired by the ACI recommendations.

Having organized a reasonably appropriate unification for the water content and the water cement ratio relationships as can be seen, the corresponding cement contents for any of the concrete mixtures to the design can now be easily arrived at (as discussed in Step 5 in the normal concrete mixture design earlier).

5.10.3 Amalgamation of the Coarse Aggregate Content Requirements

The next basic step in the design of concrete mixtures is to look at the coarse aggregate contents appropriate to the different maximum sizes, considering the fineness moduli of fine aggregate proposed to be utilized. It is quite clear from Table 5.5 that a larger maximum sized coarse aggregate will help in ensuring a much larger quantity of coarse aggregates in a unit volume of concrete. Also if the fine aggregates are of finer fractions with increasing fineness moduli, the coarse aggregate content tends to decrease.

- As was discussed in the amalgamation of the water contents, the coarse aggregate contents at the different fineness moduli of the fine aggregate for the 19 mm aggregate were considered as the base and the ratios of the coarse aggregate requirements at other maximum sizes of aggregate are established. These ratios when plotted against the maximum size of coarse aggregate show a general log linear relation with somewhat an appreciable scatter as can be seen from Figure 5.26. It is also clear from Figure 5.26 that the coarse aggregate requirements of the high strength concretes can also be seen to be higher and follow a different relation.

Incidentally it was already seen in Figure 5.9 that in the case of normal concretes the variation of the volume of coarse aggregate with fineness moduli were all linear having the same slope. This was found to be so even in the case of all the other such variations for the different concrete of the ACI recommendations other than the high strength concretes. The slope coefficient in equation for high strength concrete is 0.0 and the constant C defines the volumes of the dry-rodded coarse aggregate for unit volume of workable (reinforced) concretes for all fineness moduli of fine aggregate. Table 5.6 presents the intercept constants of the linear variations of the volume of coarse aggregate with fineness moduli which are of the form ($Y = -0.1 \times X + C$) as already seen in Figure 5.9.

It is indeed a fact that as already stated, a very large amount of concretes in practice are produced using 20 mm aggregate, and probably for this reason the proportions of the coarse aggregate content for different fineness moduli of the fine aggregate could be expected to have been adequately well established in all likelihood. Assuming this to be the case, the requirements of the volumes of dry-rodded coarse aggregate for unit volume of workable

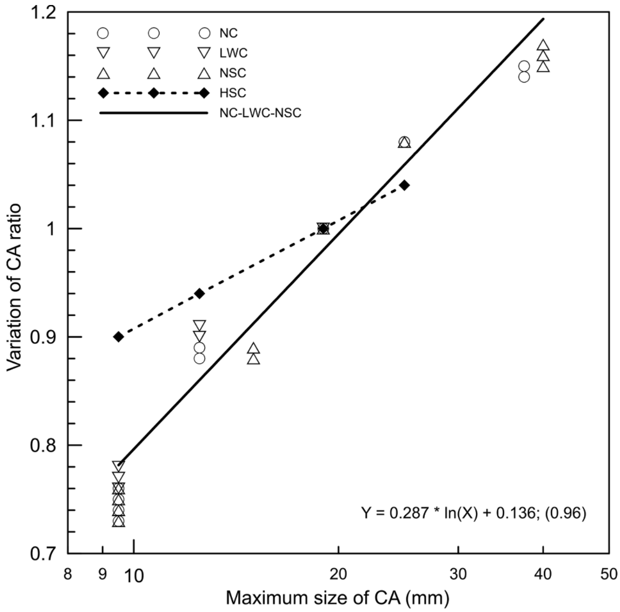

FIGURE 5.26
Variation of relative CA contents for different maximum aggregate sizes relative to 19 mm. (After ACI 211.1–4.)

TABLE 5.6

Intercept Constants of the Variations of Coarse Aggregate Volume with Fineness Moduli

	Constant (C) in Equation Y =−0.1 × X + C			
Aggregate Size	**ACI 211.1 (1991)**	**ACI 211.2 (1998)**	**ACI 211.3 (1997)**	**ACI 211.4 (1993)**
9.50	0.74	0.82	0.74	0.65
12.70	0.83	0.91	0.83	0.68
19.05	0.90	0.98	0.90	0.72
25.40	0.95		0.95	0.75
37.50	0.99		1.00	
50.00	1.02			
75.00	1.06			
150.00	1.11			

Note: Slope in equations for HSC is 0.0.

(reinforced) concretes at different fineness moduli was calculated as a ratio of the quantity required at the 20 mm maximum coarse aggregate size.

The possible relationship of all these constants associated with the variations for the different concretes as was already shown in the case of normal concrete (Figure 5.9). Presently the variation of the calculated ratios of the

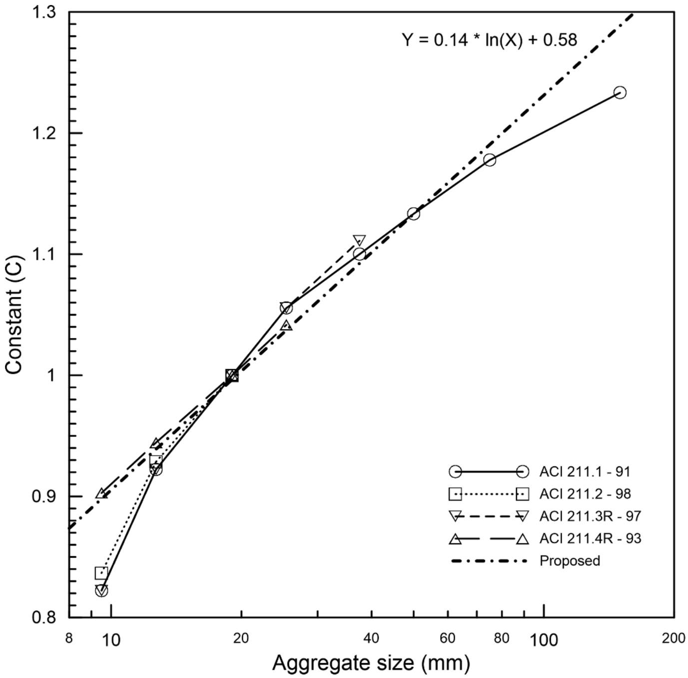

FIGURE 5.27
Variation of coarse aggregate constant with maximum coarse aggregate size relative to 20 mm. (After ACI 211.1–4.)

quantity of dry-rodded coarse aggregate for unit volume of workable concretes at different fineness moduli required to that at the 20 mm maximum coarse aggregate size was related to the maximum size of coarse aggregate as can be seen in Figure 5.27.

It was also seen that in Figure 5.27 even if the values corresponding to the maximum size below 50 mm were alone considered appropriate to be taken into consideration for understanding the distribution, the above coarse aggregate ratio with the maximum size of the coarse aggregate itself did not differ by much. Despite the variations, this could be seen to be a reasonable log linear relationship as above for the normal, lightweight and no slump concretes. However, the high strength concretes alone had higher coarse aggregate proportions recommended. This is obviously due to the fact that the higher strength concretes already have substantial quantity of fines to be able to absorb a much larger quantity of coarse aggregate.

At this stage all the constituents other than the fine aggregate have been arrived at through these amalgamated principles and the corresponding relationships. The absolute volume method can be used now to calculate the volume of fine aggregate remaining for completing the mixture proportions.

Appendix PROG-ACI-NCNA-5

```
C    *********************************************************
C    CONCRETE MIX DESIGN BY THE A.C.I METHOD
C    NORMAL NON AIR ENTRAINED CONCRETE
C    *********************************************************
       CHARACTER*50 OUTFIL,QLTY,ENV,STR
C    ********************************************************
C    PRINT *,'*********************************************'
       PRINT *,'CONCRETE MIX DESIGN - A.C.I. METHOD'
       PRINT *,'********************************************'
110  PRINT *,'CHARACTERISTIC STRENGTH OF A CYLENDER (MPa) ='
       PRINT *,'(INPUT AN INTEGER VALUE)'
       READ *, KFCK
       PRINT *,'DO YOU WANT TO DESIGN THE MIX'
       PRINT *,'FOR FCK(1) or TARGET STRENGTH(2)?'
       READ *, NCT
       IF (NCT.EQ.2) THEN
       PRINT *,'DEGREE OF QUALITY CONTROL: V.GOOD(1),
       GOOD(2), FAIR(3)'
       READ *,KQL
          ENDIF
C
       PRINT *,'MAXIMUM SIZE OF COARSE AGGREGATE (GIVE 9.5,
12.5,19,25,37.5,50,75,150)='
       READ *,CASIZE
        PRINT *,'BULK DENSITY OF C.A ='
        PRINT *,'normally 1600 kg/cu.m'
        READ*,CABULK
        PRINT *,'FINENESS MODULUS OF SAND ='
        PRINT *,'give 2.4 or 2.6 or 2.8 or 3.0'
        READ *, FAFM
       PRINT *,'REQUIRED SLUMP (in mm) ='
        PRINT *,'input value between 25-50 or 75-100 or 150-175'
        READ *,SLUMP
       PRINT *,'SPECIFIC GRAVITY OF COARSE AGGREGATE = '
        PRINT *,'normally 2.6 or 2.65'
       READ *,CASG
       PRINT *,'SPECIFIC GRAVITY OF FINE AGGREGATE ='
        PRINT *,'normally 2.6 or 2.65'
        READ *,FASG
       PRINT *,'SPECIFIC GRAVITY OF CEMENT ='
        PRINT *,'normally 3.15'
        READ *,CEMSG
       PRINT *,'SPECIFIC GRAVITY OF WATER ='
       READ *,WATSG
       PRINT *,'DO YOU WANT TO DESIGN THE MIX FOR A SPECIFIC '
       PRINT *,'ENVIRONMENT : YES (1); NO(2):'
       READ *, KKEN
```

```
       IF (KKEN. EQ.1) THEN
       PRINT *,'TYPE OF ENVIRONMENT (MILD(1), MODERATE(2),
SEVERE(3))'
       READ *,KENV
       PRINT *,'TYPE OF STRUCTURE (THIN SECTION(1),
ALL OTHER SECTIONS EXCEPT THIN SECTIONS(2))'
       READ *,STRU
       END IF
       PRINT*,'NAME OF THE OUTPUT FILE ='
       READ(*,180) OUTFIL
 180  FORMAT(A20)
c
c
       IF (NCT.EQ.2) THEN
       CALL DESNSTR (KFCK, KQL, DESSTR)
       ELSE
       DESSTR=KFCK
       ENDIF
C    SUBROUTINE DESNSTR CALCULATES THE TARGET STRENGTH
C     DESSTR IS THE TARGET/DESIGN STRENGTH
C
       CALL WCRATIO (DESSTR, WCR)
C    WCR IS WATER-CEMENT RATIO
C
           IF (KKEN.EQ.1) THEN
       CALL ENVI (KENV, STRU, WCEN)
C
           IF (WCEN.GT.WCR) THEN
           WC = WCR
           ELSE
           WC = WCEN
           ENDIF
       ELSE
       WC = WCR
       ENDIF
C    The above IF statement decides the w/c based
on strength and durability considerations
C
       CALL WATCON (CASIZE, SLUMP, WCON)
C
       CCON = WCON/WC
C
       CALL CAVAIR (CASIZE,FAFM,CAVOL,EAIR)
C
       CACON = CAVOL * CABULK
       AVW = WCON/(WATSG*1000.0)
       AVC = CCON/(CEMSG*1000.0)
       AVCA = CACON/(CASG*1000.0)
       FACON = (1.0-(EAIR+AVW+AVC+AVCA))*FASG*1000.0
       YMIX = WCON + CCON + FACON + CACON
```

```
       TAGG = CACON + FACON
       ACR = TAGG/CCON
       FAR = (FACON/TAGG)*100.0
       CEM = 1.0
       FA = FACON/CCON
       CA = CACON/CCON
C
       CALL ESTYMIX (CASIZE, EYMIX)
C
       open(2,file=OUTFIL,status='unknown')
C
C
       IF (NCT.EQ.2) THEN
            IF (KQL.EQ.1) THEN
                 QLTY = 'VERY GOOD'
           ELSEIF (KQL.EQ.2)THEN
                 QLTY = 'GOOD'
           ELSEIF (KQL.EQ.3) THEN
                 QLTY = 'FAIR'
                ENDIF
       ENDIF
c
c
       IF (KKEN.EQ.1) THEN
           IF (KENV.EQ.1) THEN
               ENV = 'MILD'
           ELSEIF (KENV.EQ.2) THEN
               ENV = 'MODERATE'
           ELSEIF (KENV.EQ.3) THEN
               ENV = 'SEVERE'
           ENDIF
       ENDIF
C
       IF (KKEN.EQ.1) THEN
           IF (STRU.EQ.1) THEN
                STR = 'THIN SECTIONS'
           ELSEIF (STRU.EQ.2) THEN
                STR = 'ALL OTHER SECTIONS EXCEPT THIN SECTIONS'
           ENDIF
       ENDIF
       WRITE (2,250)
 250        FORMAT (5X, 'CONCRETE MIX DESIGN (ACI METHOD)')
            WRITE (2,255)
 255   FORMAT (5X, '-----------------------------------')
            WRITE (2,260) KFCK
 260   FORMAT (/,1X, 'Characteristic Strength of the concrete
mix = ',
     1 I4,' MPa')
      IF (NCT.EQ.1)THEN
       WRITE (2,265)
```

```
 265   FORMAT (1X,'The mix is designed for Fck only')
            ELSE
        WRITE(2,270) QLTY,DESSTR
 270   FORMAT(1X,'Degree of Quality Control = ',A15,/,1X,
     1 'Target Strength of the mix = ',F7.2,' MPa')
        ENDIF
        IF (KKEN.EQ.1) THEN
        WRITE (2,275) ENV
 275   FORMAT (1X, 'Type of Environment of Exposure = ', A15)
        WRITE (2,276) STR
 276   FORMAT (1X,'Type of Structure = ',A40)
            ENDIF
        WRITE (2,280) CASIZE
 280   FORMAT(1X, 'Maximum size of the Coarse Aggregate =',F6.1,
'mm')
        WRITE(2,281) CABULK
 281   FORMAT(1X,'Bulk den. of the Coarse Aggregate =',F7.1,
'kg/cu. m')
        WRITE(2,282) CASG
 282   FORMAT(1X, 'Specific gravity of the Coarse aggregate =',
F6.2)
        WRITE(2,285) FAFM
 285   FORMAT(1X,'Fineness modulus of the Fine Aggregate =',
F6.2)
        WRITE(2,287) FASG
 287   FORMAT(1X,'Specific gravity of the Fine Aggregate =',
F6.2)
        WRITE (2,290) SLUMP
 290   FORMAT (1X,'The required Slump of the mix = ', F6.1,' mm')
        WRITE (2,300)
 300   FORMAT (/,1X,'THE CONCRETE MIX DATA IS GIVEN BELOW')
        WRITE (2,310) WC,CCON
 310   FORMAT (/,1X,'Water Cement Ratio =',F5.2,/,1X,
      1 'Cement Content =',F8.1,' kg/cu. m')
            WRITE (2,311) WCON
 311   FORMAT ( 1X,'Water Content =      ',F6.2,'kg/cu,m')
            WRITE (2,312) FACON
 312   FORMAT(1X,'Fine Agg. Content = ',F8.1,' kg/cu m')
            WRITE(2,314) CACON
 314   FORMAT(1X,'Coarse Agg. Content =',F8.1,' kg/cu m')
        WRITE (2,320) ACR,FAR
 320   FORMAT(1X,'Aggregate Cement Ratio =',F6.2,/,1X,
      1 'Fine Aggregate Ratio =',F6.2)
        WRITE (2,330) CEM,FA,CA,WC
 330   FORMAT (/,1X,'MIX PROPORTIONS =',F5.2,':',F5.2,':',F5.2,
':',F5.2)
            WRITE (2,340) YMIX
 340   FORMAT (/,1X,'Yield of the mix = ',F8.1,'kg/cu. m')
            WRITE (2,345) EYMIX
```

```
 345  FORMAT (1X,'Estimated Yield of the mix =  ',F8.1,'kg/cu.m')
            WRITE (2, 350)
 350  FORMAT (1X,'-------------------------------------------')

            GOTO 900
C
C ***********************************************************
900  STOP
       END


       SUBROUTINE DESNSTR (KFCK, KQL, DESSTR)
       LOGICAL S1, S2, S3

       S1 = (ABS(KQL-1.0)).LT.0.005
       S2 = (ABS(KQL-2.0)).LT.0.005
       S3 = (ABS(KQL-3.0)).LT.0.005

       IF(S1.OR.S2.OR.S3)THEN
           IF (KFCK.EQ.15) THEN
             DESSTR = FLOAT(KFCK)+7.03
           ELSEIF (KFCK.EQ.20)THEN
             DESSTR = FLOAT(KFCK)+7.03
           ELSEIF (KFCK.EQ.25) THEN
             DESSTR = FLOAT(KFCK)+8.44
           ELSEIF (KFCK.EQ.30) THEN
             DESSTR = FLOAT(KFCK)+8.44
           ELSEIF (KFCK.EQ.35) THEN
             DESSTR = FLOAT(KFCK)+8.44
           ELSEIF (KFCK.EQ.40) THEN
             DESSTR = FLOAT(KFCK)+9.84
           ELSEIF (KFCK.EQ. 45) THEN
             DESSTR = FLOAT(KFCK)+9.84
           ENDIF
       ENDIF
       RETURN
       END

      SUBROUTINE WCRATIO (DESSTR, WCR)
      A = 71.2112
      B = 154.255
      C = 92.6315-DESSTR
      WCR = (B-SQRT(B**2-4.*A*C))/(2.*A)
      RETURN
      END

      SUBROUTINE WATCON (CASIZE, SLUMP, WCON)
      LOGICAL AS1, AS2, AS3, AS4, AS5, AS6, AS12, AS34, AS56
      LOGICAL ACAS1,ACAS2,ACAS3,ACAS4,ACAS5,ACAS6,ACAS7,ACAS8
```

```
C
      AS1 = (ABS(SLUMP - 25.0)).LT.0.005
      AS2 = (ABS(SLUMP - 50.0)).LT.0.005
      AS12 = (SLUMP.GT.25.0).AND.(SLUMP.LT.50.0)
      AS3 = (ABS(SLUMP - 75.0)).LT.0.005
      AS4 = (ABS(SLUMP - 100.0)).LT.0.005
      AS34 = (SLUMP.GT.75.0).AND.(SLUMP.LT.100.0)
      AS5 = (ABS(SLUMP-150.0)).LT.0.005
      AS6 = (ABS(SLUMP-175.0)).LT.0.005
      AS56 = (SLUMP.GT.150.0).AND.(SLUMP.LT.175.0)
      ACAS1 = (ABS(CASIZE - 9.5)).LT.0.005
      ACAS2 = (ABS(CASIZE - 12.5)).LT.0.005
      ACAS3 = (ABS(CASIZE - 19.0)).LT.0.005
      ACAS4 = (ABS(CASIZE - 25.0)).LT.0.005
      ACAS5 = (ABS(CASIZE - 37.5)).LT.0.005
      ACAS6 = (ABS(CASIZE - 50.0)).LT.0.005
      ACAS7 = (ABS(CASIZE - 75.0)).LT.0.005
      ACAS8 = (ABS(CASIZE - 150.0)).LT.0.005
      IF (AS1.OR.AS2.OR.AS12) THEN
           IF (ACAS1) THEN
               WCON = 207.0
           ELSEIF (ACAS2) THEN
               WCON = 199.0
           ELSEIF (ACAS3) THEN
               WCON = 190.0
           ELSEIF (ACAS4) THEN
               WCON = 179.0
           ELSEIF (ACAS5) THEN
               WCON = 166.0
           ELSEIF (ACAS6) THEN
               WCON = 154.0
           ELSEIF (ACAS7) THEN
               WCON = 130.0
           ELSEIF (ACAS8) THEN
               WCON = 113.0
           ENDIF
      ELSEIF (AS3.OR.AS4.OR.AS34) THEN
           IF (ACAS1) THEN
               WCON = 228.0
          ELSEIF (ACAS2) THEN
               WCON = 216.0
          ELSEIF (ACAS3) THEN
               WCON = 205.0
          ELSEIF (ACAS4) THEN
               WCON = 193.0
          ELSEIF (ACAS5) THEN
               WCON = 181.0
          ELSEIF (ACAS6) THEN
               WCON = 169.0
          ELSEIF (ACAS7) THEN
```

```
            WCON = 145.0
        ELSEIF (ACAS8) THEN
            WCON = 124.0
        ENDIF
    ELSEIF (AS5.OR.AS6.OR.AS56) THEN
         IF (ACAS1) THEN
            WCON = 243.0
        ELSEIF (ACAS2) THEN
            WCON = 228.0
        ELSEIF (ACAS3) THEN
            WCON = 216.0
        ELSEIF (ACAS4) THEN
            WCON = 202.0
        ELSEIF (ACAS5) THEN
            WCON = 190.0
        ELSEIF (ACAS6) THEN
            WCON = 178.0
        ELSEIF (ACAS7) THEN
            WCON = 160.0
        ENDIF
    ENDIF
    RETURN
    END



    SUBROUTINE ENVI (KENV, STRU, WCEN)
    IF (KENV.EQ.1)THEN
        IF (STRU.EQ.1) THEN
            WCEN = 2.0
         ELSEIF (STRU.EQ.2) THEN
            WCEN = 2.0
         ENDIF
    ELSEIF (KENV.EQ.2)THEN
        IF (STRU.EQ.1) THEN
           WCEN = 0.45
        ELSEIF (STRU.EQ.2) THEN
           WCEN = 0.50
        ENDIF
    ELSEIF (KENV.EQ.3)THEN
        IF (STRU.EQ.1) THEN
            WCEN = 0.40
        ELSEIF (STRU.EQ.2) THEN
            WCEN = 0.45
        ENDIF
    ENDIF
    RETURN
    END
```

```
SUBROUTINE CAVAIR (CASIZE, FAFM, CAVOL, EAIR)
IF (ABS (CASIZE).EQ.9.5) THEN
     CAVOL = 0.74-(0.1 * FAFM)
     EAIR = 0.03
ELSEIF (ABS(CASIZE-12.5).LT.0.005)THEN
     CAVOL = 0.83-(0.1*FAFM)
     EAIR = 0.025
ELSEIF (IFIX (CASIZE).EQ.19) THEN
     CAVOL = 0.90-(0.1*FAFM)
     EAIR = 0.02
ELSEIF (IFIX(CASIZE).EQ.25) THEN
     CAVOL = 0.95-(0.1*FAFM)
     EAIR = 0.015
ELSEIF (ABS(CASIZE).EQ.37.5) THEN
     CAVOL = 1.0-(0.1*FAFM)
     EAIR = 0.01
ELSEIF (IFIX(CASIZE).EQ.50) THEN
     CAVOL = 1.02-(0.1*FAFM)
     EAIR = 0.005
ELSEIF (IFIX(CASIZE).EQ.75) THEN
     CAVOL = 1.05-(0.1*FAFM)
     EAIR = 0.003
ELSEIF (IFIX(CASIZE).EQ.150) THEN
     CAVOL = 1.11-(0.1*FAFM)
     EAIR = 0.002
END IF
RETURN
END


SUBROUTINE ESTYMIX (CASIZE, EYMIX)
IF (ABS(CASIZE).EQ.9.5) THEN
   EYMIX  = 2280
ELSEIF (ABS(CASIZE).EQ.12.5) THEN
   EYMIX  = 2310
ELSEIF (IFIX(CASIZE).EQ.19) THEN
   EYMIX  = 2345
ELSEIF (IFIX(CASIZE).EQ.25) THEN
   EYMIX  = 2380
ELSEIF (ABS(CASIZE).EQ.37.5) THEN
   EYMIX  = 2410
ELSEIF (IFIX(CASIZE).EQ.50) THEN
   EYMIX  = 2445
ELSEIF (IFIX(CASIZE).EQ.75) THEN
   EYMIX  = 2490
ELSEIF (IFIX(CASIZE).EQ.150) THEN
   EYMIX  = 2530
END IF
RETURN
END
```

Appendix NCNA-5

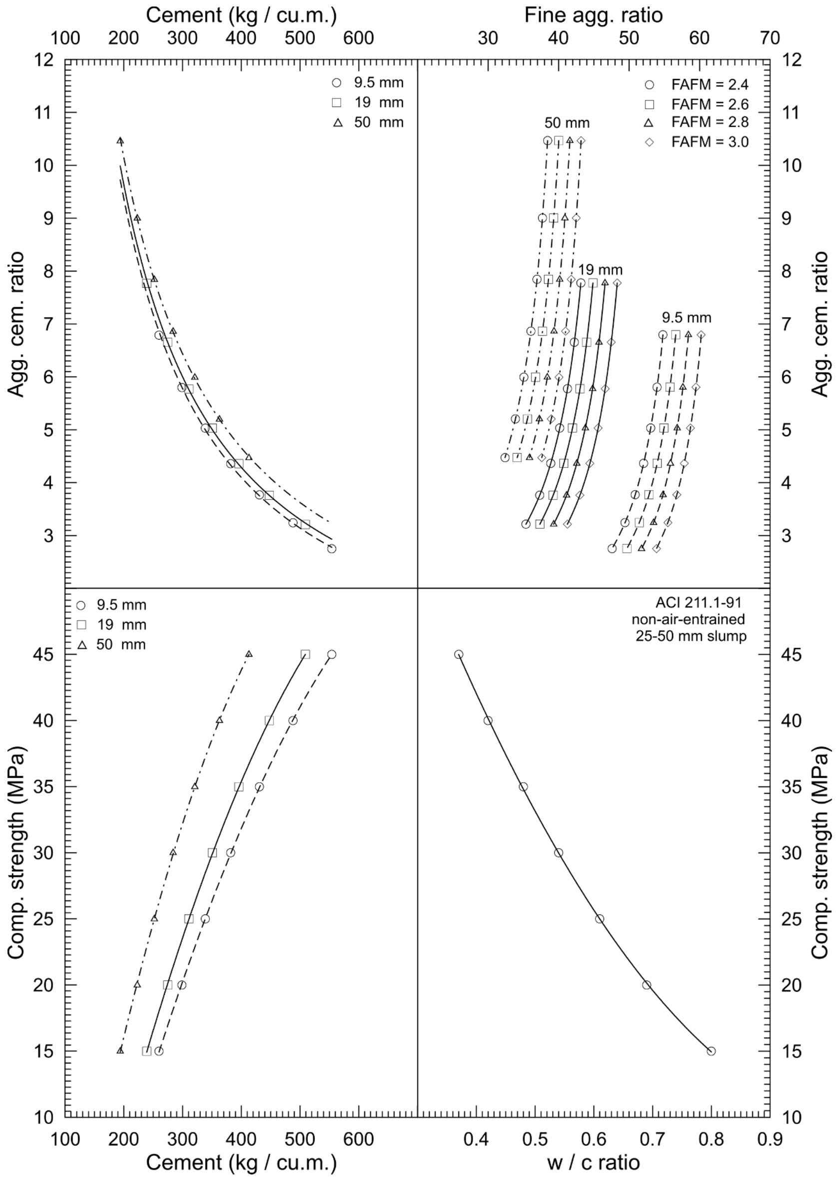

FIGURE NCNA-5.1
Nomogram for non-air-entrained concrete (9.5, 19, and 50 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

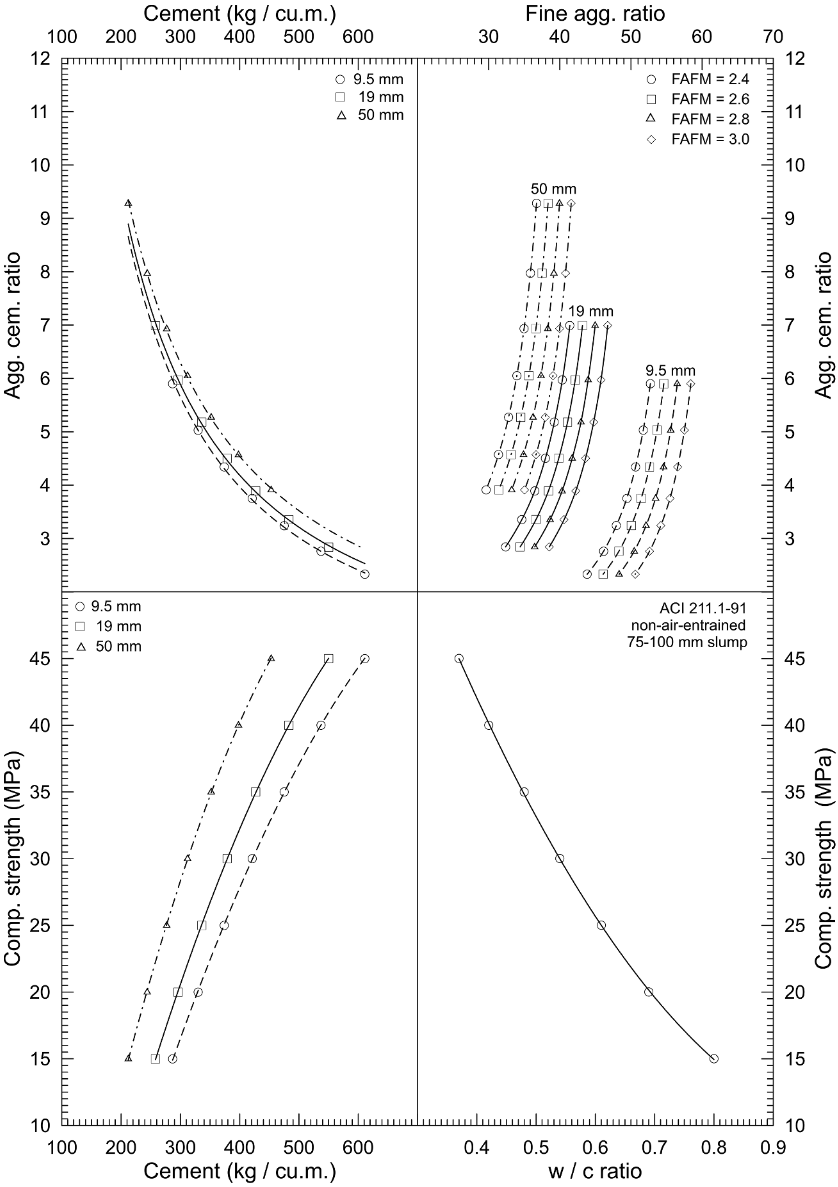

FIGURE NCNA-5.2
Nomogram for non-air-entrained concrete (9.5, 19, and 50 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

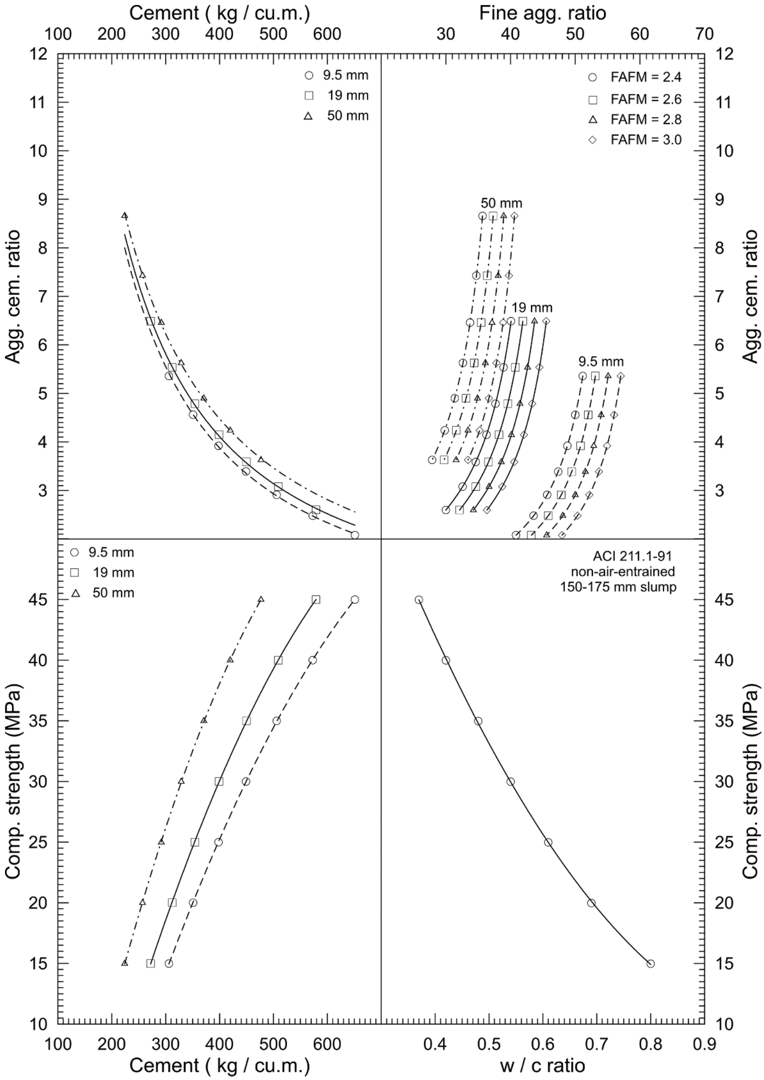

FIGURE NCNA-5.3
Nomogram for non-air-entrained concrete (9.5, 19, and 50 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

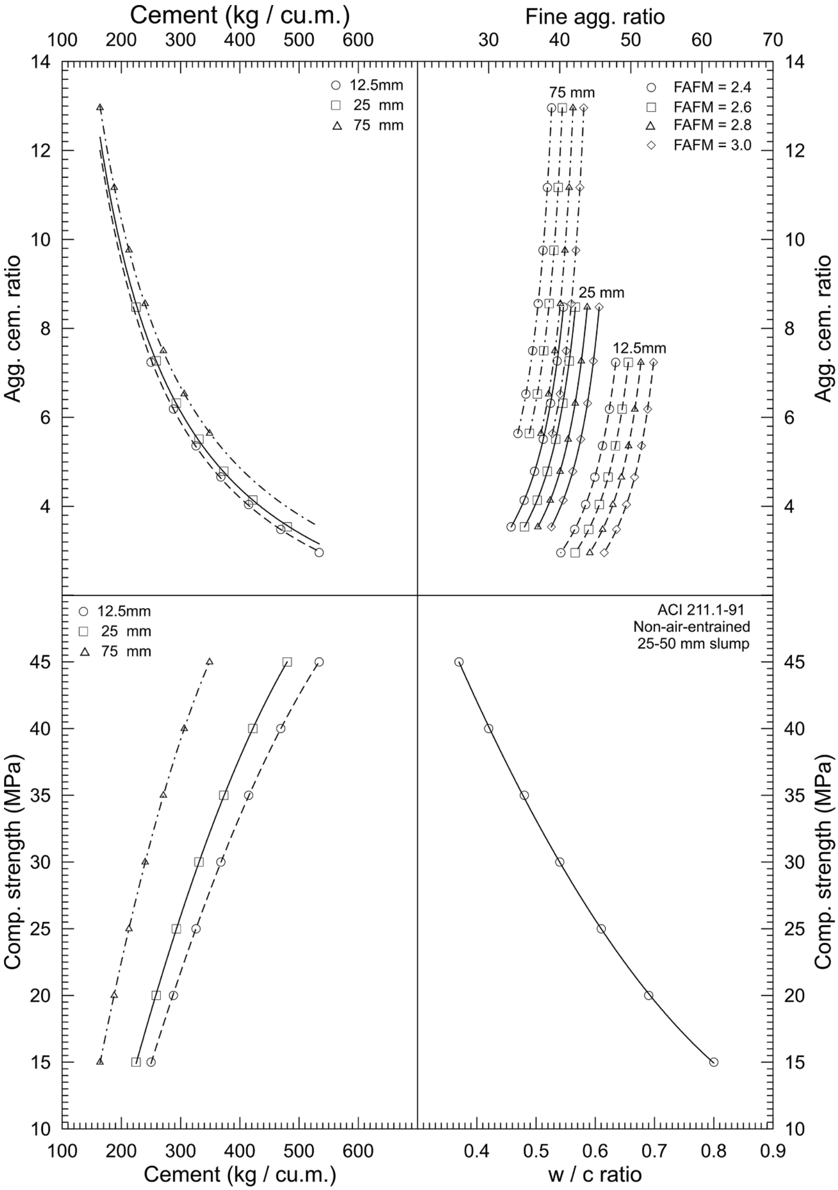

FIGURE NCNA-5.4
Nomogram for non-air-entrained concrete (12.5, 25, and 75 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

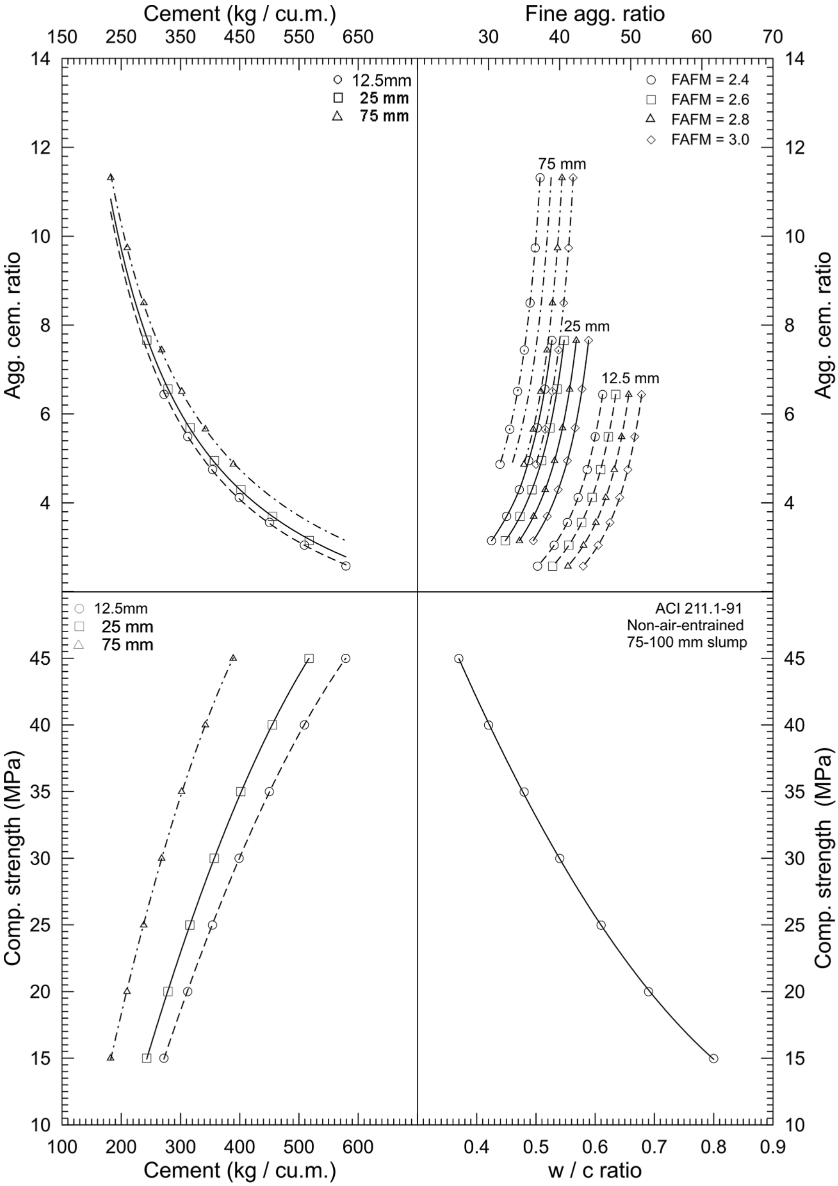

FIGURE NCNA-5.5
Nomogram for non-air-entrained concrete (12.5, 25, and 75 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

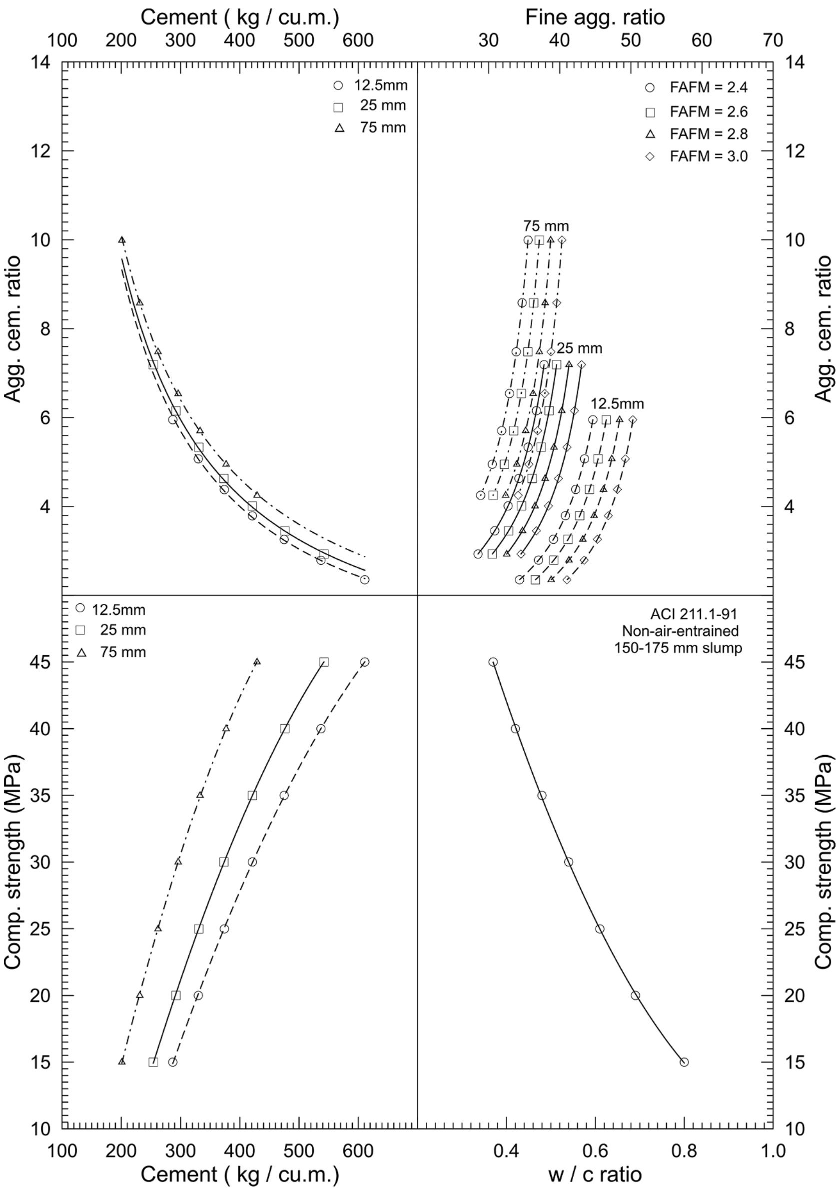

FIGURE NCNA-5.6
Nomogram for non-air-entrained concrete (12.5, 25, and 75 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

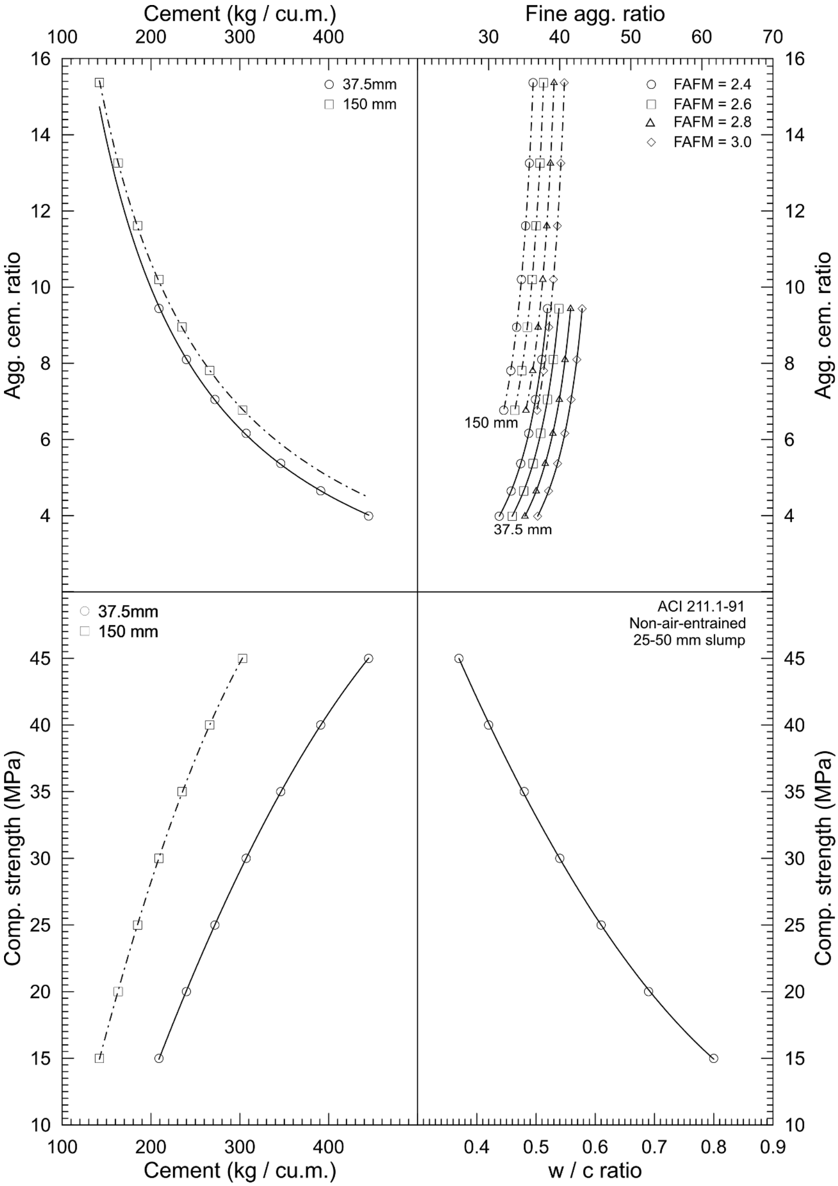

FIGURE NCNA-5.7
Nomogram for non-air-entrained concrete (37.5 and 150 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

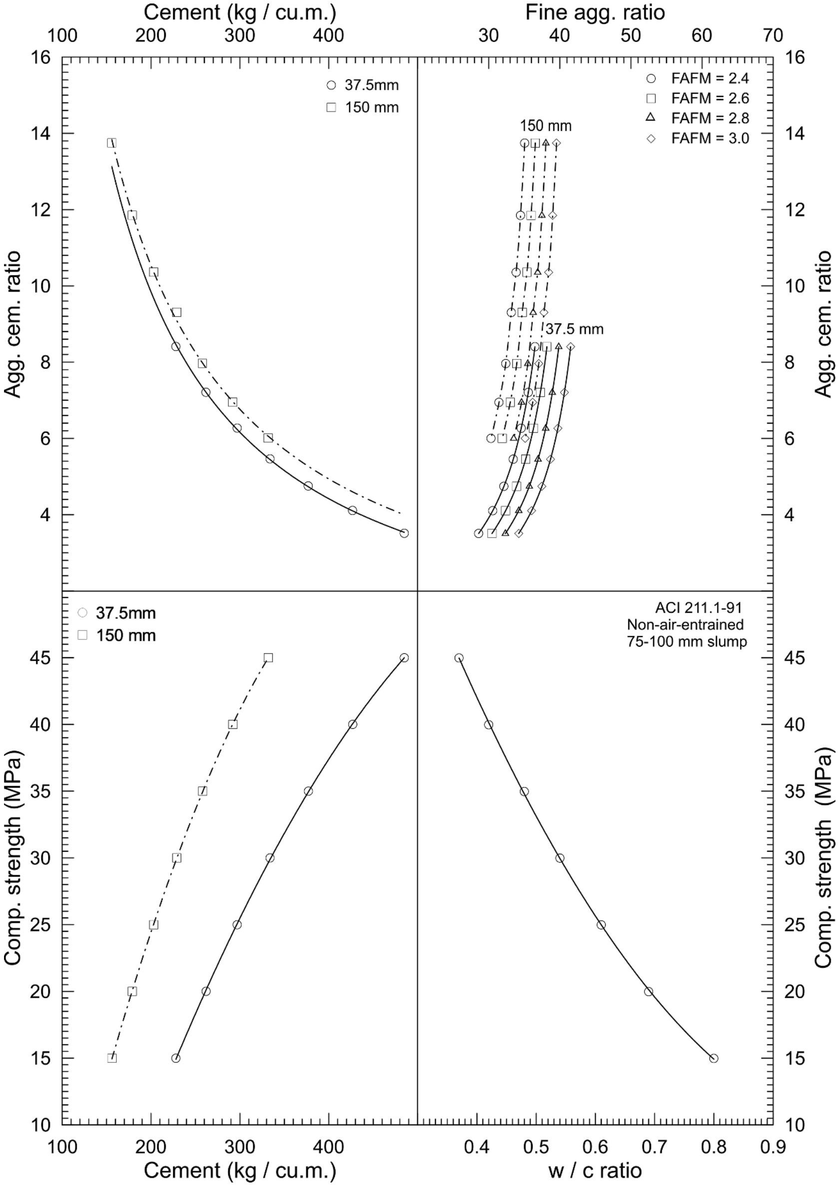

FIGURE NCNA-5.8
Nomogram for non-air-entrained concrete (37.5 and 150 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

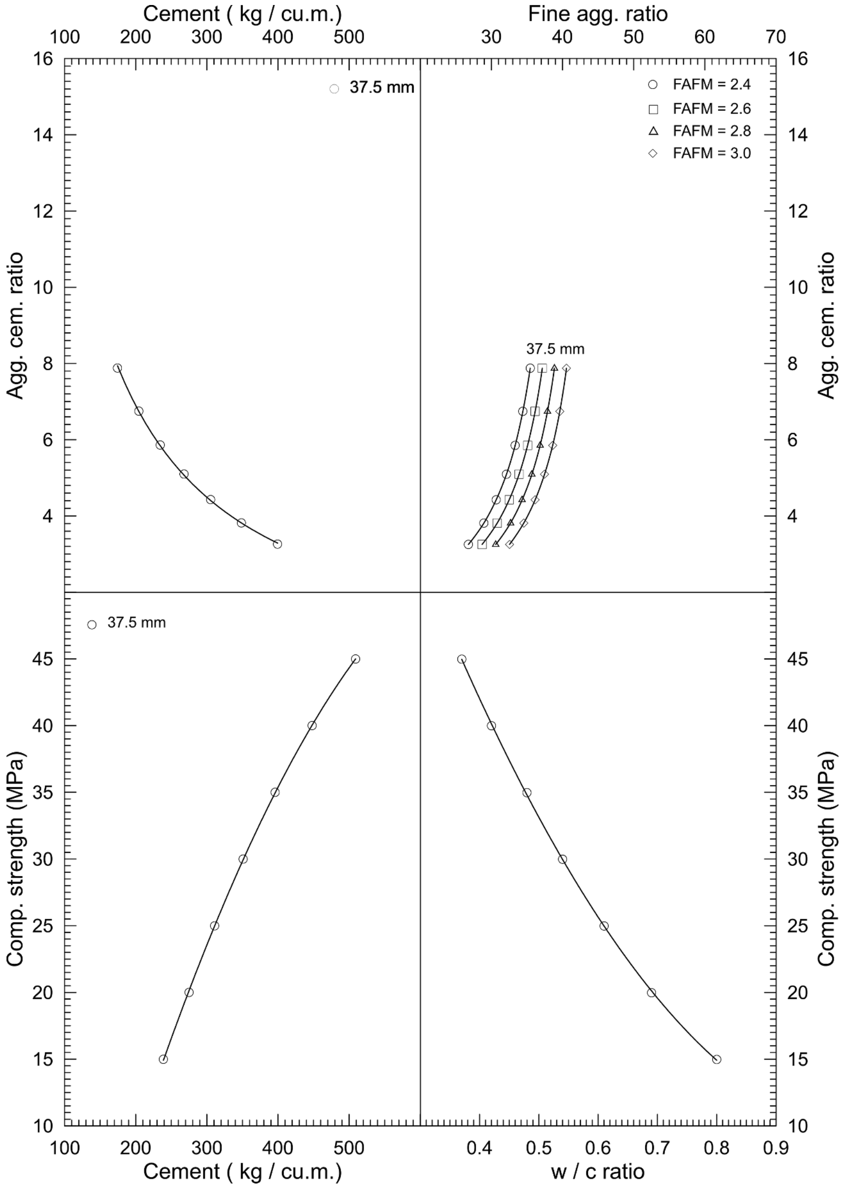

FIGURE NCNA-5.9
Nomogram for non-air-entrained concrete (37.5 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

Appendix NCA-5

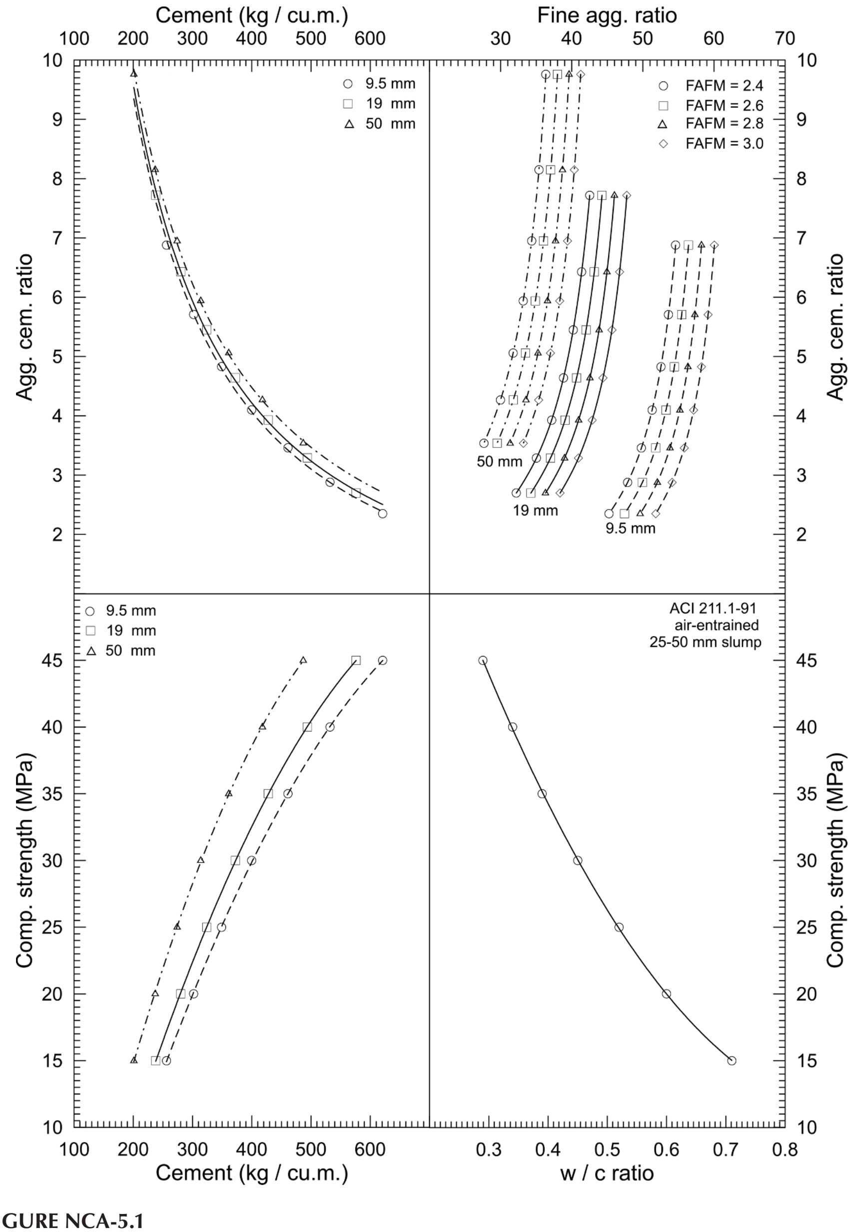

FIGURE NCA-5.1
Nomogram for air-entrained concrete (9.5, 19, and 50 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

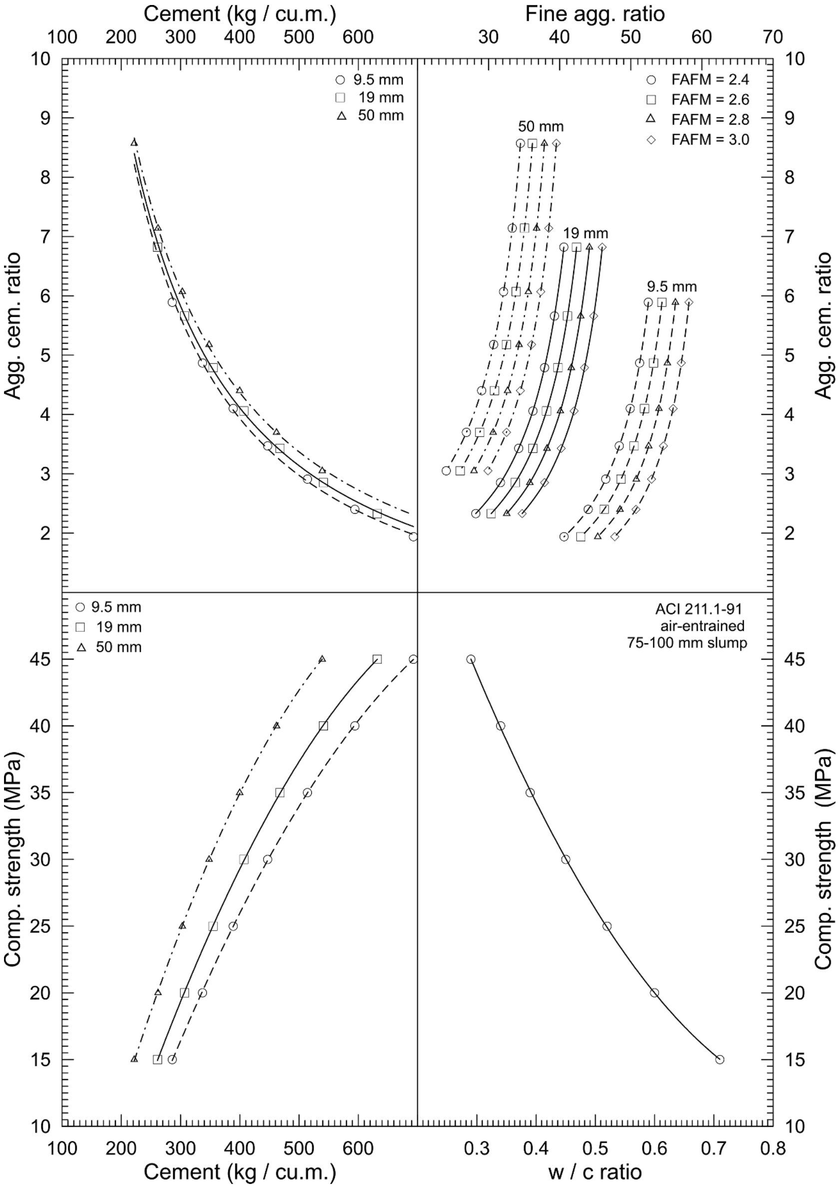

FIGURE NCA-5.2
Nomogram for air-entrained concrete (9.5, 19, and 50 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

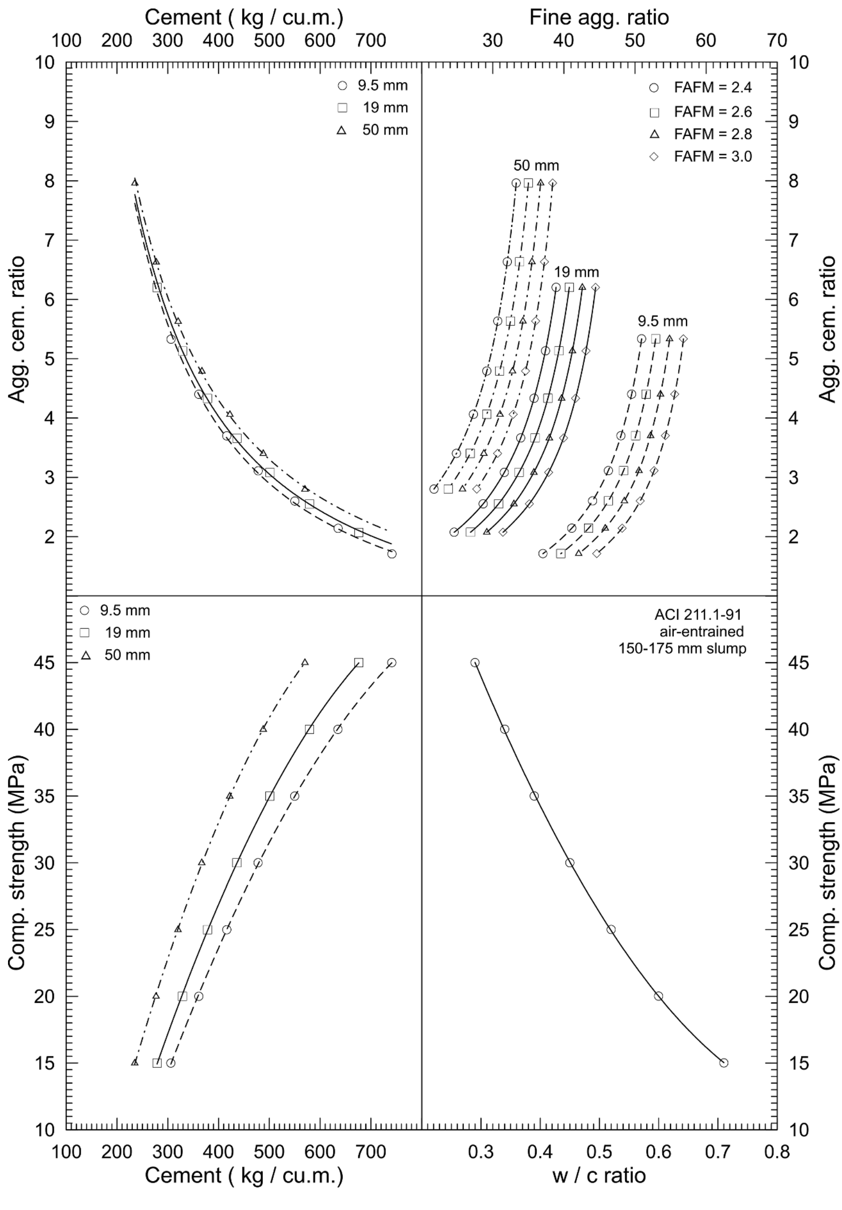

FIGURE NCA-5.3
Nomogram for air-entrained concrete (9.5, 19, and 50 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

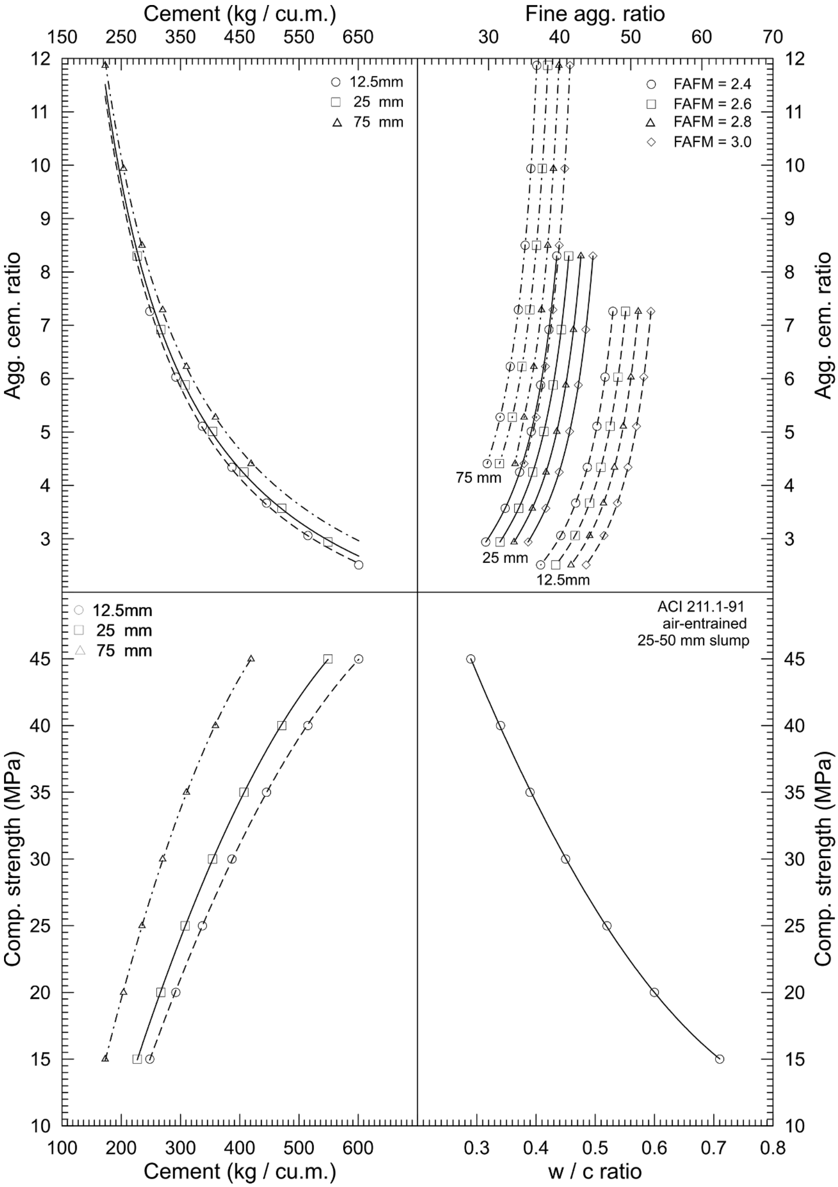

FIGURE NCA-5.4
Nomogram for air-entrained concrete (12.5, 25, and 75 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

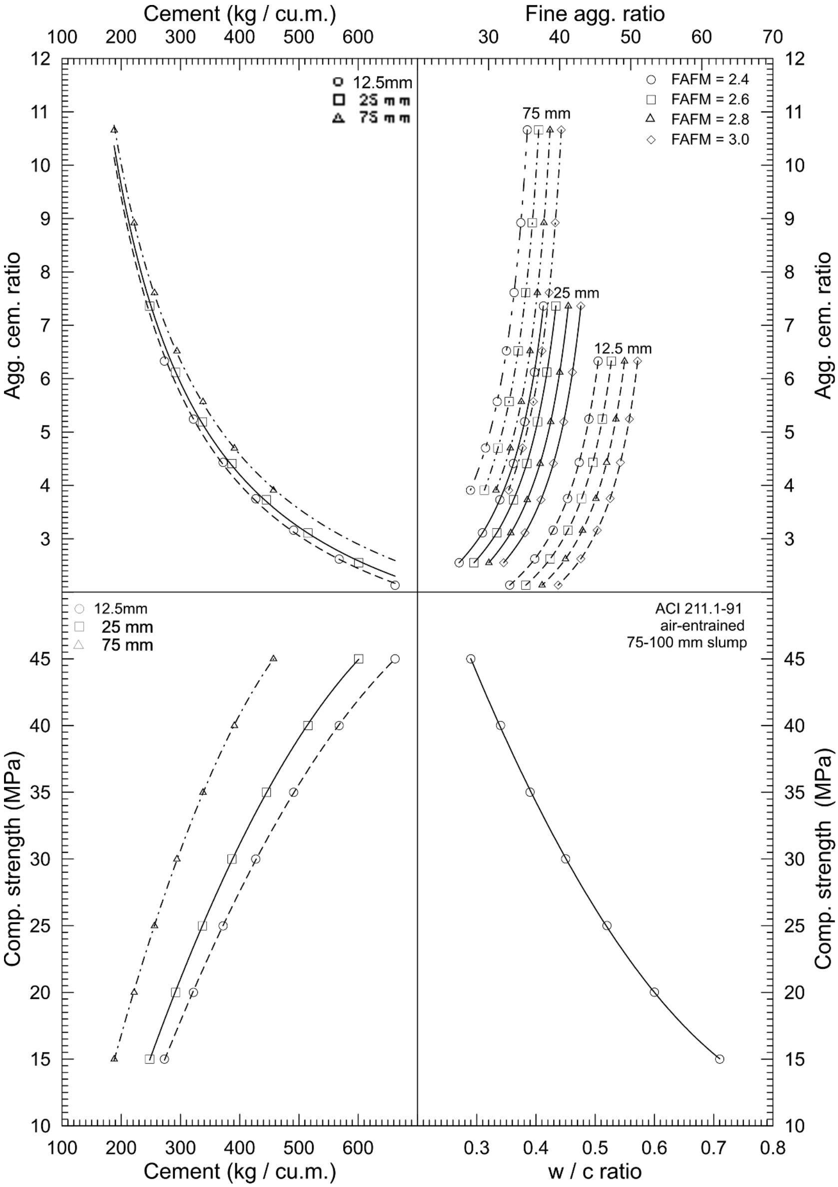

FIGURE NCA-5.5
Nomogram for air-entrained concrete (12.5, 25, and 75 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

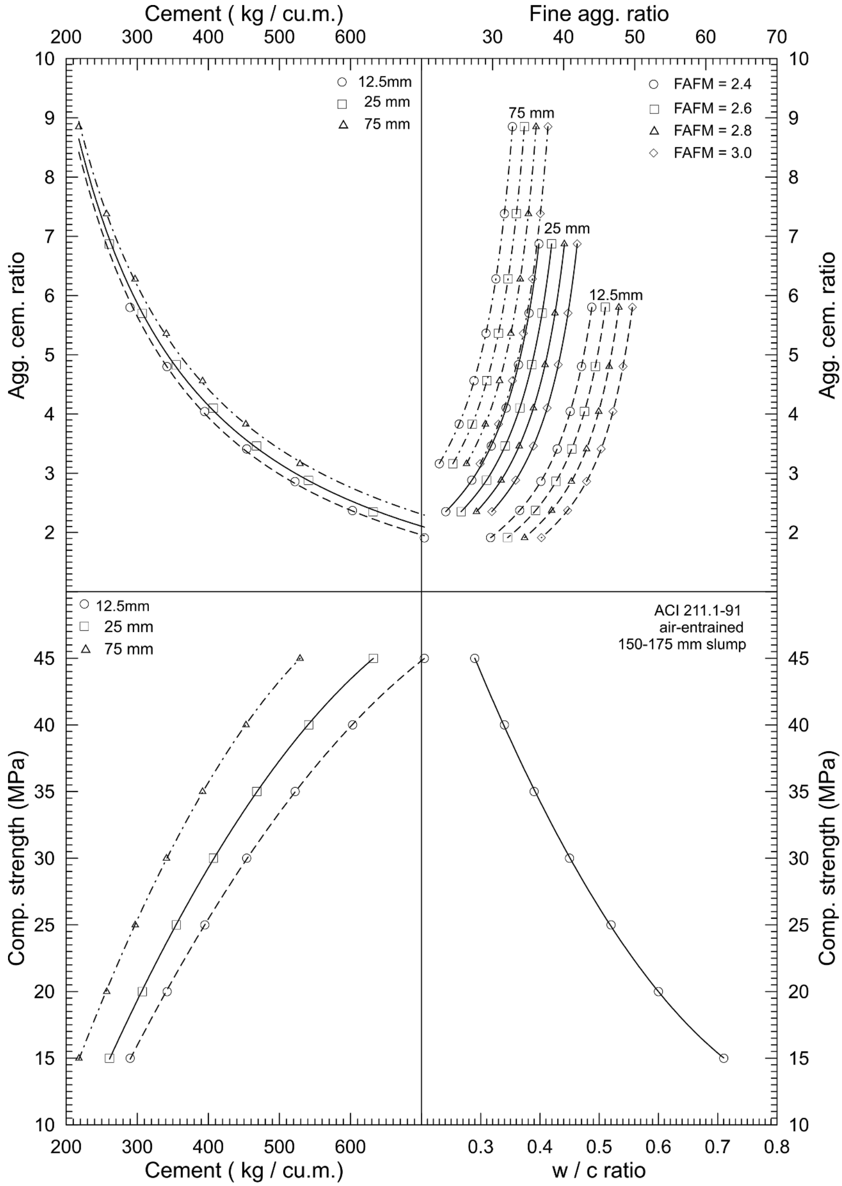

FIGURE NCA-5.6
Nomogram for air-entrained concrete (12.5, 25, and 75 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

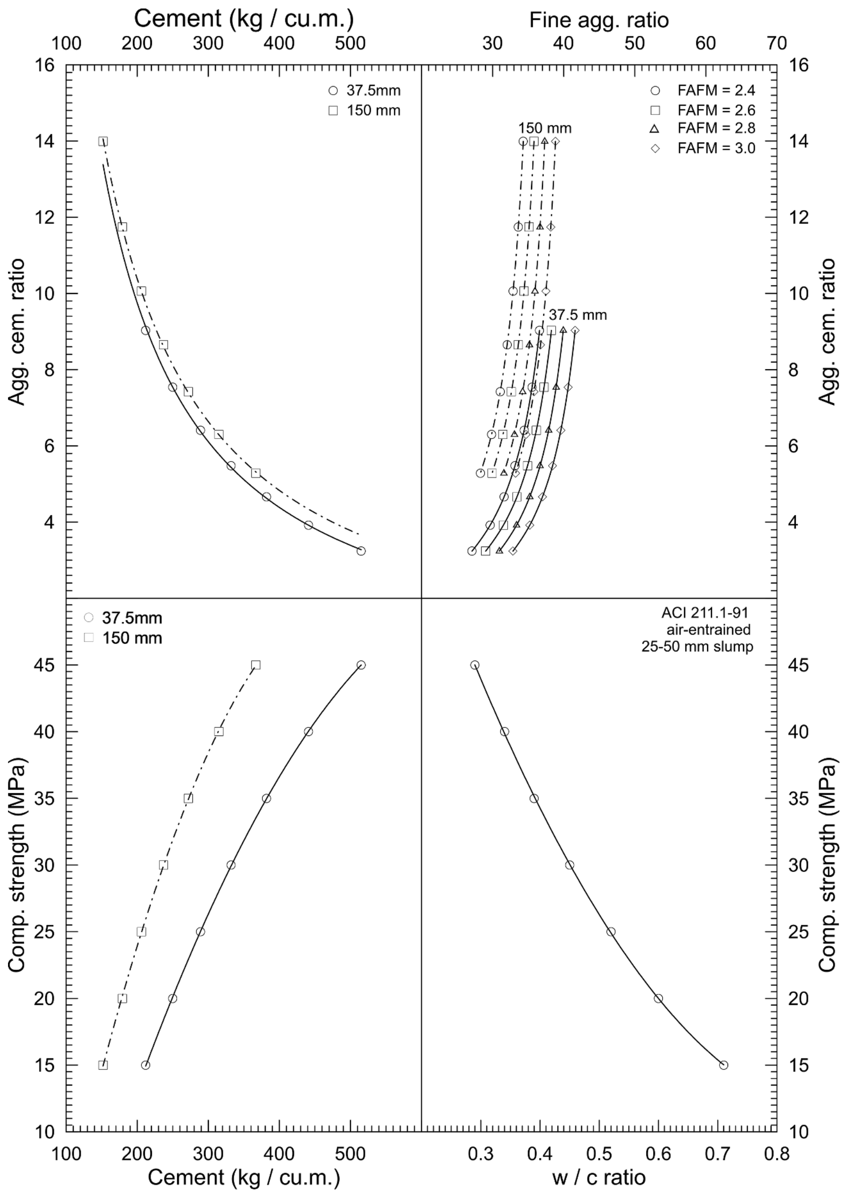

FIGURE NCA-5.7
Nomogram for air-entrained concrete (37.5 and 150 mm aggregate, 25–50 mm slump). (After ACI 211.1, 1991.)

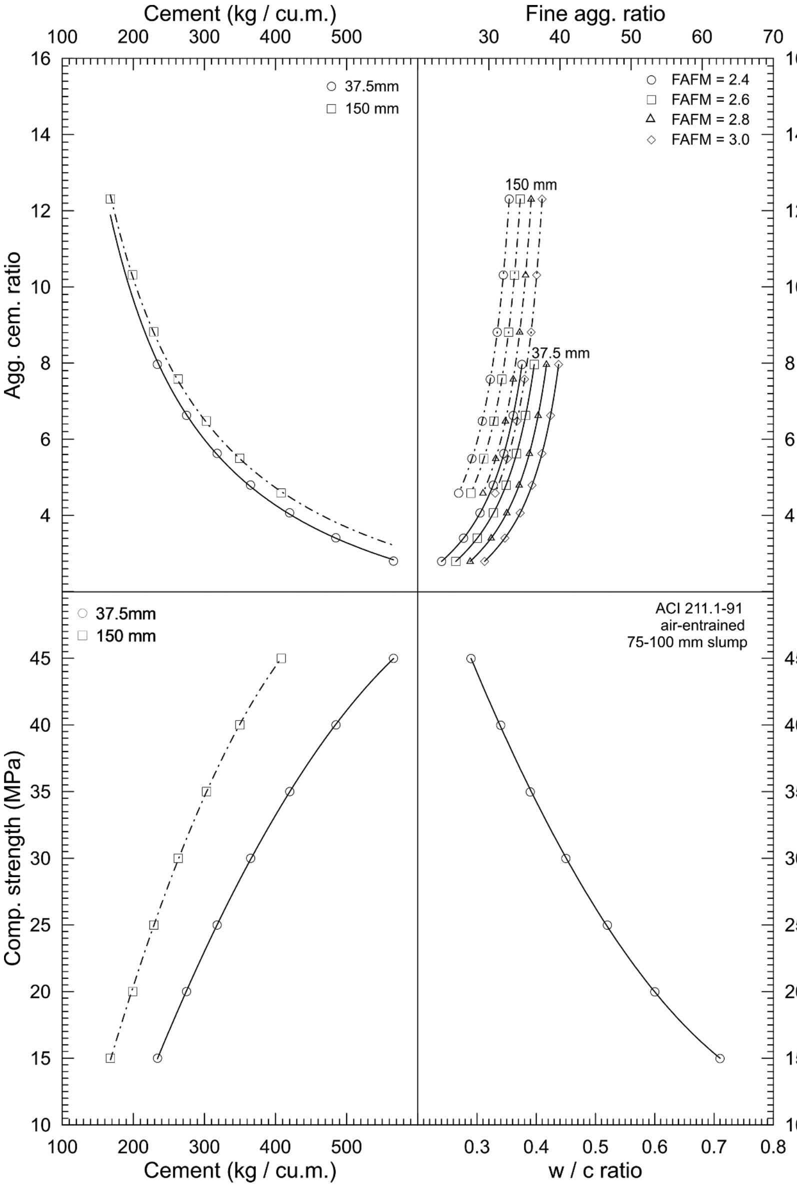

FIGURE NCA-5.8
Nomogram for air-entrained concrete (37.5 and 150 mm aggregate, 75–100 mm slump). (After ACI 211.1, 1991.)

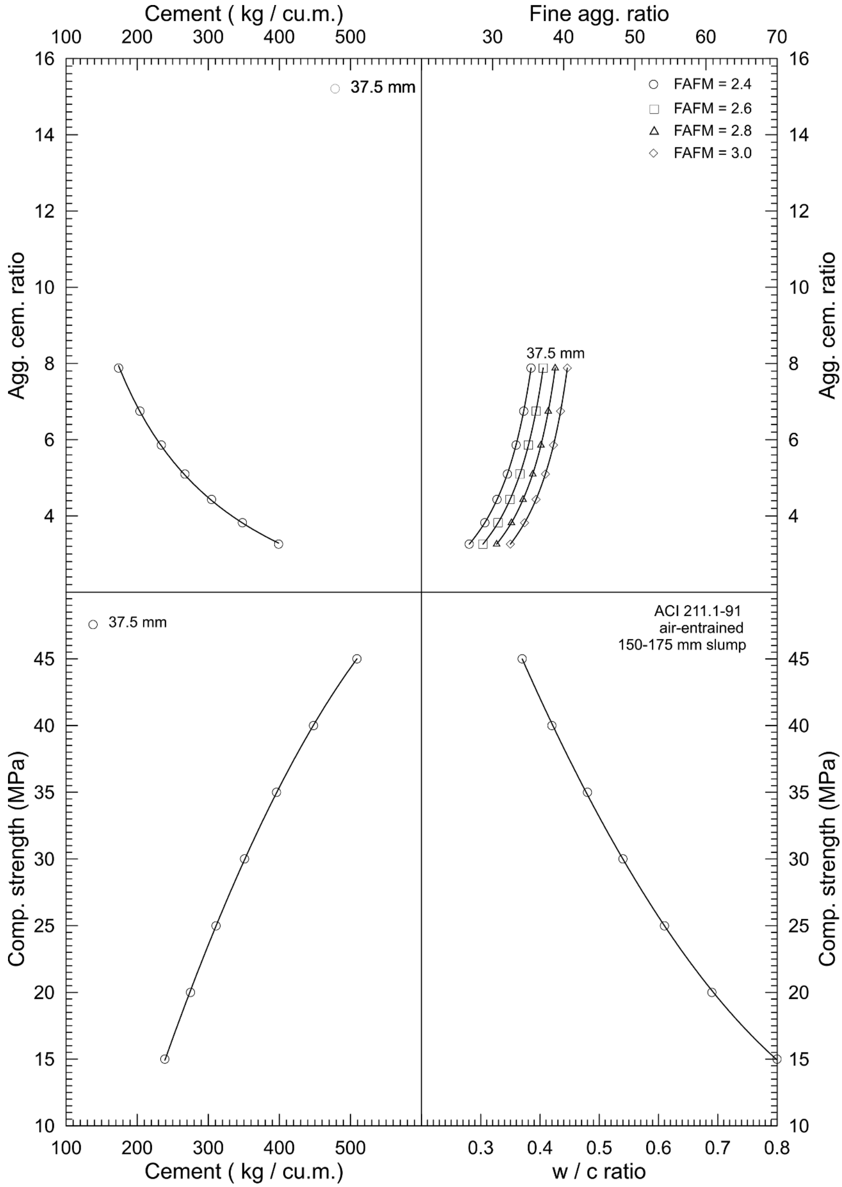

FIGURE NCA-5.9
Nomogram for air-entrained concrete (37.5 mm aggregate, 150–175 mm slump). (After ACI 211.1, 1991.)

Appendix NSNA-5

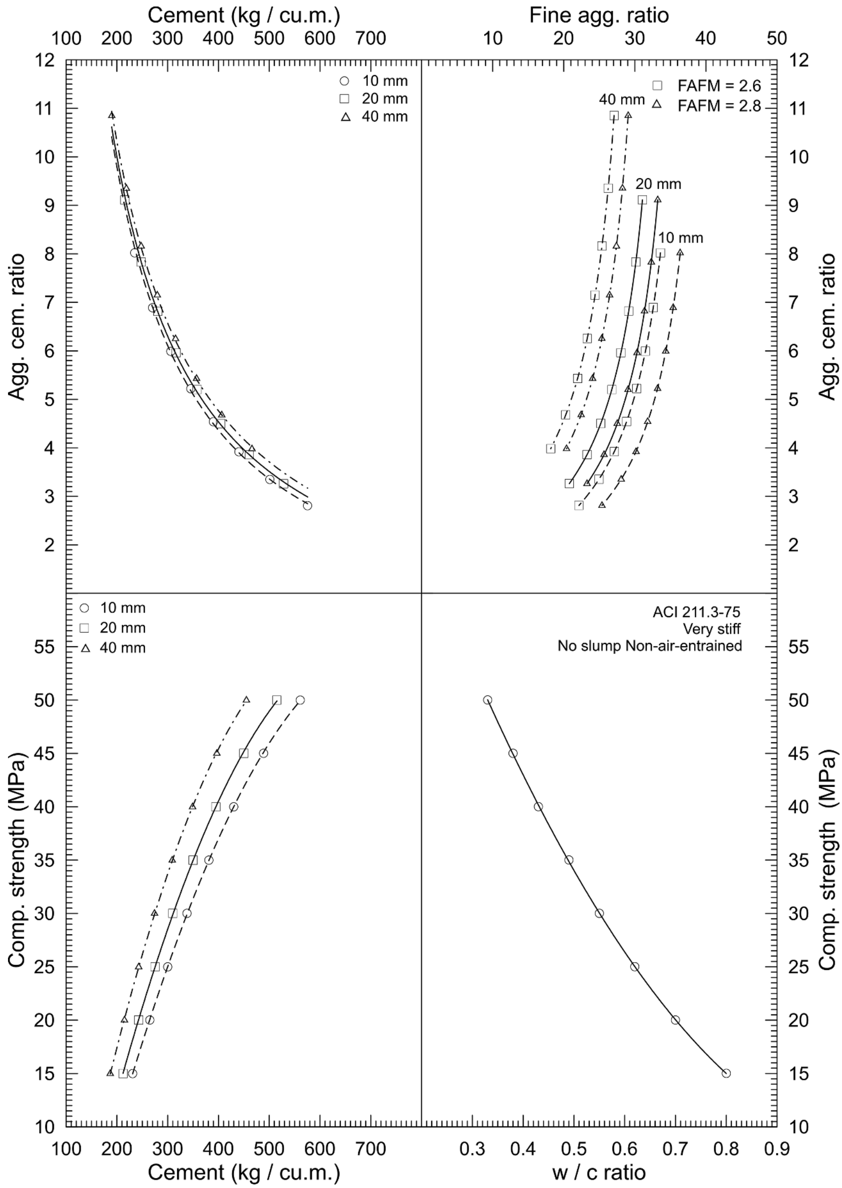

FIGURE NSNA-5.1
Nomogram for non-air-entrained no-slump concrete (10, 20, and 40 mm aggregate, very stiff—slump). (After ACI 211.3, 1997.)

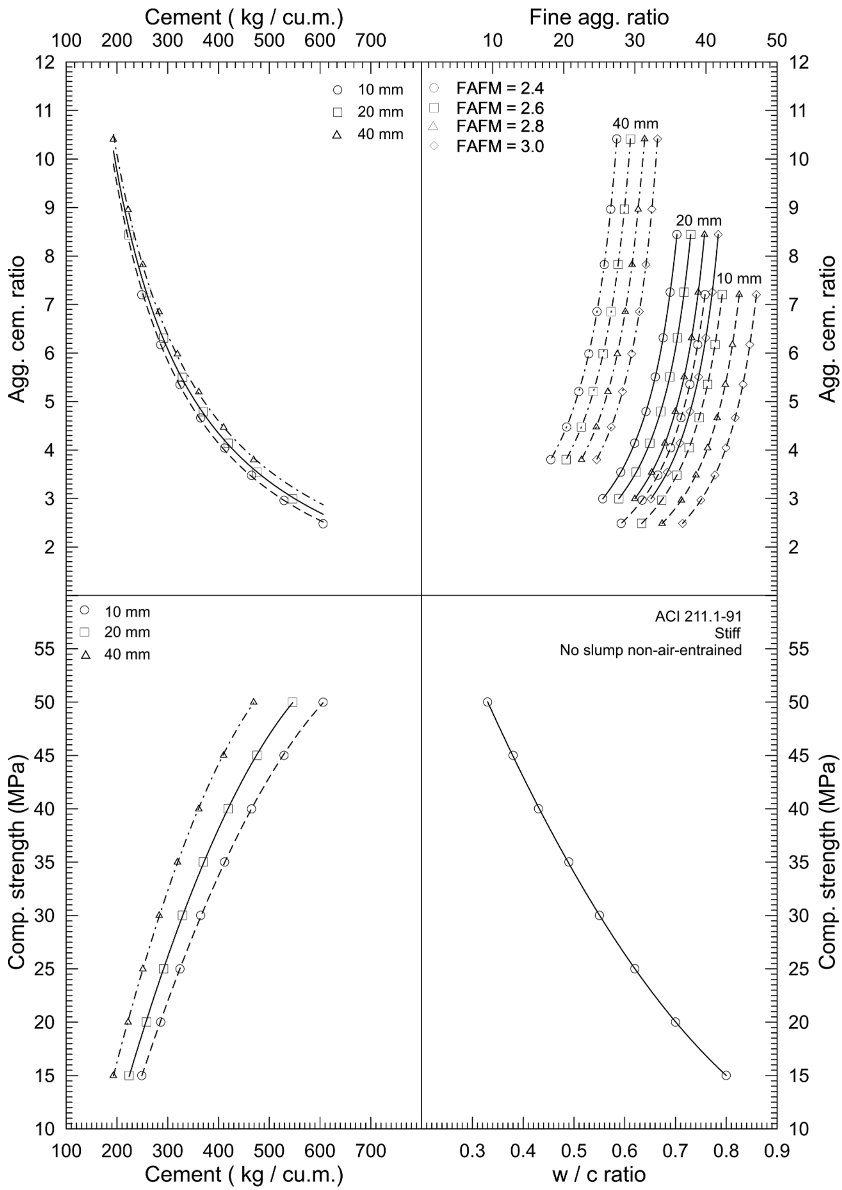

FIGURE NSNA-5.2
Nomogram for non-air-entrained no-slump concrete (10, 20, and 40 mm aggregate, stiff—slump). (After ACI 211.3, 1997.)

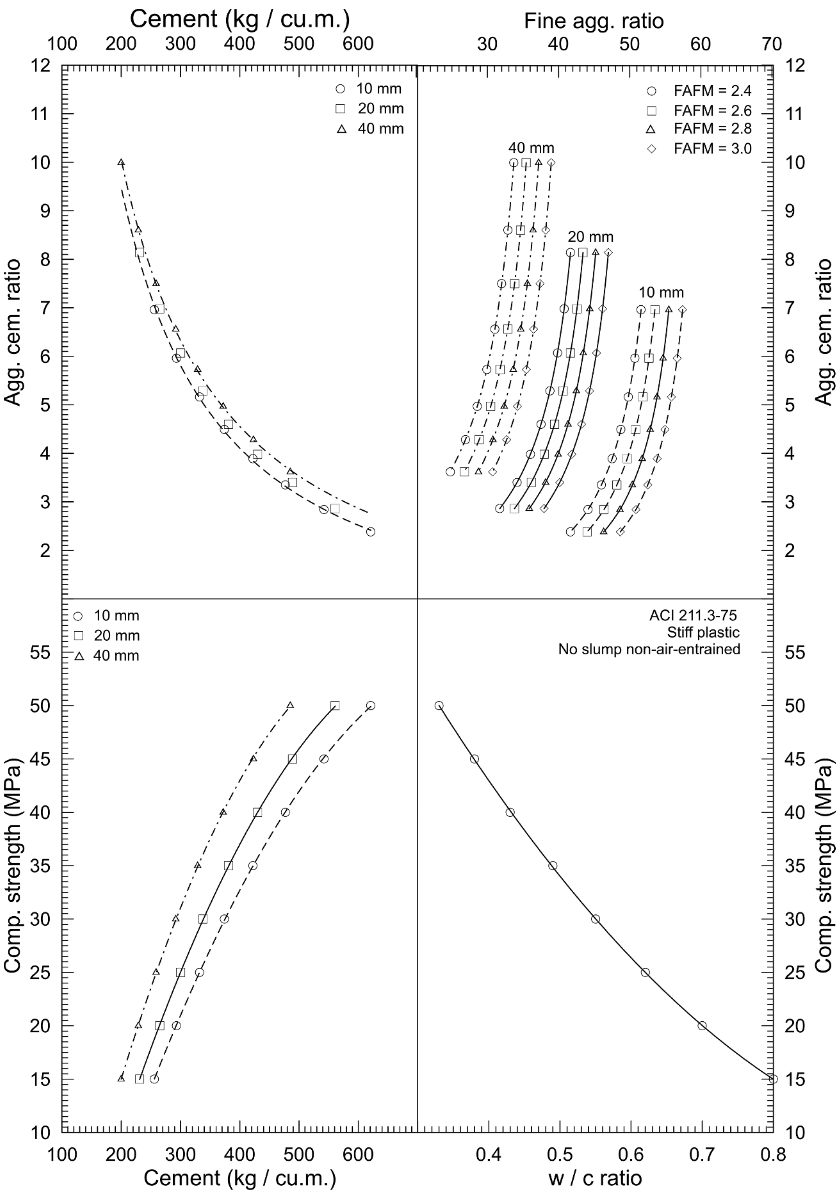

FIGURE NSNA-5.3
Nomogram for non-air-entrained no-slump concrete (10, 20, and 40 mm aggregate, stiff plastic—slump). (After ACI 211.3, 1997.)

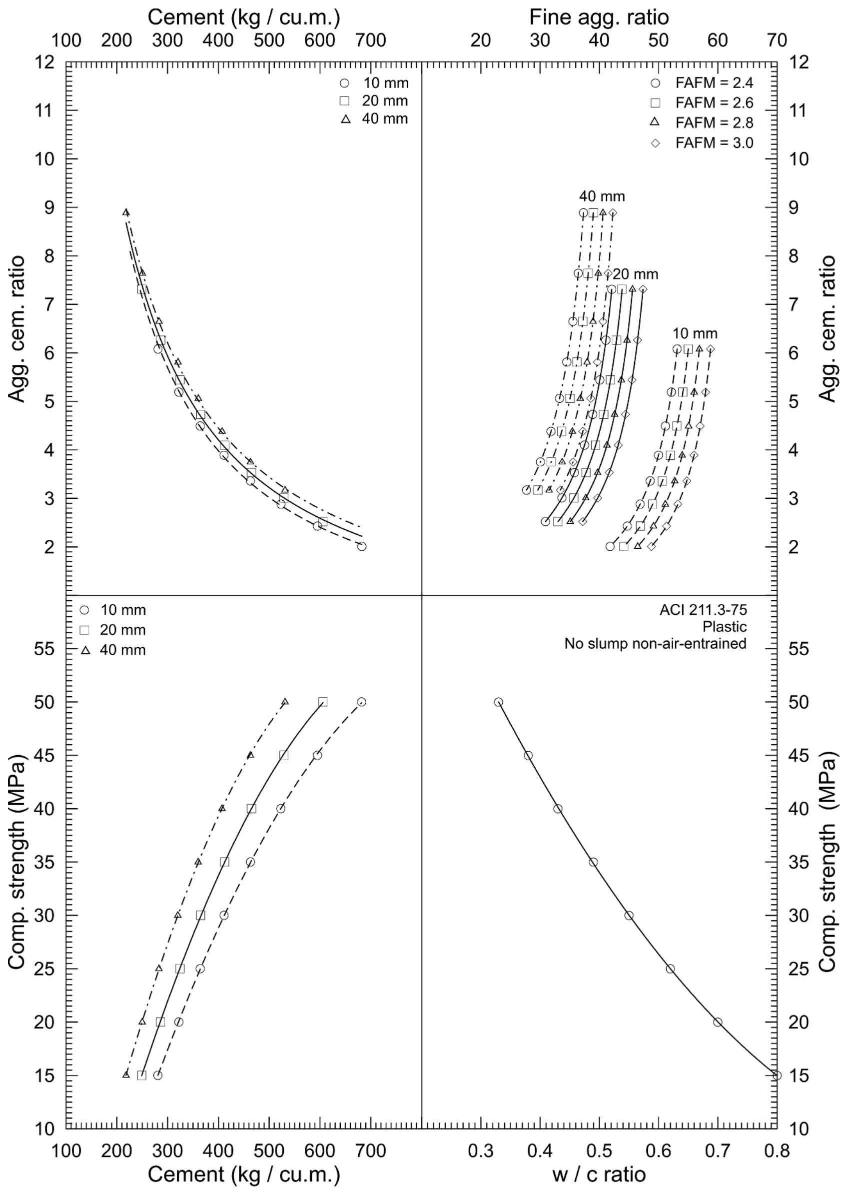

FIGURE NSNA-5.4
Nomogram for non-air-entrained no-slump concrete (10, 20, and 40 mm aggregate, plastic—slump). (After ACI 211.3, 1997.)

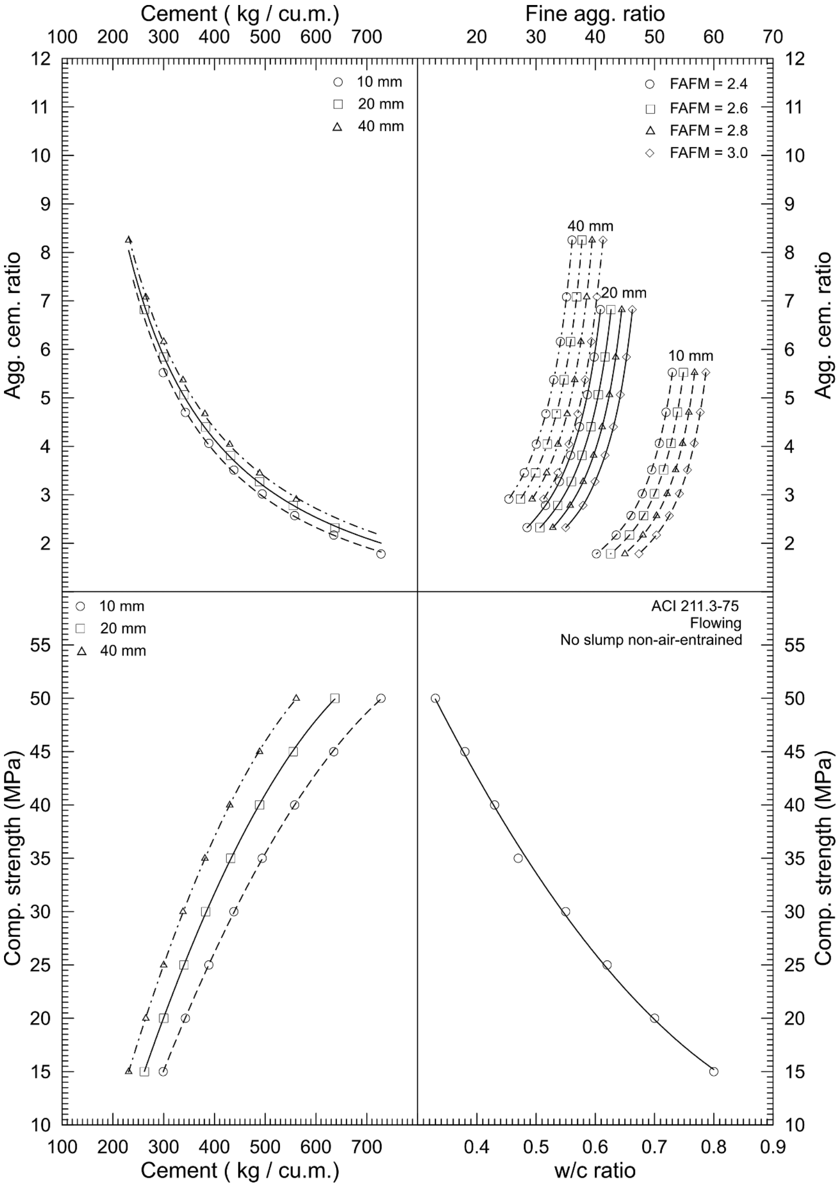

FIGURE NSNA-5.5
Nomogram for non-air-entrained no-slump concrete (10, 20, and 40 mm aggregate, flowing—slump). (After ACI 211.3, 1997.)

Appendix NSA-5

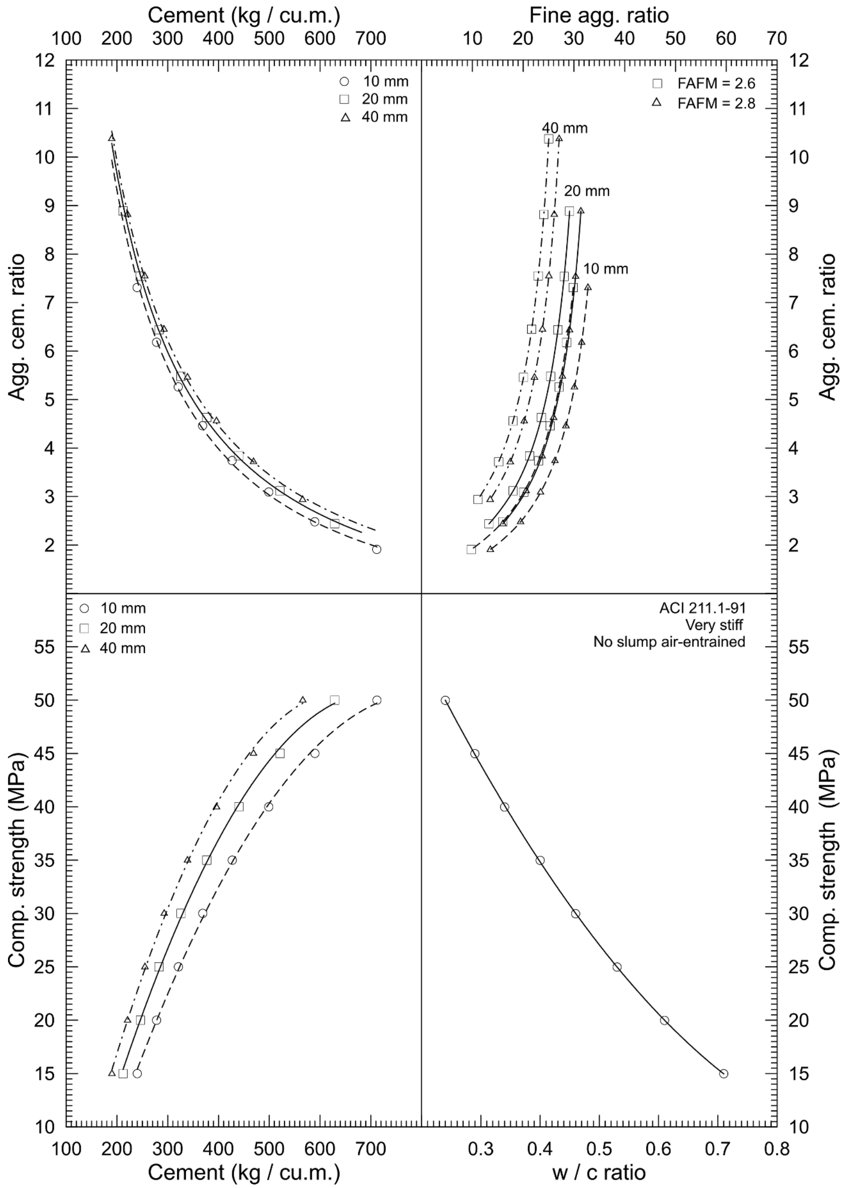

FIGURE NSA-5.1
Nomogram for air-entrained no-slump concrete (10, 20, and 40 mm aggregate, very stiff—slump). (After ACI 211.3, 1997.)

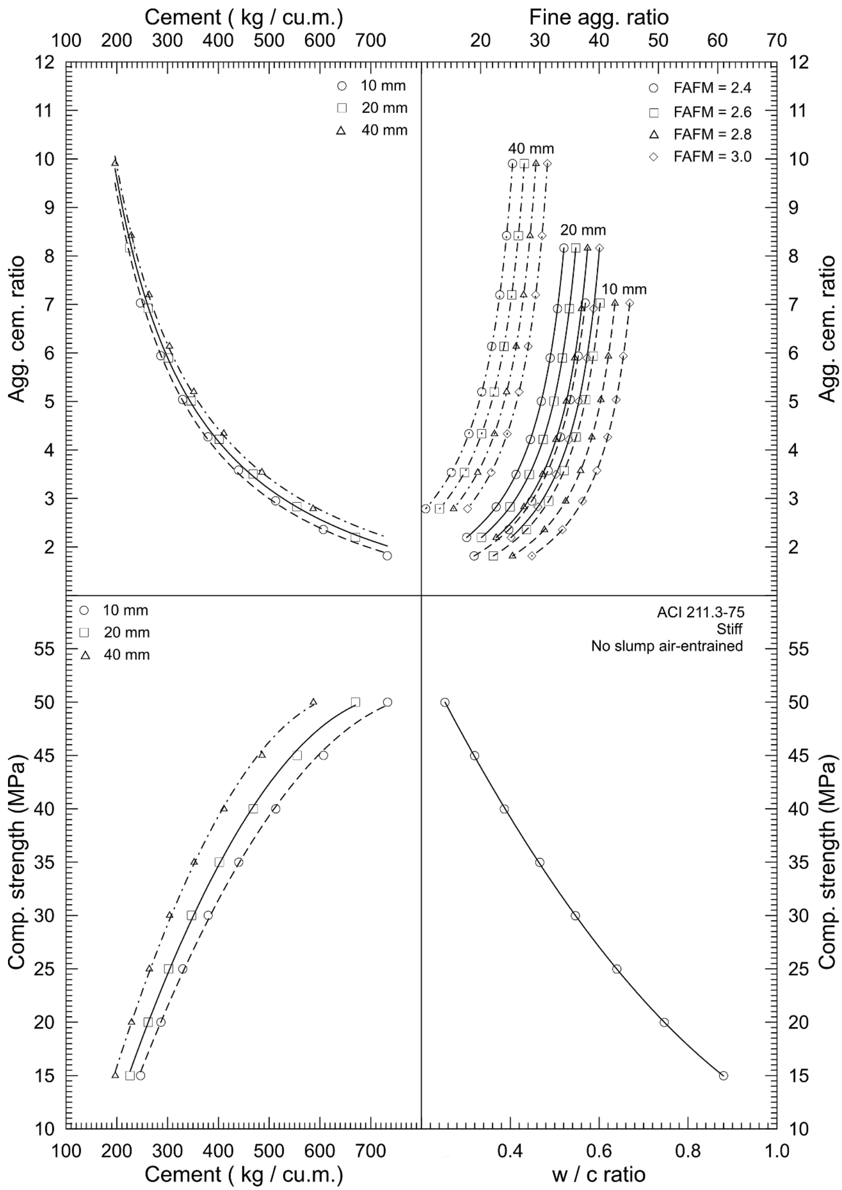

FIGURE NSA-5.2
Nomogram for air-entrained no-slump concrete (10, 20, and 40 mm aggregate, stiff—slump). (After ACI 211.3, 1997.)

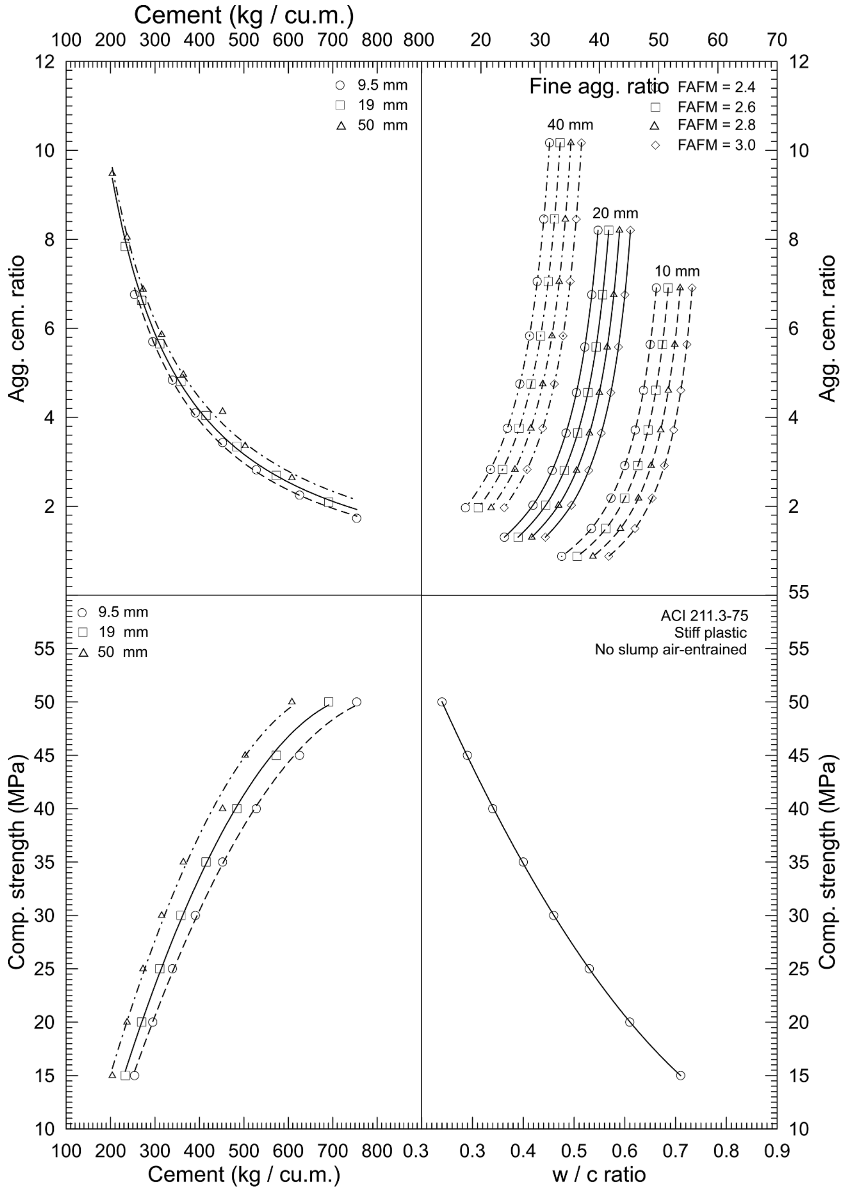

FIGURE NSA-5.3
Nomogram for air-entrained no-slump concrete (10, 20, and 40 mm aggregate, stiff plastic—slump). (After ACI 211.3, 1997.)

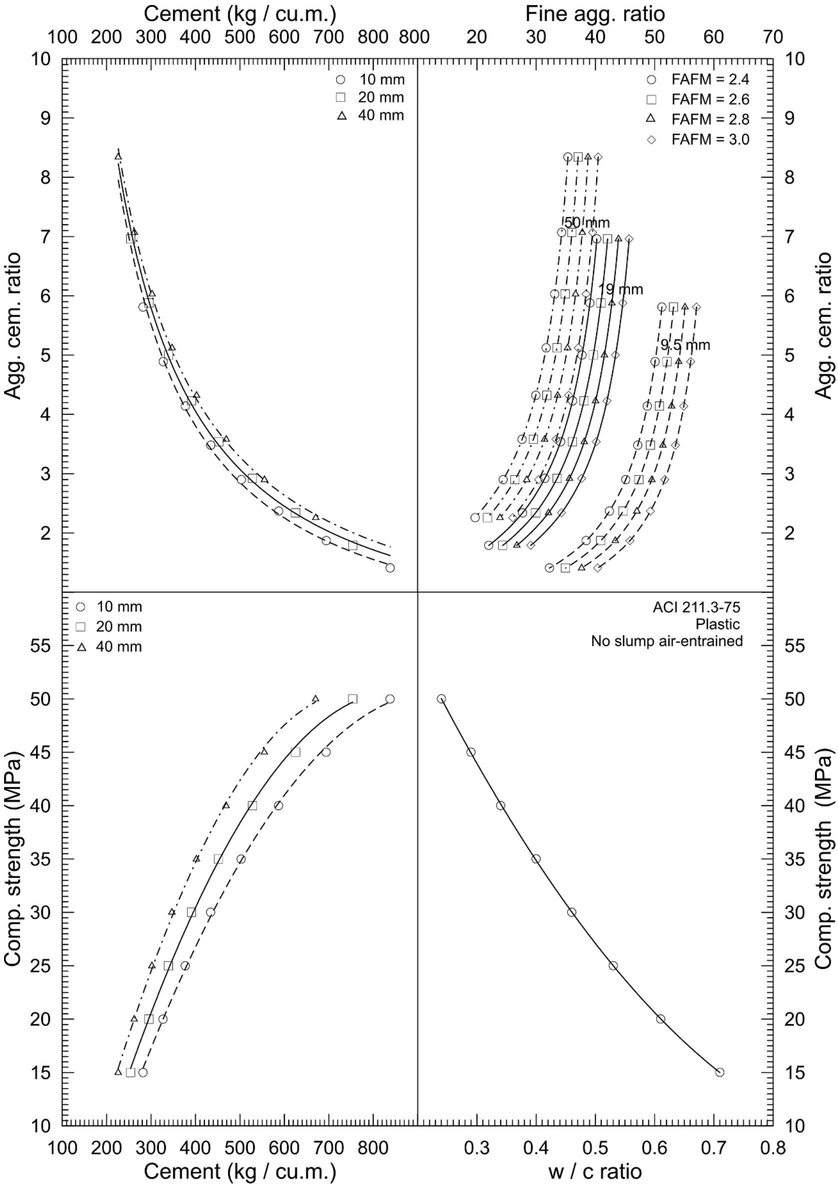

FIGURE NSA-5.4
Nomogram for air-entrained no-slump concrete (10, 20, and 40 mm aggregate, plastic—slump). (After ACI 211.3, 1997.)

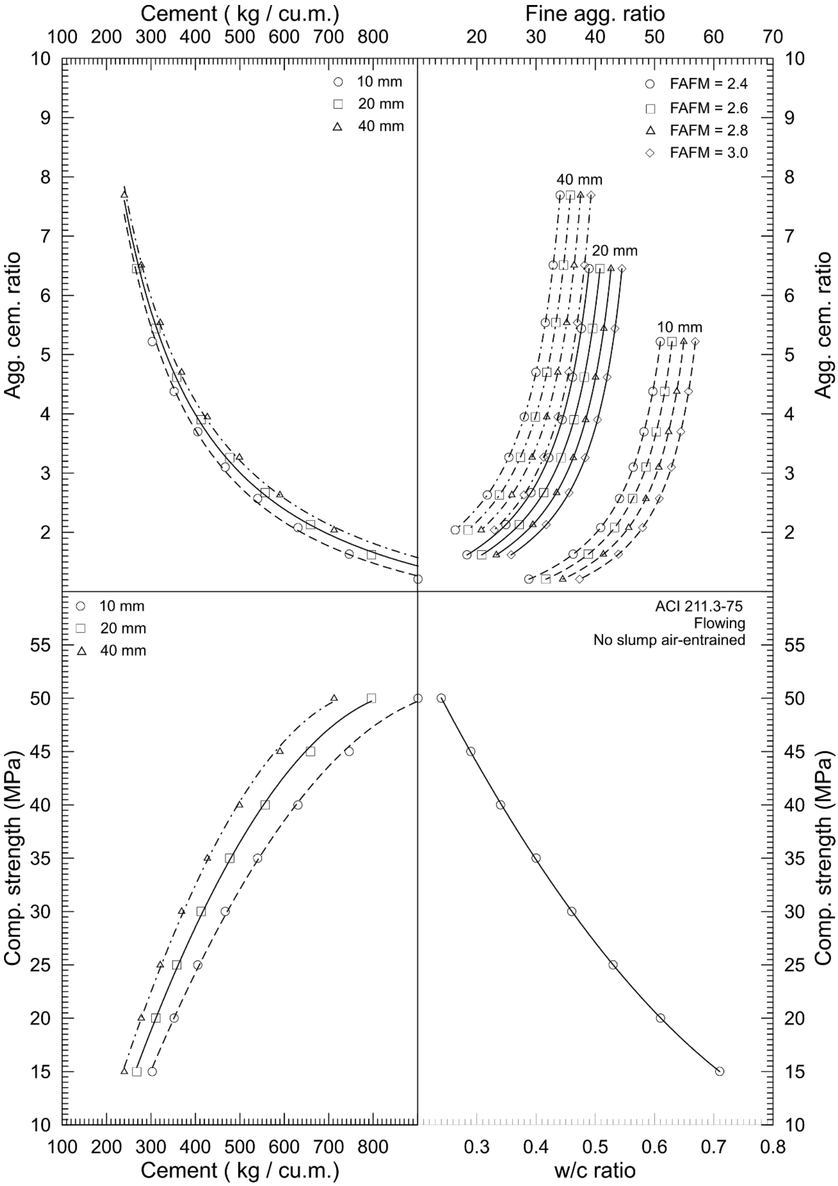

FIGURE NSA-5.5
Nomogram for air-entrained no-slump concrete (10, 20, and 40 mm aggregate, flowing—slump). (After ACI 211.3, 1997.)

Appendix HSN-5

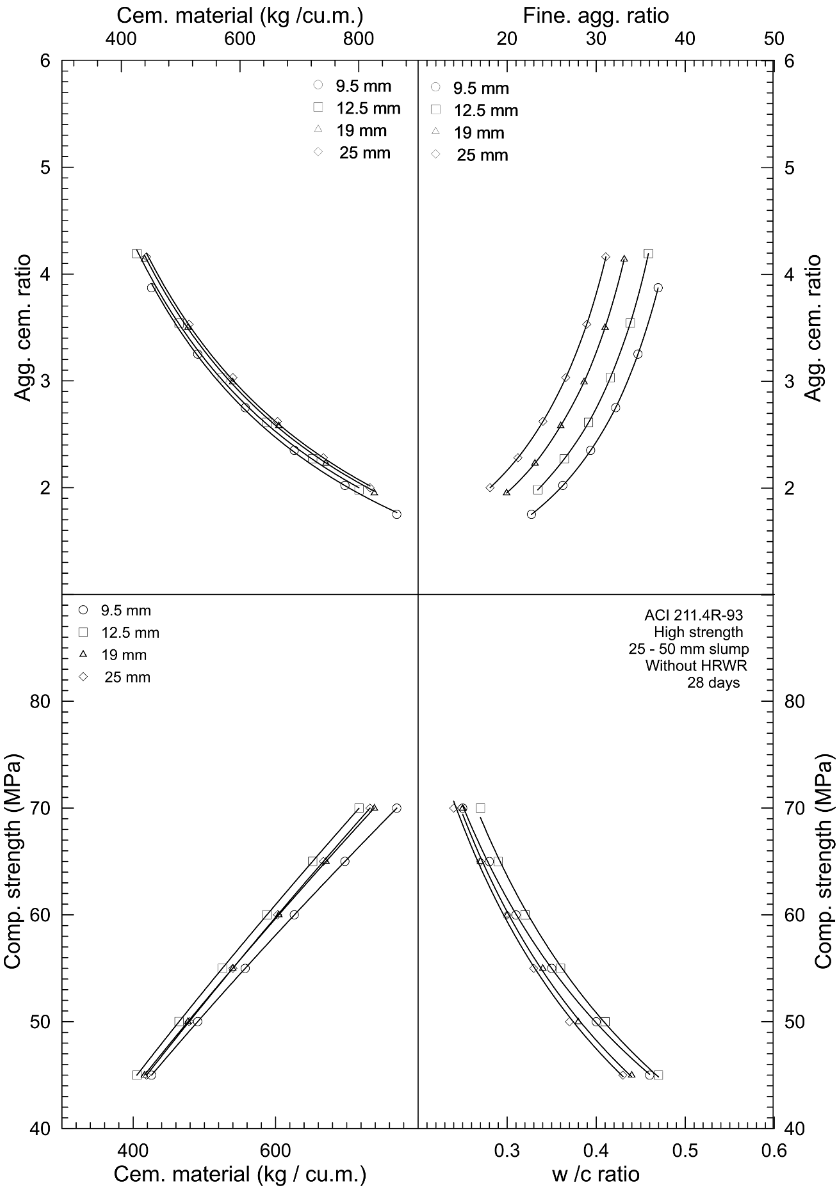

FIGURE HSN-5.1
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 25–50 mm slump, 28 days). (After ACI 211.4, 1993.)

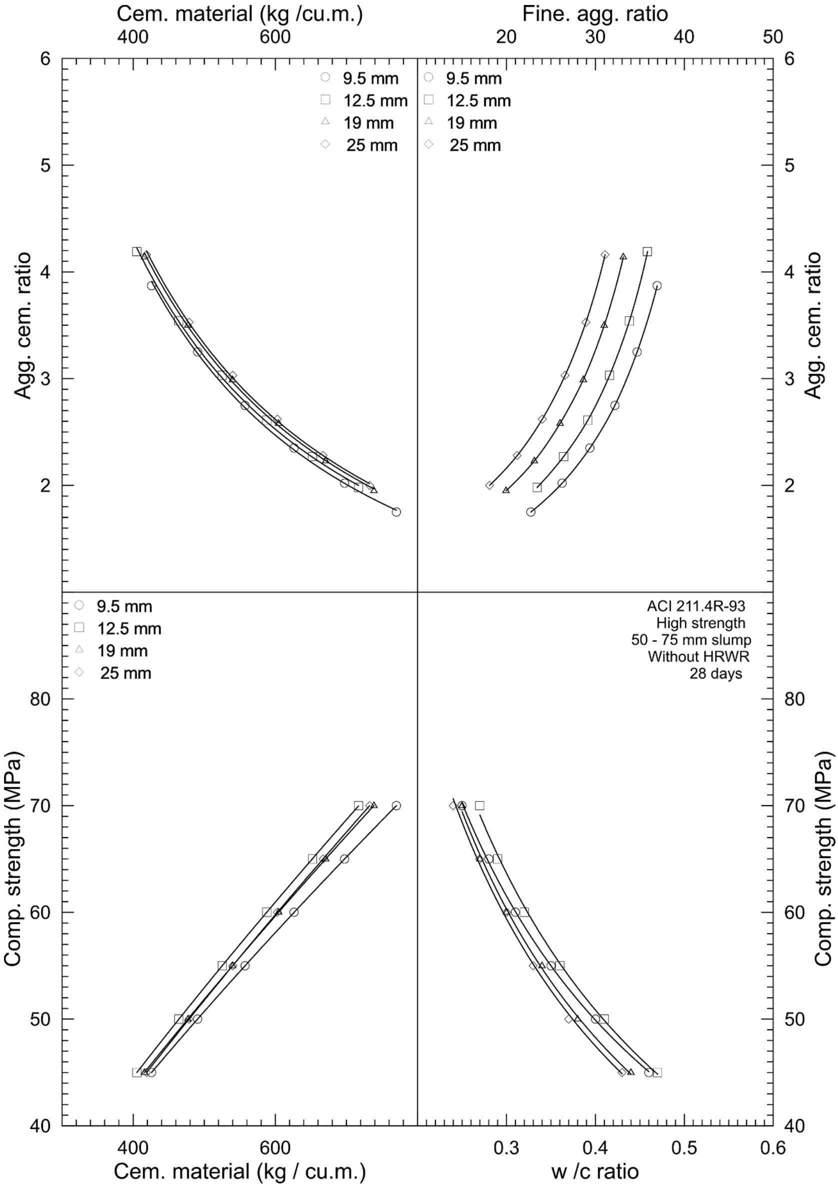

FIGURE HSN-5.2
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 50–75 mm slump, 28 days). (After ACI 211.4, 1993.)

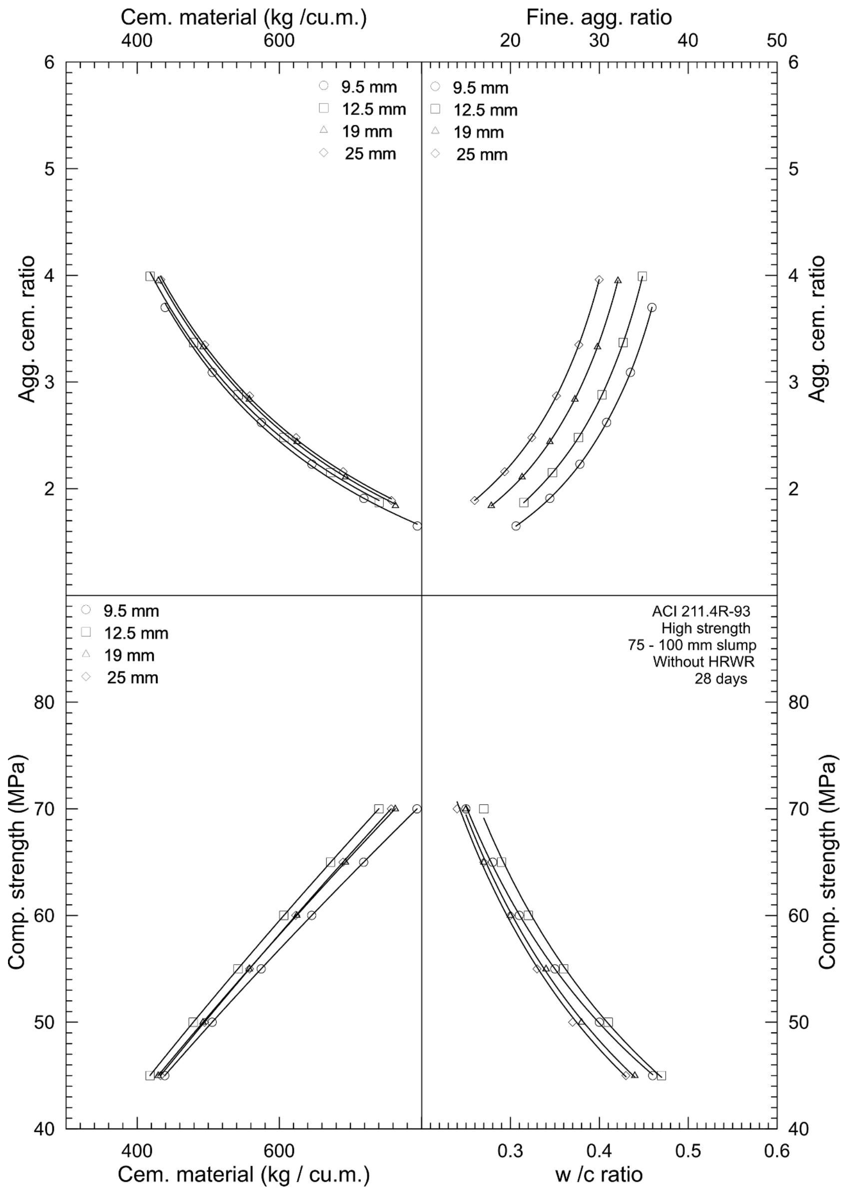

FIGURE HSN-5.3
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 75–100 mm slump, 28 days). (After ACI 211.4, 1993.)

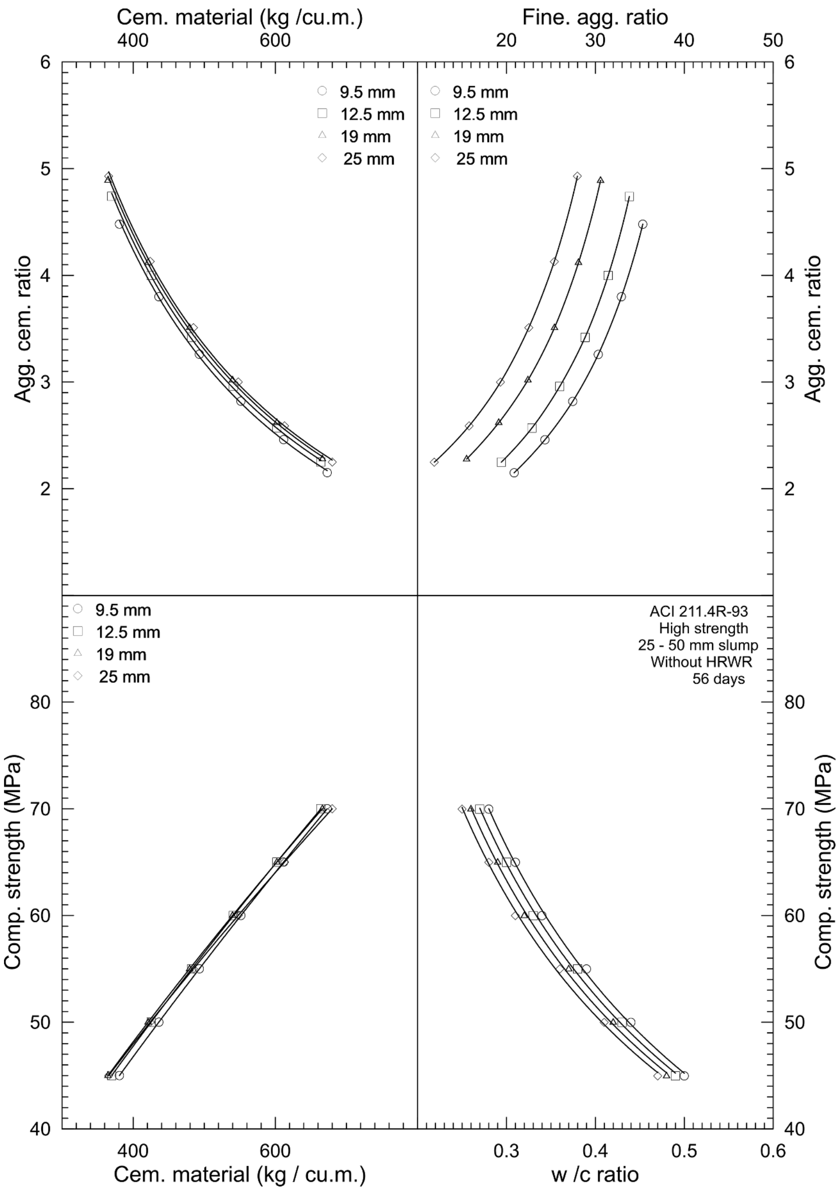

FIGURE HSN-5.4
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 25–50 mm slump, 56 days). (After ACI 211.4, 1993.)

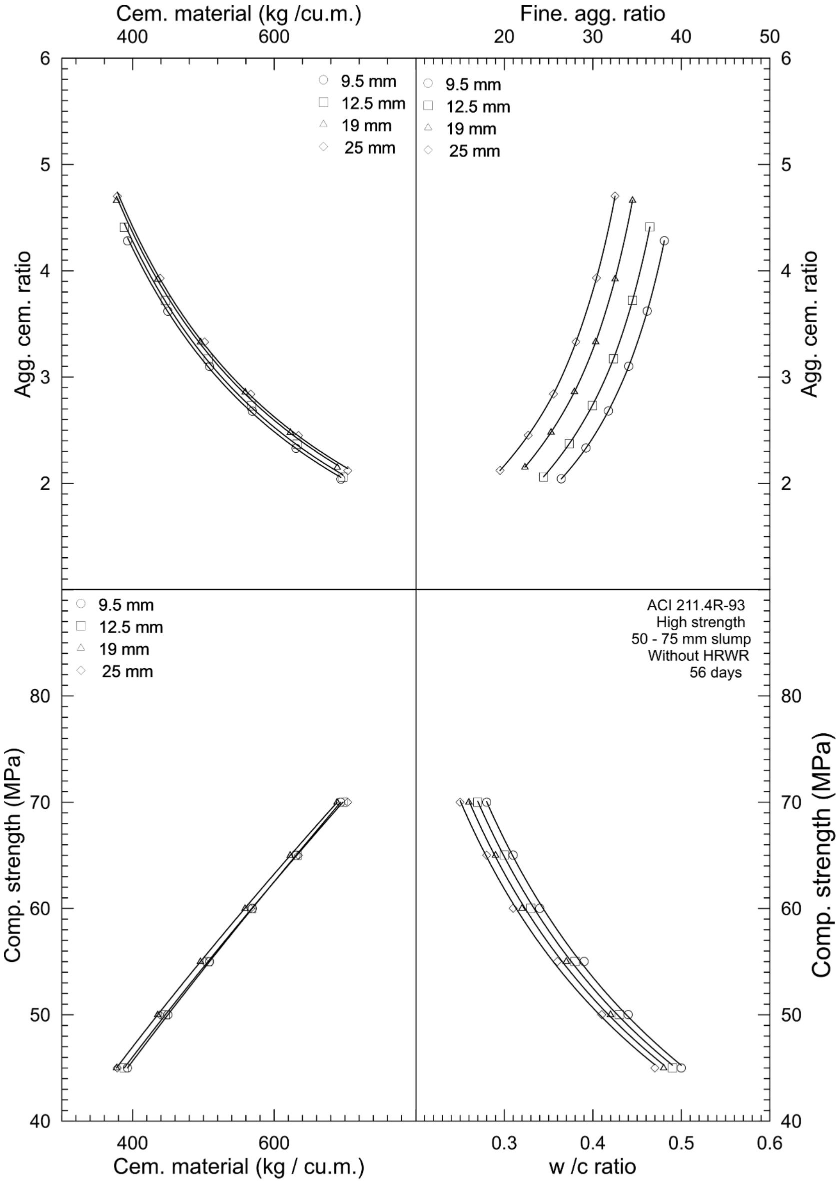

FIGURE HSN-5.5
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 50–75 mm slump, 56 days). (After ACI 211.4, 1993.)

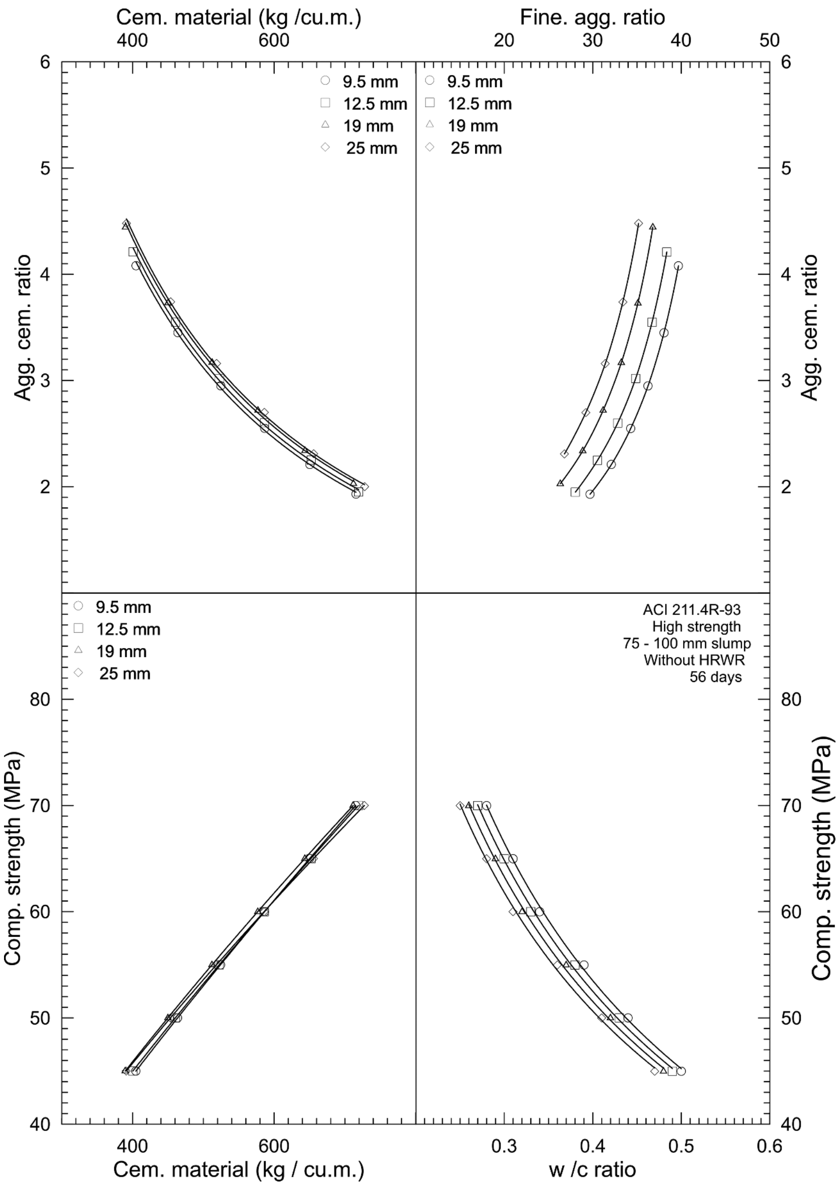

FIGURE HSN-5.6
Nomogram for high strength concrete without HRWR (9.5, 12.5, 19, and 25 mm aggregate, 75–100 mm slump, 56 days). (After ACI 211.4, 1993.)

Appendix HSP-5

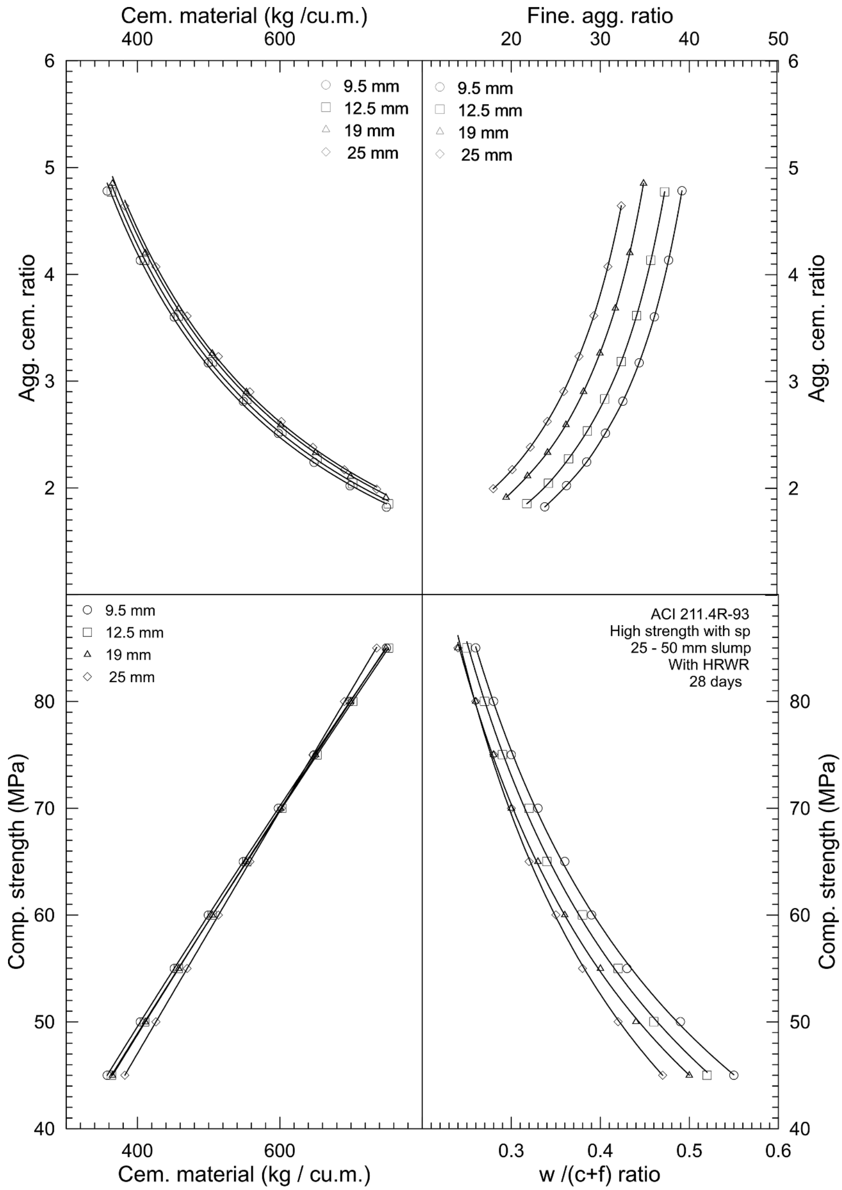

FIGURE HSP-5.1
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 25–50 mm slump, 28 days). (After ACI 211.4, 1993.)

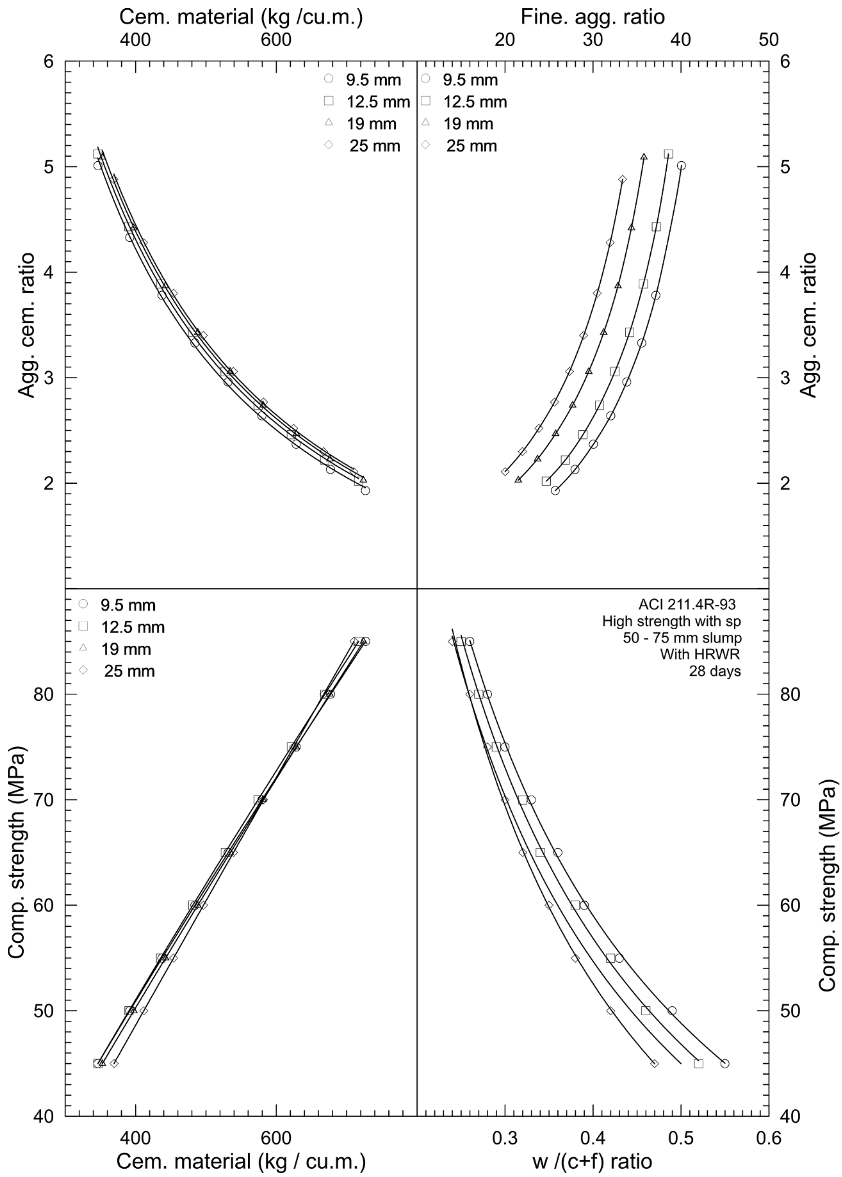

FIGURE HSP-5.2
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 50–75 mm slump, 28 days). (After ACI 211.4, 1993.)

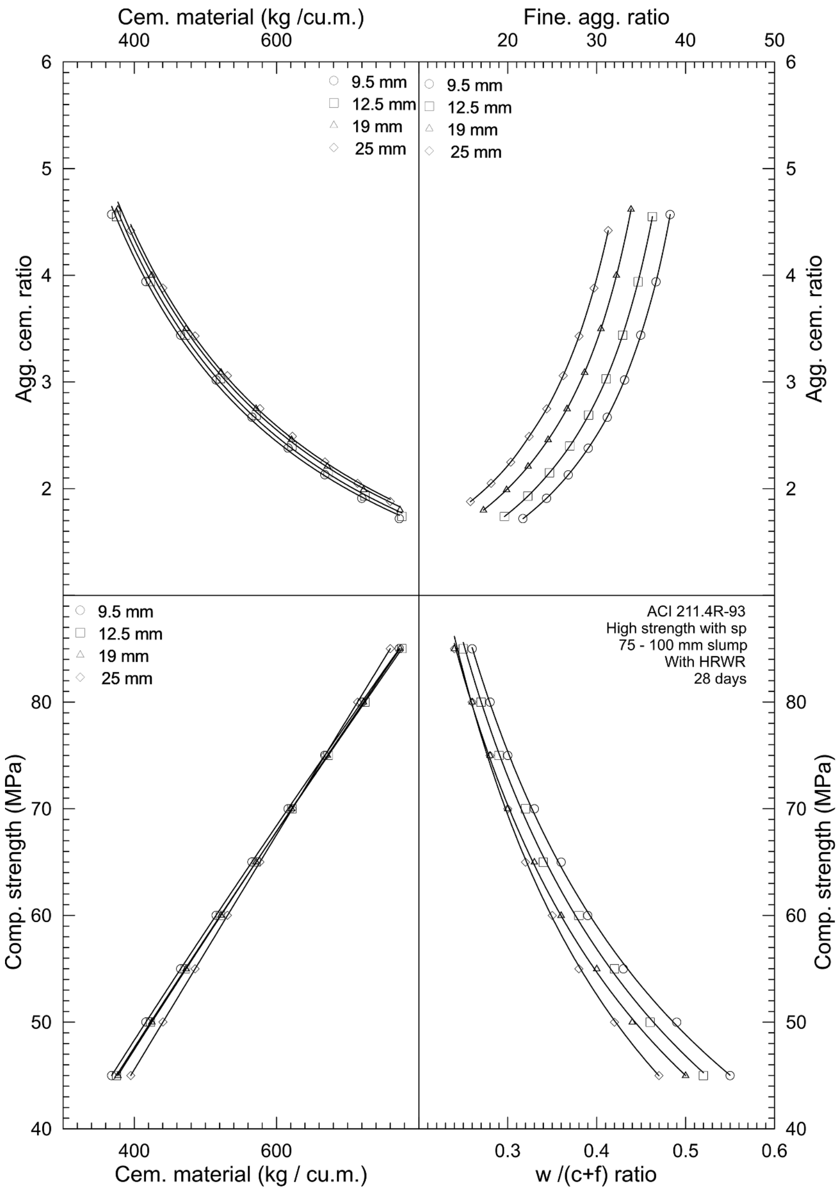

FIGURE HSP-5.3
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 75–100 mm slump, 28 days). (After ACI 211.4, 1993.)

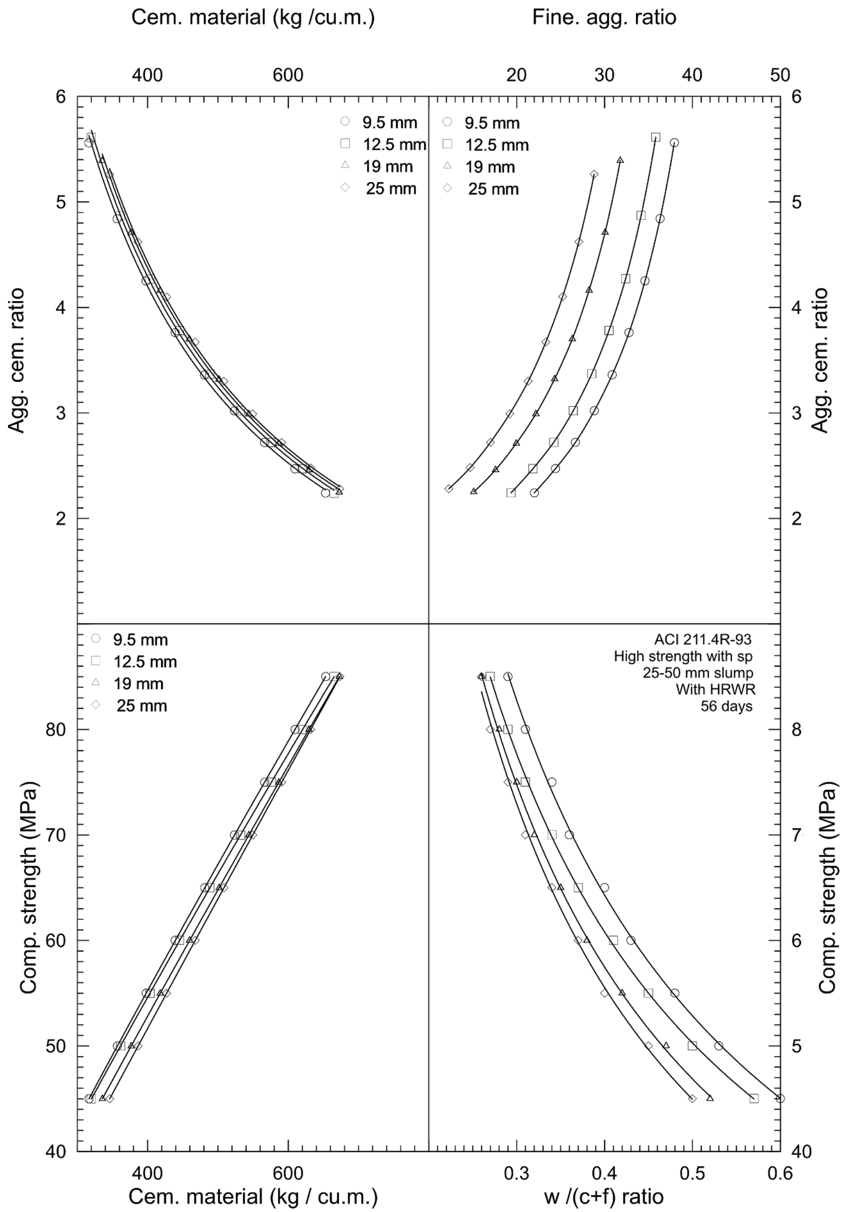

FIGURE HSP-5.4
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 25–50 mm slump, 56 days). (After ACI 211.4, 1993.)

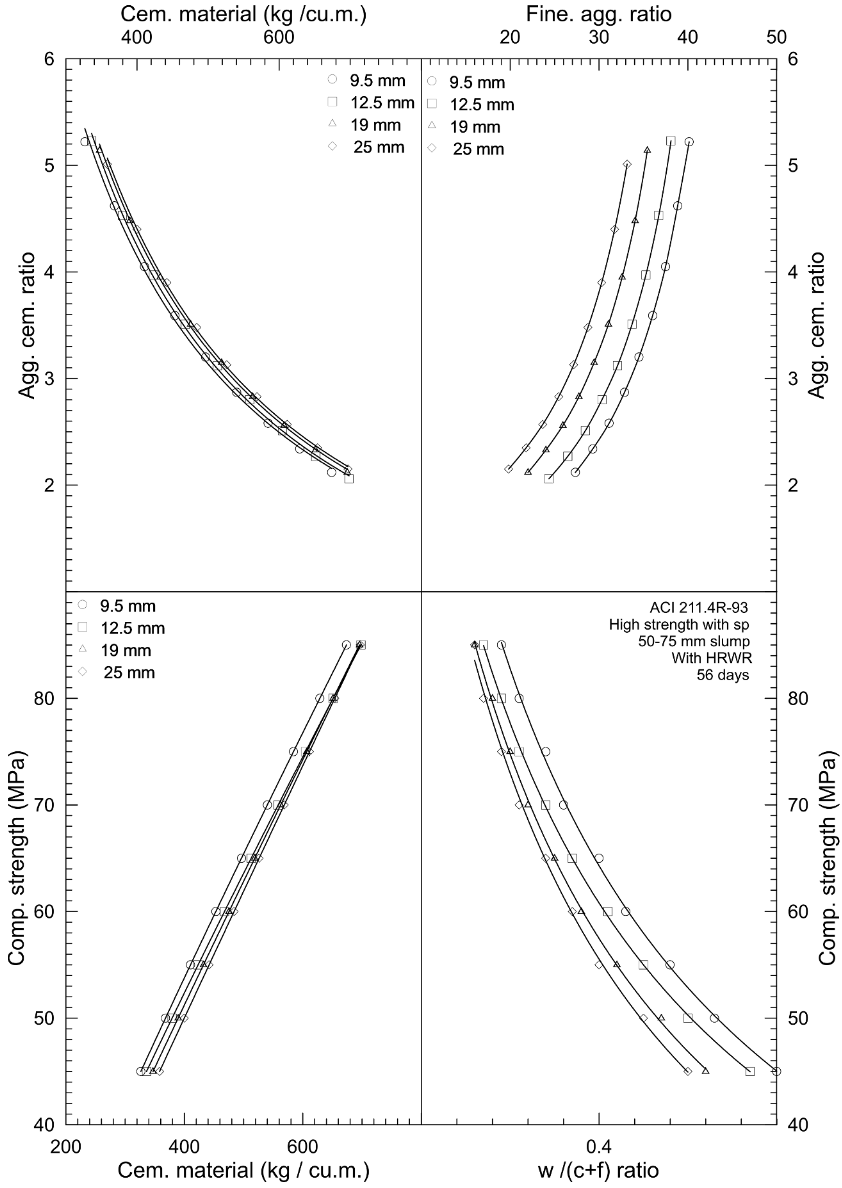

FIGURE HSP-5.5
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 50–75 mm slump, 56 days). (After ACI 211.4, 1993.)

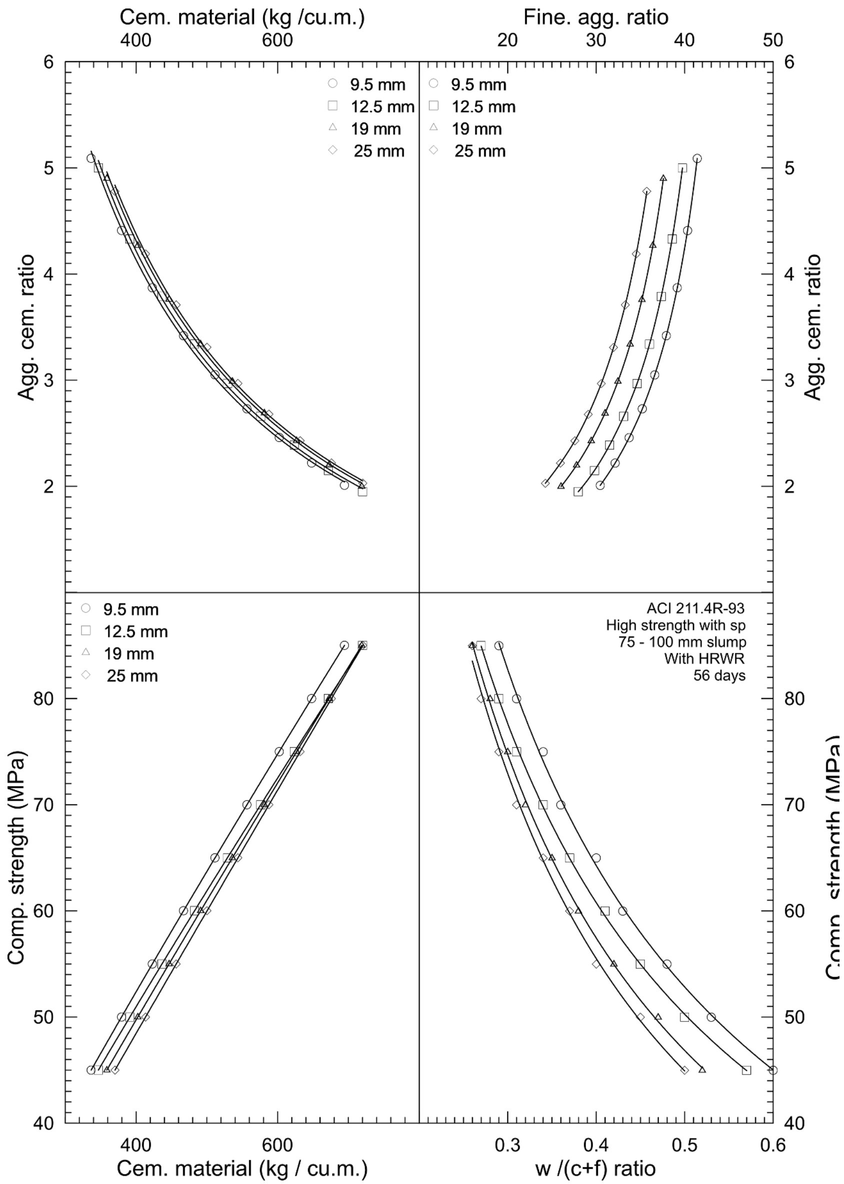

FIGURE HSP-5.6
Nomogram for high strength concrete with HRWR (9.5, 12.5, 19, and 25 mm aggregate, 75–100 mm slump, 56 days). (After ACI 211.4, 1993.)

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6

The British Approach

6.1 Developments and Perspective

Developments toward the concept of the present day hydraulic cements primarily started with the construction professionals in the early part of the eighteenth century in Britain. With its several colonies, the British concrete mix design principles and methodology were responsible for several constructions all over the world and have been the forerunner for many other national recommendations in those erstwhile colonial states. The ubiquitous reference "Road Note No. 4—Design of concrete mixes" (RRL, 1950) is very common in several of these national recommendations. An important and noteworthy characteristic of the British approach is that the design method makes it possible to arrive at compositions for concretes of a specific strength at the different ages. This indeed is the hallmark of the developments that started with the Road Note No. 4 and its modifications to the present DoE method (Neville, 2013), unlike the 28 day strength design of approach by most others. Another important aspect of the British approach, starting even from second edition of the Road Note No. 4, is the importance and the stress that is given to the method of combining the aggregates of different sizes to enforce an overall grading to ensure the highest strength possible for the resulting concrete. The fact that incomplete compaction due to an appropriate consistency can lead to severe loss in strength of the concrete (assessed to be 30% for every 5% air voids in the system) has been recognized explicitly. These early beginnings got modified over the years several times (Mcintosh and Erntroy, 1955; Mcintosh, 1966; Teychenné, 1997, etc.) culminating in the present British method.

After this brief outline in arriving at the provisions of British recommendations for concrete mixture designs, the actual procedure and the recommendations provided therein were looked into explicitly to understand the specific relationships of the various factors involved. It is obvious from the very beginning that the British regulations of concrete mixture designs starting even from the earliest Road Note No. 4 have concentrated on the strength to water cement ratio relationships at the various ages like—1, 3, 7, 28, 90 days and beyond. Obviously, the rate of hydration of the different constituents in cement being time-dependent, the relationships follow different paths.

A brief outline of the possible concrete compositions are also evaluated and discussed. A critical look at the water cement ratio strength relationships proposed by the British method presents a considerable challenge for any mathematical manipulations. The earlier attempts discussed were at best only approximations that could be considered adequate for the normal low or medium strength concrete compositions. An effort was made to look at it from different perspectives and to see if a much broader and more reliable formulation is possible. The broad differences from the earlier American regulations were also discussed.

Incidentally, over the years during its several research activities of concrete composites in the laboratory, a large database of the normal concretes studied within and also those that are compiled as a part of the research efforts was available. In an effort to correlate the strength characteristics of concretes with age, the available database was also used. This could be useful in looking at and projecting the correspondence of the relationships from the database to the British recommendations available.

6.2 Earlier Methodologies

It is quite obvious that the overall philosophy of concrete-like compositions was available even several centuries before the introduction of hydraulic cements. This fact is evident from the lime and lime-pozzolanic constructions of Romans and Babylonians dating back to over 3000 years or even more. In fact one can say that the present cementitious compositions owe a lot to the unsung innovators of these yesteryears. Probably the specific facets of their uncanny ability to design materials that lasted over 2000 years (a standing example of that being the Pantheon in Rome) has not been appropriately understood even today, and many of the present-day so called inventions are in fact reproductions of some of the tenets that are not so clearly and explicitly stated by them.

In this perspective, as already stated, the Road Note No. 4 is one of the earliest efforts that envisages to explain the design of concrete mixtures forming the basis for the modern-day recommendations of several national and international standards. The fact that in those early times itself the importance of workability along with the influence of aggregate grading on the strength characteristics of concrete were being discussed should not be lost sight of. The information contained regarding the method of combining different sizes of aggregates is probably relevant if not of primary importance even in the context of the entire range of concrete mixtures of today. While it may be felt superfluous if not outdated by some to talk about this earlier report, it is obvious that it paves the way for an appropriate and correct understanding of the mix design methodology even today.

The philosophy or purpose of the design of a concrete mixture as stated by Road Note No. 4 (RRL, 1950) is probably the most apt of the definitions—that "in its simplest form, obtaining a concrete of the required strength and workability at the lowest cost, by a suitable choice of materials and of the proportions in which they are used." It also proposes the following basic steps:

- Defining a minimum strength making allowance for its variability,
- Determining the water cement ratio required for the given strength,
- Establishing the degree of workability required for the specific job,
- Arriving at the aggregate cement ratio at the required water cement ratio (for the given strength) and workability considering the grading, size and type of aggregates.

The different values obtained above help in establishing the concrete mixture details. These apart, the specifications lay stress on the grading of aggregates by suggesting both individual and combined aggregate grading along with a procedure for combining the aggregates.

The provisions of Road Note No. 4 include specific water cement ratio to strength relationships at the different ages of 1, 3, 7, 28 and 90 days apart from the long-term strength at one year for both ordinary Portland cement (OPC) as well as rapid hardening cement (RHC), which are presented in Figure 6.1. Another important observation could be that the water cement

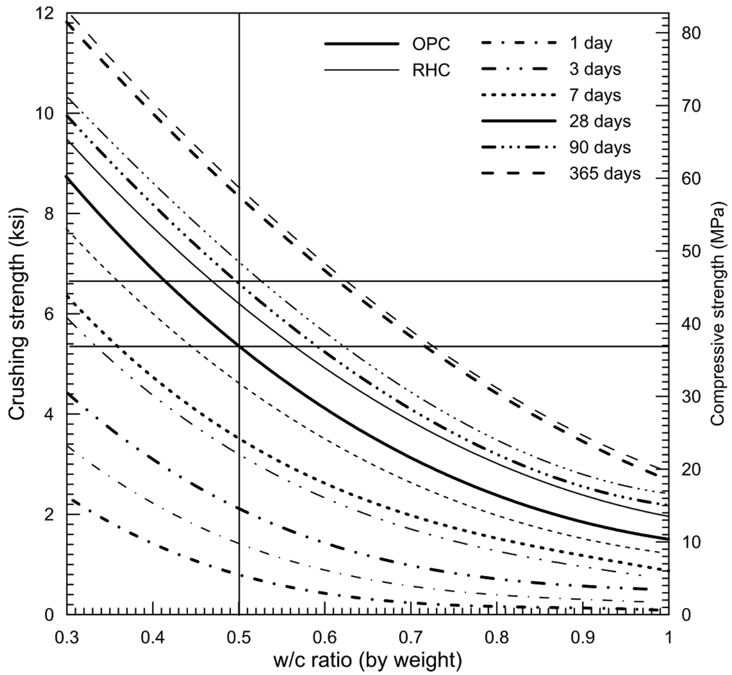

FIGURE 6.1
Strength to water cement ratio relations after Road Note No. 4. (After RRL, 1950.)

ratio to strength relationship as defined suggests the possibility of obtaining strength of about 70 MPa in concrete at 90 days at a water cement ratio approximately 0:30. Compared to the normal concrete regulations in ACI, these values differ both in terms of the maximum strengths and the range of strengths available. A more detailed discussion on the comparison of the different provisions of the various national bodies will be taken up later. However, it is easy to see that at the water cement ratio of 0.50 the strength expected of OPC at 28 days is 37 MPa, which is in line with the 32.5 grade cements of the Euro standards even from the early 50s. The fact that these cements can reach about 46 MPa at 90 days suggest that some of these could even be comparable to the 42.5 grade cements of the Euro standards of today. Some of these aspects regarding the cement strength to concrete strength relationship at a water cement ratio of 0.50 were already discussed earlier.

In attempting to have a clearer understanding of the water cement ratio relationships at the different ages presented, mathematical expressions for each of these have been arrived at. In fact, the variations in the relationships at the lower ages appear to be better defined through a polynomial relationship. Attempts were made to fit a polynomial of the second order and arrive at the possible relationships between the different constants in the form below.

$$f_c = A - B * X + C * \mathrm{pow}(X,2)$$

The variations in constants A, B and C with age as presented in Figure 6.2 as can be seen. The fact that such attempts are possible should be well recognized and appreciated.

After arriving at this water cement ratio for the required strength, the aggregate cement ratio can be fixed based on the workability required for the particular construction for any given aggregate size, grading and type. These values are given in the form of tables for the 20 mm (1 inch—rounded, irregular and angular) aggregates as well as 38 mm (1 1/2 inch—irregular) aggregates. It is felt that the aggregate cement ratios are in general quite well formulated at a water cement ratio of 0.50 due to the fact that concretes at that particular water cement ratio do not suffer from difficulties of compaction. Hence the values of different parameters at the water cement ratio of 0.50 could be taken as the representative values for normalization of the entire set of tables. In view of this, the ratios of different aggregate cement ratios to that at the water cement ratio of 0.50 were evaluated.

The variation of aggregate cement ratio fractions at the different water cement ratios thus obtained are presented in Figure 6.3, which indicates a clear log linear relationship given below.

$$Y = 1.5 * \ln(X) + 2.05$$

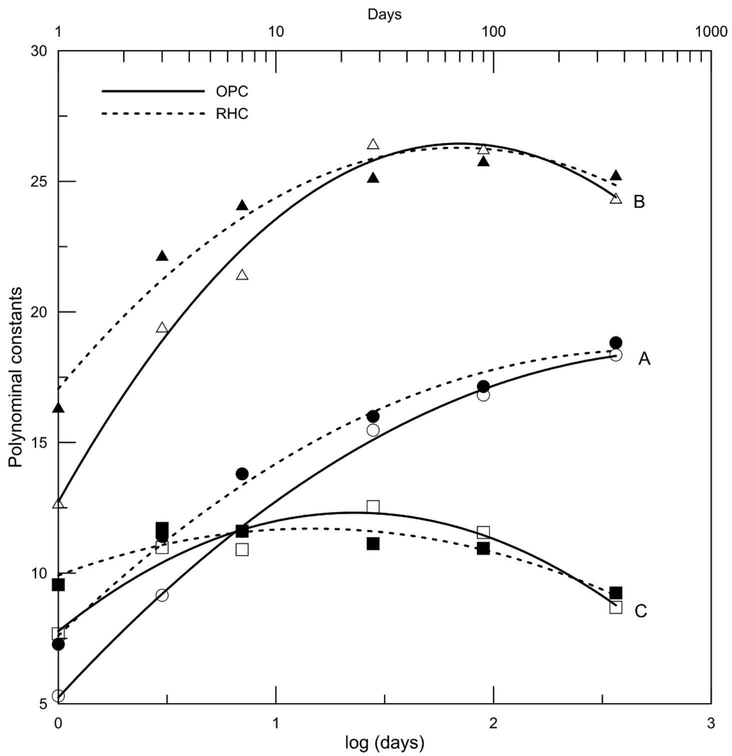

FIGURE 6.2
Constants of strength relations with age in Road Note No. 4. (After RRL, 1950.)

where Y is the aggregate cement ratio fraction and X is the water cement ratio.

The values chosen for establishing this relationship included all those for the different types of 19 mm aggregate size, though the inclusion of that for 38 mm did not make any major changes to the relationship that could be of consequence.

Finally, an important difference considering the concrete mixture design recommendations by the various national organizations is that it includes specific grading curves for both 19 and 38 mm aggregates. The corresponding curves for 10 aggregates were later introduced by Mcintosh and Erntroy (1955) and Mcintosh (1966). Incidentally, there appears to be a fairly smooth variation in the proportions at the different sizes for 38 mm aggregates, while the same cannot be said for the 19 mm and 10 mm sizes (Figure 6.4). Though it is possible to set specific relationships for each of these, the variations that are seen basically prohibit such an attempt. However, it is obvious that the grading of the 38 mm aggregates can be reasonably managed to be having a close relationship with the recommendations, provided the end of values on either side are given a go by as can be seen in aggregate grading

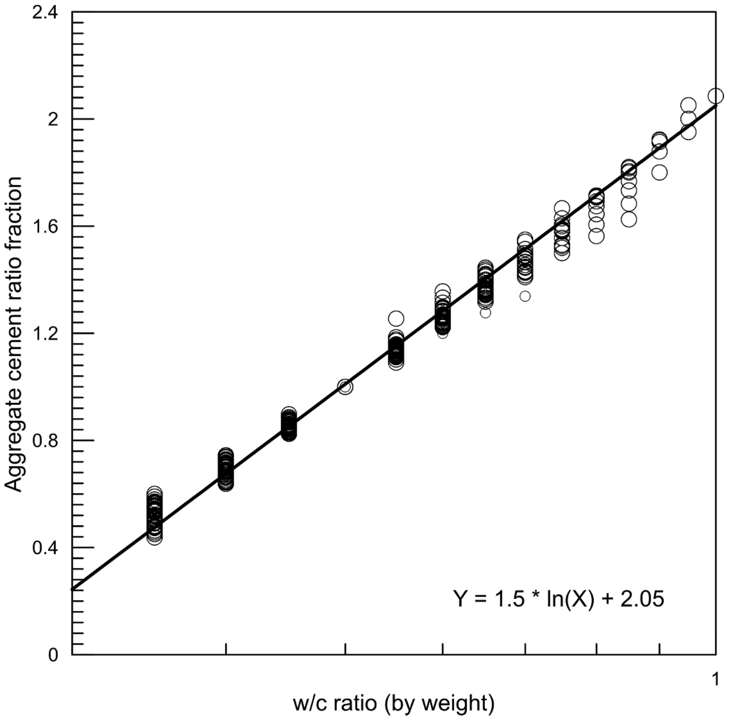

FIGURE 6.3
Variation of aggregate cement ratio fraction with w/c ratio in Road Note No. 4. (After RRL, 1950.)

curve no. 1 for 38 mm in Figure 6.4. Similar relations can be evolved for all the other grading curves at the 38 mm can be written as:

$$Y_1 = 100 * \text{POW}\left(X/70, 0.55\right)$$

$$Y_2 = 100 * \text{POW}\left(X/65, 0.45\right)$$

$$Y_3 = 100 * \text{POW}\left(X/53, 0.40\right)$$

$$Y_4 = 100 * \text{POW}\left(X/45, 0.55\right)$$

where Y_1–Y_4 are the percentage of aggregate fraction passing at the size X for the different grading curves of 38 mm maximum size aggregate.

The present British design methodology appears to follow very similar principles as envisaged in the original Road Note No. 4 methods proposed, though there appears to be a shift in terms of the relationships for water requirements as well as the aggregate proportioning methodology. These will be discussed in the ensuing parts with a view to establish specific relationships even to the modified parameters that have been advocated.

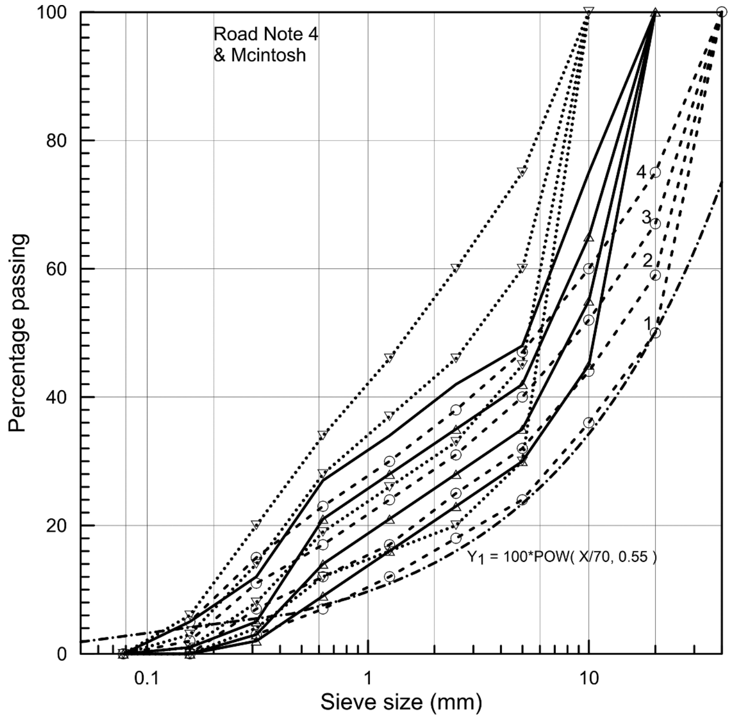

FIGURE 6.4
Combined aggregate grading curves in Road Note No. 4. (After RRL, 1950.)

6.3 An Outline of the British Method

The British concrete design methodology retrained essentially its identity from the time of its earliest publication in 1950 in the form of Road Note No. 4, while undergoing specific modifications. A method for combating aggregates to arrive at specific grading distributions was presented in the second edition (RRL, 1950). Later efforts of Mcintosh and Erntroy (1955) and Mcintosh (1966) introduced the recommended grading distributions for 10 mm. Erntroy and Shacklock (1954) suggested a graphical procedure for higher strength concrete mixes (essentially concretes of strength above 50 MPa) by introducing a parameter called the reference number four relating the strength and water cement ratio.

An early form of the present British concrete mixture design was introduced in 1975, which introduced the concept of specifying the water content requirements for both uncrushed and crushed aggregates at the different workability required, based on the work of Mcintosh and Erntroy (1955). It appears that the principle presumption was, an appropriate combined grading distribution of the coarse and fine aggregates together the water requirement for a specific slump is the primarily factor that depends on the specific surface. A similar approach was also presented by Murdock (1960) through the surface area index. It also contained the proportion of the fine aggregate as a percentage of total aggregate at the different water cement ratios for the different slump regimes for the different maximum size of coarse aggregate. This aspect of the design recommendations clearly indicates the indirect dependence of the fine aggregate content, which will be the most influencing component in the wetted surface area characteristics of the total aggregate mass.

The second aspect of design of concrete mixtures by this method involves the selection of the water cement ratio for the strength required after a due consideration of the variations possible through standard deviation principles. The choice of the appropriate water cement ratio to strength relationship in the present British method changes from the original Road Note No. 4 relations that are based on age to a concept based on the strength of a representative concrete mix at a water cement ratio of 0.50, while accounting for the type of cement and the type of aggregate. It is in a way similar to the already known principle that the cement strength and the concrete strength are indeed the same at a water cement ratio of 0.50 (Walz, 1971). It was also seen during these discussions in Chapter 4 that the cement strength and concrete strength are essentially the same even at 7 days, and one could presume it would remain so at the different ages. Once the water content as a water cement ratio is defined appropriately, the aggregate content is estimated based on the wet density of concrete, which would be distributed as the corresponding coarse and fine aggregates from the fine aggregate contents discussed earlier, resulting in the complete details of the concrete mixture. In the last iteration of its modernization efforts, the British recommendations were modified in terms of the proportioning of fine aggregate percentage of the total aggregate through the governing parameter of the percentage of fine aggregate passing the 600 μm sieve, deviating from the earlier zones for sand prescribed. In brief, the present mix design methodology available can be summarized as presented below. However, the fact that there are superseding or concurrently valid recommendations called the Euro norms (BS EN 206, 2000) makes the entire situation more fluid as there is a possibility of Britain leaving the Euro nations group. The Euro code regulations and the philosophy behind it will be discussed in the next chapter. Even so it is indeed important to understand the basic mechanisms of the available British mix design methodology to get a comprehensive picture of the mix design procedures and the different philosophies that have enabled and driven their formulation.

The British recommendations for the design of normal concrete mixes first came into existence in 1975 (Teychenné, 1975). The corrected version of it was published in 1992 while the second edition of the same came out in 1997 (Teychenné, 1992, 1997). A broad outline of the steps involved in the design of normal concrete mixes in accordance with these can be summarized as the following:

- The first step arrived at the water cement ratio for the required strength depending on the type of cement, its strength to water cement ratio being the guideline for choosing the appropriate curve in the water cement ratio strength relationships.
- The next aspect is to ascertain the water content required for the consistency needed, keeping in view the aggregate characteristics of type and the maximum size. From these two, the cement content can now be established.
- The expected fresh concrete density of concrete for the proposed water content and specific gravity of the coarse aggregate taken from the recommendations helps in establishing the total aggregate content next.
- The fine aggregate proportion in the total aggregate is chosen based on the amount of fines below 600 μm in the fine aggregate, keeping in view the workability, maximum size of the coarse aggregate and the water cement ratio, which are already known. Having defined all the other constituents, the coarse aggregate content can be established. Incidentally, for arriving at an optimum grading of the coarse aggregate in general, the recommendations suggest for 10 and 20 mm aggregates a combination of (1:2) and for 10, 20 and 40 mm aggregates a combination of (1:1.5:3), in case an appropriate combination cannot be ascertained for the aggregate characteristics and distribution.

The specific aspects regarding some of the important parameters that could make a difference to the strength and more importantly the performance of the designed concrete mixtures may need some classifications at this particular stage.

6.4 Aggregate Qualifications

It is quite clear that the British concrete mixture design specifications have an eye on the coarse aggregate grading and distribution of the different components as can be seen by the inclusion of a broad guideline for mixing of the 10, 20 and 40 mm aggregates in it. The more comprehensive and in-depth discussion will invariably result in the later chapters while discussing the requirements of performance. However, it is probably important to recognize and understand the implications of negating the requirements of the combined aggregate grading, which was the hallmark of Road Note No. 4, way back from its second edition. The second aspect that is rather striking in the broader perspective is that the recommendations appear to permit a very large quantity of even 80%–100% sand finer than 600 µm, without any other limits like the amounts finer than maybe 100 µm. This puts a great burden on the appropriate distribution needed for the coarse aggregates in the first place. The very small quantities of fine aggregate proposed may also be insufficient to address interstitial spaces in the coarse aggregate skeleton even if there is a significant quantity of cement to compensate the lower water cement ratios. A relook or even an effort to appropriately address this is essential to ensure a compact mass without serious honeycombing effects or highly permeable concretes. In a way this is a path for the development of pervious concrete (also called porous concrete or permeable concrete) itself, where the matrix is just sufficient to coat the aggregate skeleton to bind it, but yet is insufficient to fill all the interstitial space available. This can of course be further promoted by preferentially avoiding a few specific intermediate fractions to create the interstitial space necessary intentionally.

6.5 Age Effect and Comparison

At first glance, one can clearly see that the different water cement ratio to strength relationships proposed in the British regulations (Teychenné, 1997) are not related to the age as was the case in Road Note No. 4, with which it all started. An alternative presumption could be that it represents the cement strengths, as the preferred curve for relating the strength to water cement ratio is to be chosen based on the strength of concrete at the 0.50 water cement ratio, which was already explained in presenting the strength characteristics of cements as proposed by Walz (1971). In this perspective, it is probably appropriate to see if the available water cement ratio strength relationships in the British regulations may still indeed be representing the variations of the water cement ratio strength relationships with age. Naturally, it is essential to have a reasonable dataset to make such an evaluation possible, and some of these aspects are discussed later after looking at the mathematical modulations possible for the mix design methodology proposed in the British regulations.

6.6 Possible Mathematical Formulations

At the very outset in trying to establish the possible mathematical formulations for an appropriate representation of the British regulations, it is necessary to first look at the complicated picture of the water cement ratio to strength relationships proposed. It actually differs from the earlier tradition of these relationships having to represent the age but yet looks similar. The broad set of possible mathematical relationships attempted appear to show that essentially these curves can be represented not through the exponential equations attempted earlier in the case of ACI regulations, but needed in cubic polynomial to be reasonably accurate.

As a first step, the polynomial relations for each of these curves presented in the British regulations were established. Looking at the possibility of trying to simplify but yet arrive at a coherent set of equations to be reasonably representative, the higher order constants (250 and 75 as can be seen) have been unified to specific values in a few iterations while two constants representing the intercept and the first order (P and Q) have been reassessed through several iterations. The final possible polynomial fits obtained are presented in Figure 6.5.

The two constants (P and Q) associated with the equation for the calculation of water cement ratio strength relationships were then found to be associated with the strength of concrete at the water cement ratio of 0.50 in that equation; the significance of each need not be lost. It appears that in an effort to continue with the traditions established through Road Note No. 4

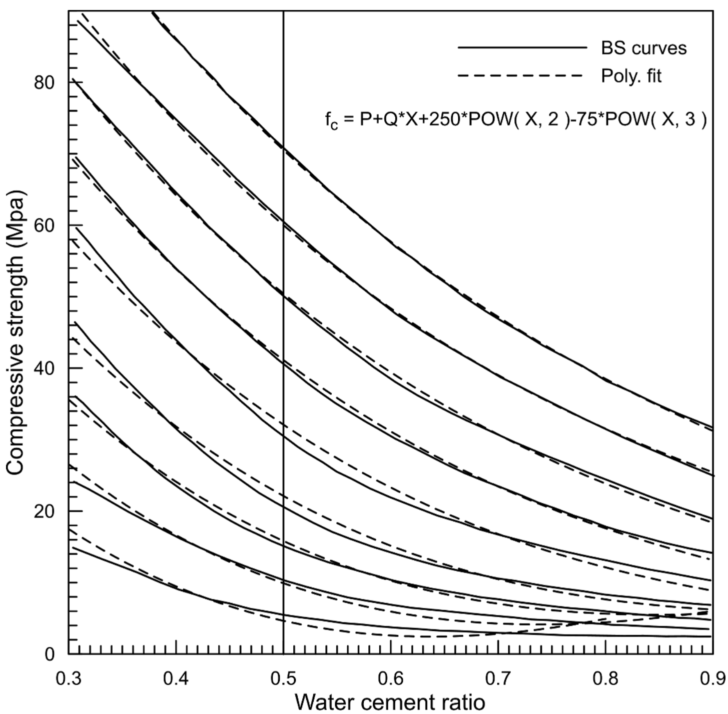

FIGURE 6.5
Water cement ratio strength relationship—polynomial fits (British).

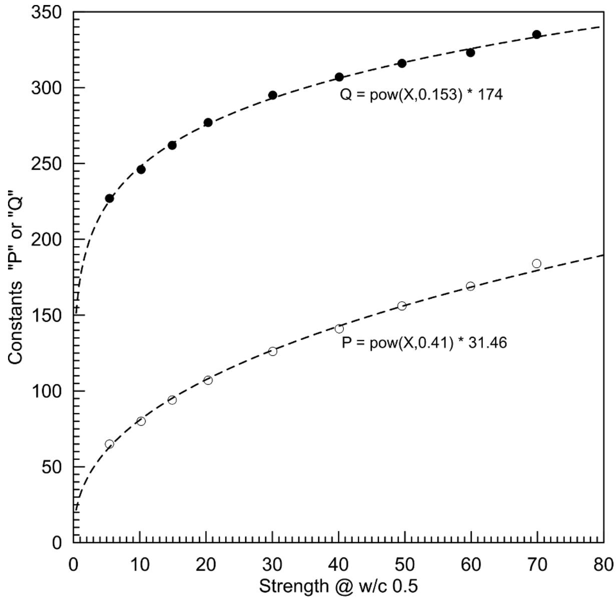

FIGURE 6.6
Polynomial function constants of the w/c relations (British).

but yet to be more compliant to the facts that at the water cement ratio of 0.50 the strengths of both cement and concrete are nearly the same as established by Walz (1971), the British regulations for concrete mixture designs appear to have struck a via media by amalgamating both the philosophies. The root constants (P and Q) appear to be varying as shown (Figure 6.6). The resulting polynomial representation of the British relationships are also plotted in Figure 6.5, clearly indicating that the variations as can be seen appear to be less than 1 to 2 MPa throughout the assessment.

It is indeed a fact that the water cement ratio strength relationships over the years have been presented in several different types of functional relationships, starting with the power relationship by Abrams (1920). Maybe if one looks at a much larger spectrum of the water cement ratio strength relationships possible, particularly the lower end (far below the 0.3, reaching up to 0.15) of the power relationships may be a much better choice. But in the present context the concrete mixture designs of that particular type, essentially with the use of the most modern water reducers and high-efficiency pozzolanic admixtures, are not a matter for discussion and as such are not being presented. A brief look into the representation of the present British relations for water cement ratio to strength appear to show that the bottommost curves representing the very low strength concretes or concretes at very early ages seem to agree with some possible power relationships, but the more mature concretes of higher strengths we will be highly overestimated at lower water cement ratios by any such attempts to represent them by power relationships.

There have also been some simplifications attempted through the use of the cement water ratio to strength relationship to arrive at possible linear relationships, though valid over a very limited range of cement water ratio as discussed in some of the earlier chapters. There have been others who suggested a log linear relationship for the water cement ratio strength characteristics of normal concretes (Popovics, 1998) as was seen earlier. There are others who suggested a bilinear character for these log linear relationships that can presumably even more emphatically be attributed to the inadequate compaction possibility and the consequent loss of strength in such concretes at the lower water cement ratios, causing the bilinearity as observed (Popovics, 1998; Dewar, 1999).

In fact the most obvious relationships that could easily be established for most of the water cement ratio strength relationships is probably an exponential function that will limit the strength values to reasonable levels, maybe to effectively compensate for non-compactability of the mixes at the lower water cement ratios. In a way it is the same as the log linear relationships that were hitherto presented above. With this perspective the possible exponential functions for each of the curves in the British regulations were reassessed. The general trend in the variation of the two constants representing the multiplier and the exponent was readjusted appropriately, and the functions will be established. Representations of the effects of such an effort to have a progressive set of curves along with the original British relationships are presented in Figure 6.7. The variation of the corresponding

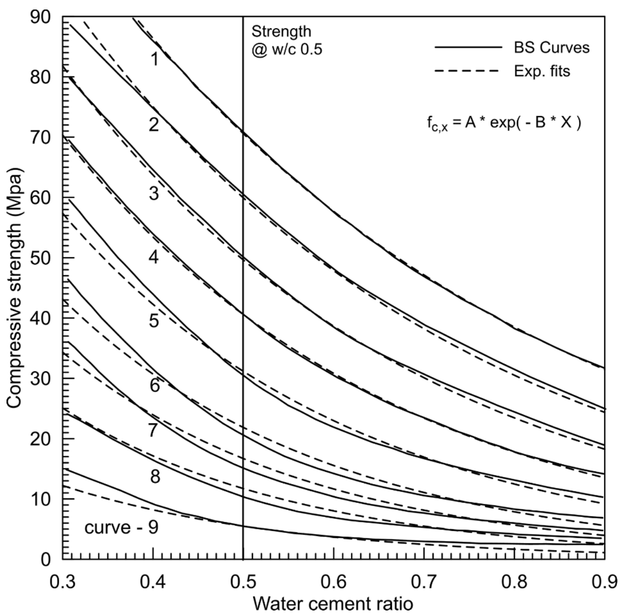

FIGURE 6.7
Water cement ratio strength relationship—exponential fits (British).

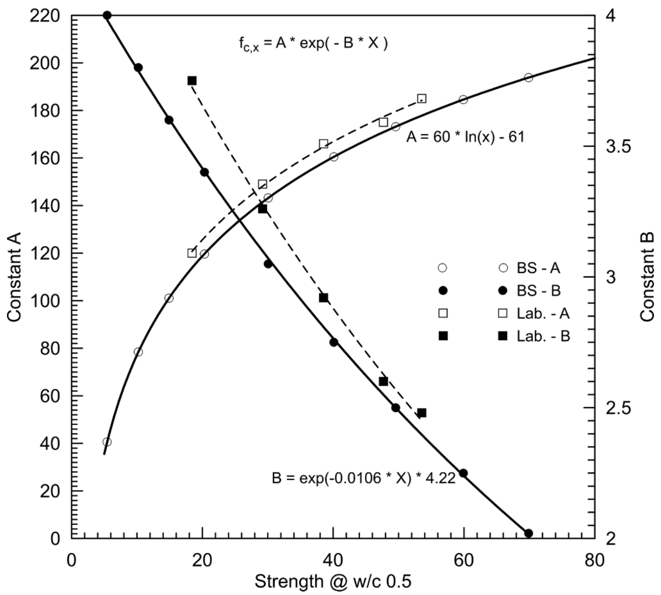

FIGURE 6.8
Exponential function constants of the w/c relations (British).

constants with the respective water cement ratios at 0.50 for the functions generated for the various relationships were presented in Figure 6.8. These two representations of the British regulations through either the polynomial or the exponential functions as shown and the constants associated with them will pave the way for an effective mathematical representation of the complete scenario of the strength to water cement ratio relationships as given. The representations were enforced to be broadly on the conservative side, which may underestimate the strength by about 1 or 2 MPa, at the most.

While the report discussions present a way forward for a mathematical representation of water cement ratio strength relationships presented by the British regulations, it is still not clear if they represent these functions as variations with age or they were meant to be only the representation of the cement strength. In principle, cement strengths below 25 MPa have no real significance in the present day world, though they may still be valid for low grade masonry cements or maybe even lime mortars. To have a clear picture of what these relationships represent, an effort was made to compile the water cement ratio strength relationships of the experimental investigations in the laboratory. In fact, having tasked itself for over three decades toward the development of very high strength, high-performance concretes with several different chemical and mineral admixture combinations (including the ultrahigh performance concretes), the laboratory indeed had broad spectrum of results on concretes of various types. Also the laboratory investigated as a part of its academic and industry interactions several other cements that are produced in the country for their effectiveness in concrete as desired by some of the major cement producers and compared characteristics of normal cements with the pozzolanic counterparts made with the same clinker. For this investigation, only the concretes that correspond to the specifications of normal concretes without any pozzolanic admixtures were chosen for comparison. These consisted of nine series containing different normal concrete compositions of varying strength to water cement ratio as can be seen in Figure 6.9. It may also be noted that the laboratory also made an assessment of the pozzolanic strength efficiency of the several mineral admixtures, and comparisons were made with similar concretes that were available from literature. In making an assessment of the efficiency of concretes with mineral admixtures from literature, the comparisons were invariably made only with normal concretes from the same investigations to ensure an authentic representation of the pozzolanic efficiency, without being influenced by the characteristics of the cements in general. Figure 6.9 also contains the 28 day water cement ratio strength characteristics of the normal concretes that were compiled as a part of the investigations on fly ash (Rao, 1996), ground granulated blast furnace slag (Sree Rama Kumar, 1999) and silica fume (Prakash, 1996), to ensure the authenticity of the relationships proposed. It is also to be clearly stated at this particular stage itself that this particular expression for the 28 day strength of the different water cement ratios is exceeded by almost 60%–70% of the results

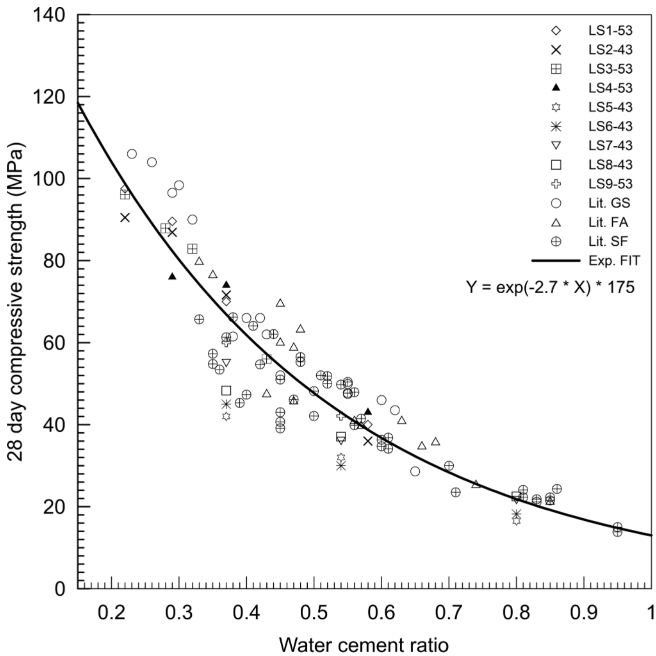

FIGURE 6.9
28 day water cement ratio strength relationship (Laboratory).

with values exceeded by about 5–10 MPa in most cases. The upper bound equation with only about 20% exceedance was also looked at, but for reasons of abundant safety in ensuring the required strength, the present equation was presumed to be the best representation of the 28 day strength.

It is to be noted that similar water cement ratio strength relationships at all the ages of 1, 3, 7, 28 and 90 days have indeed been established and recorded. However, to ensure reasonable flow of the discussions and the continuity, the complete set of graphs that correspond to these presentations have all been given at the end of this chapter in Appendix LAB-6. The corresponding mathematical expressions as can be seen are presented in the graph itself as is generally the case in the present context throughout this compilation. Even in the case of each of these mathematical expressions, it was ensured that the proposed equation in general is a safe lower limit and has enough potential to be exceeded in most cases where the concretes are adequately formulated and compacted. The earlier discussions clearly show that this effort was undertaken to have a relook at the British recommendations, essentially to see if they could be attributed to the relationships at a specific age if possible through comparison with the present laboratory investigations. Figure 6.10 presents a comparison of such minimum possible strength assessments at the various water cement ratios for the different ages as can be seen. The graph clearly indicates that laboratory relations established follow the general

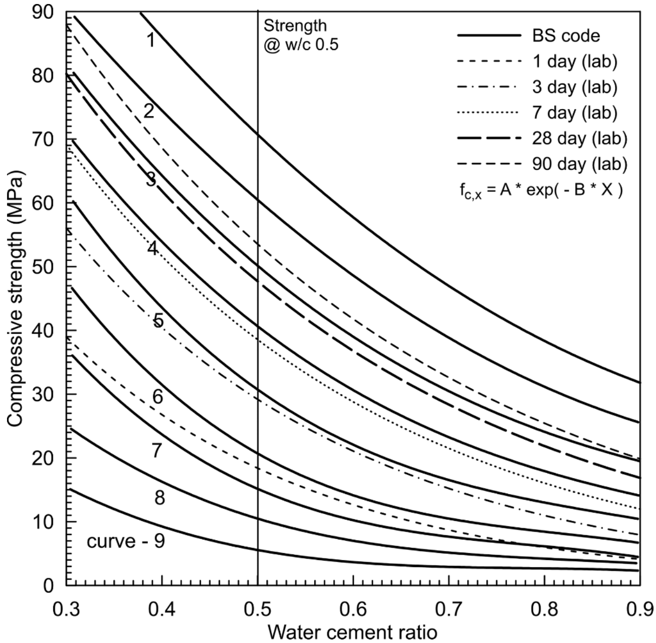

FIGURE 6.10
Water cement ratio strength relationship—exponential fits (British).

trend as envisaged by the British regulations. A more specific look also presents that the curves 6, 5, 4 and 3 could be considered a fair representation of the 1, 3, 7 and 28 day strength to water cement ratio relationships, particularly considering the exceedance levels of the results of each of the laboratory relationships compared. The 90 day strength relationship alone was found to be fairly short of the expected strengths as in curve 2. In specific, the 28 day strength characteristics at the different water cement ratios appear to coincide with curve 3 for all practical purposes, and can be chosen as their representative relationship for normal concretes. It also appears that the strength of the cements as seen from the strength of concretes at 0.50 water cement ratio could well be 50 MPa and will be used as such in all future discussions. A close relation between the laboratory and the British code relationships could also be seen from the close proximity of the exponential relationship constants (A and B) established for the laboratory results of the various ages, which were compared to the British in the earlier Figure 6.8.

After having looked at the w/c relations at some length, the possible modeling of the other design parameters was studied critically. As a first step, the variation of the strength characteristics with age for the two cements (OPC and RHC) at the water cement ratio 0.50 as proposed by the British regulations were looked at, establishing relations between the strength of any age to that at the 28 day. One could see that this follows almost a log linear relationship with age as is normal in the strength development of cements in general (Figure 6.11).

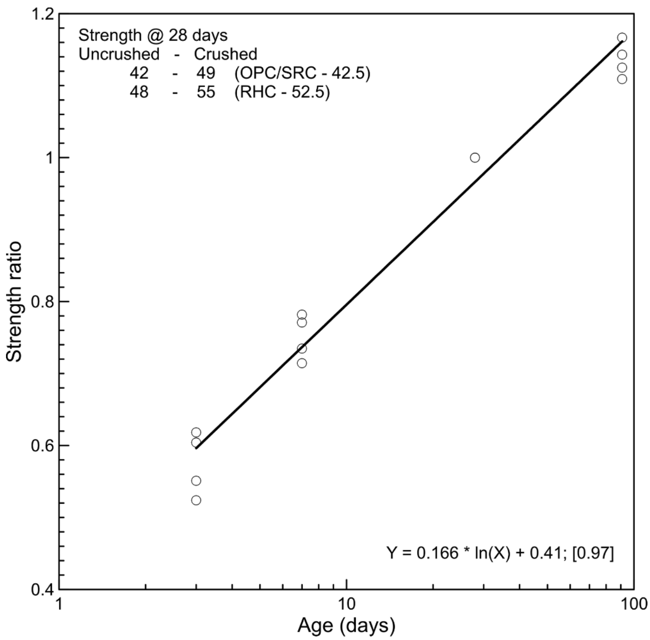

FIGURE 6.11
Relative variation of strengths with age of the different cements.

The predictions appear to show that the maximum variation resulting could be within 1–2 MPa. It is also to be noted that the rapid hardening cement (RHA) as referred to in the previous discussions could be treated as the 53 grade cements of the Euro norms presently.

The British regulations also provide an approximate estimate of the water content required for a given level of workability (defined in terms of the slump and VB time) for the different aggregates sizes. Considering that a slump of 60 mm is adequate for the compaction in general, the ratios of the water cement ratios compared to it are plotted against the proposed slump values. The relationships were found to be linear as can be seen from Figure 6.12. A modified relationship to arrive at an appropriate average consistent with both the types of aggregates is also presented as can be seen. With the water content and the water cement ratio defined for the requirements of concrete to be used in the application, the cement content can be established directly. Naturally, both the water cement ratio and the minimum cement content associated with the concrete should conform to the environmental requirements in which the structure is supposed to perform.

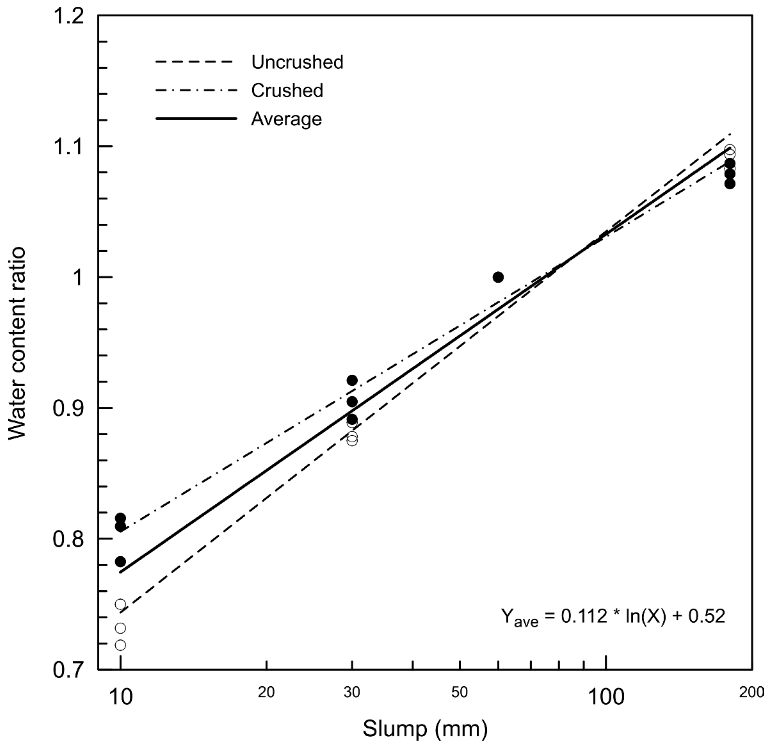

FIGURE 6.12
Variation of water requirement with slump (British).

The next step in the design of concrete mixtures presently through the British regulations is to establish the density of fresh concrete based on the appropriate specific gravity of the combined aggregates (crashed or uncrushed). The constants of the relationships recommended by the code appear to show that they follow a linear relationship facilitating an understanding of the fresh concrete density variations with the specific gravity of the combined aggregates at the different water contents, though the possibility of an extension to levels beyond 3.0 specific gravity have to be ascertained. In any case, such an estimate if required is not very long to compute as the water content and probably the corresponding cement contents are already known and assuming the specific gravity of the combined aggregate, the remaining volume is simple to arrive at (Figure 6.13).

The final step in the design of the concrete mixture is to have a fix on the fine aggregate percentage for a given water cement ratio. Even at the very outset, the idea of trying to put together a mathematical formulation that could put a fix on the fine aggregate percentage at the different slumps with varying finenesses of sand (five different percentages of material passing 600 μm) for all the three maximum sizes of the coarse aggregate was known to be a difficult task. Even the idea of summarizing the requirements for one single maximum size of the coarse aggregate will need the compilation

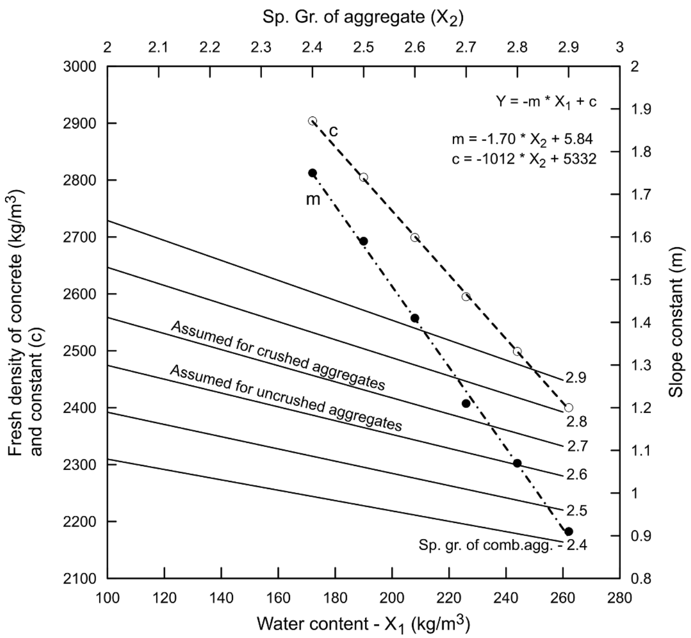

FIGURE 6.13
Variation of fresh concrete density with specific gravity of aggregate.

of the possible variations of 20 types of fine aggregates. In view of this, it was proposed to look at integrating the relationships for a single slump of 60–180 mm for the universally utilized 20 mm aggregates of the British regulations. The variation of the two constants associated with the linear relationships representing the sand passing 600 μm is presented in Figure 6.14. Similar relationships can be evaluated for all the other cases presented in the British regulations.

The above steps present a brief outline of the concrete mixture design principles propounded in the British code as well as the possible mathematical manipulations for the same. In some way the present effort throws light on the design methodology and its appropriate modulation. However, even after such a careful consideration of all the various parameters that would influence the performance of the designed concrete mixtures, the British regulations incidentally suggest that the resulting concrete mixture be verified and modulated through trial mixes. The experience in the laboratory shows that most of the concrete mixtures designed appear to conform to the expectations and may even exceed the constituents if carefully chosen.

Without going into serious details of how and why or the alternative possibilities for modifying concrete mixtures to accommodate pozzolanic admixtures, it should be recognized that the British code provides simple

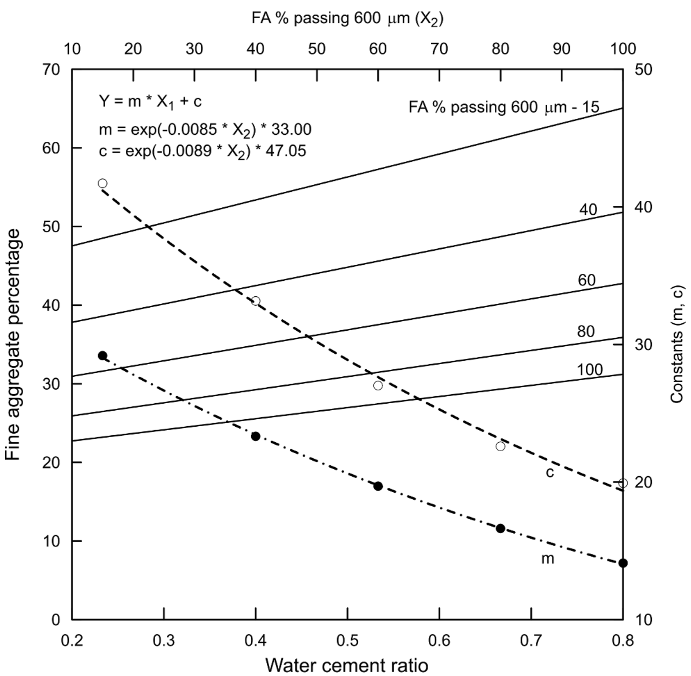

FIGURE 6.14
Variation of fine aggregate percentages with 600 μm parsing materials.

modifications to arrive at some of these concrete mixtures. Modifications essentially suggested related to the effects of air entrainment, the addition of the mineral admixtures pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS). It is only appropriate to discuss maybe ever so briefly the how of these modifications and their implications to complete these discussions.

Air entrainment is an effective methodology to reduce the effects of frost and deicing salts. Air entrainment through chemical admixtures could also improve workability, and the code suggests entrainment levels ranging from 3% to 7%. One important factor that should be recognized is that for every 1% increase in volume of air entrainment there is invariably an approximate loss of about 5.5% in the compressive strength. However, experience in the laboratory appears to show that the commonly entrapped air that is normally a part of the type of concrete mixture (varying with several parameters like consistency, cementitious materials content and maybe even other admixtures live plasticizers), if it could be reworked to accommodate the effects of air entraining admixtures in very small quantities, could impart substantial beneficial effects to the performance of the concrete.

The second modification that is probably universally sought is the incorporation of fly ash or the pulverized fuel ash as is specified in the British regulations. At the very outset, the most important observation could be that the code provides for reductions ranging from 5% to 30% depending upon both the PFA content and the consistency level at which it is being attempted. It is to be recognized that this beneficial effect is actually not just due to the spherical nature of the pulverized fuel ash as generally envisioned, but could also be the effect of the increased fines that are required to compensate for the percentage of cement that is being replaced. In fact, the code introduces the concept of efficiency, indeed very aptly, and while recognizing that the efficiency factor "k" could vary from 0.20 to 0.45, suggests a conservative value of 0.30 at all the replacement percentages permitted. The British regulations site some of the earliest works on fly ash, justifying the recommendations (Smith, 1967; Hobbs, 1980).

A more detailed and probably accurate assessment of efficiency of fly ash in concrete was already attempted in the laboratory (Ganesh Babu, 1992) and will be briefly discussed in some of the later chapters. In some of the earlier attempts, the nomograms corresponding to the concrete mixture designs containing the few levels of fly ash were attempted, but these are not being presented, as it is possible to convert the normal mixture design constituents calculated from the normal concrete nomograms without much difficulty through the cementitious efficiency factor "k" presented earlier. In simple terms, the cement replays should be compensated by effectively ensuring that the cementitious efficiency of fly ash replaced will account for the cement replacement level. Naturally, the specific gravities of cement and fly ash being far too different, the volume of fly ash will be much larger than the volume of cement being replaced and will have to be accounted for in the absolute volume method while calculating the weights and volumes of the constituents.

The final modification that the British code presents is the methodology to incorporate GGBS in the cementitious matrix. The effectiveness of GGBS in improving the sulphate resistance and resistance to alkali silica reactivity apart from reduced temperature rise in concrete have been accepted. The code allows for the direct replacement of 30%–50% while recognizing that replacements up to 70% are possible. It is also to be recognized that the suggested replacements are indeed direct mass for mass replacements, indicating the fact that the cementitious strength efficiency of the GGBS is about 1.0 at all levels. The possible requirement for the readjustment of the mix constituents to comply with the absolute volume calculations of the final design mix is obviously necessary.

6.7 A Simplified Solution

The British concrete mixture design methodology is indeed a very cohesive and condensed summary of the several possible mix design requirements in the industry, unlike the American regulations which look at each specific concrete type (even some of the minor variations, but for the variations in the consistency and the maximum aggregate size) with a different perspective and proposes a specific methodology. While there is obviously a broad continuum in the overall philosophy, probably for reasons of being specific to certain industrial utility, they are clearly subdivided and presented. While this has of direct relevance to specific concrete composite, the fact is that the overall perspective is still not conveyed directly to the user, while this is kept in the background by the formulators. The British philosophy of the design of concrete composites appears to contrast with the American method in more than one way by prescribing a broad outline philosophy that will ensure an understanding of the fundamental principles for such a design. Each of these have their proponents and the adherents in the community.

Just as it was the case in presenting the ACI recommendations, attempts were made to effectively follow the design methodology and assemble a computer program based on the recommendations and a few of the mathematical formulations in each of the discussions. As we have already discussed, the broad outline of searching a program structure is already available in Chapter 5, and the same is not proposed appended once again. However, it may be more appropriate to present a few normal concrete mixture designs in the form of nomograms to help as a ready reckoner to the field practitioner. It may also be a guide to the academic and research community to compare the various possibilities and arrive at the broad understanding of the different constituents in the mixture for the investigation on hand. A typical nomogram of the series representing normal concretes design in accordance with the British regulations is presented in Figure 6.15. An effort was made to condense the information to fit into a

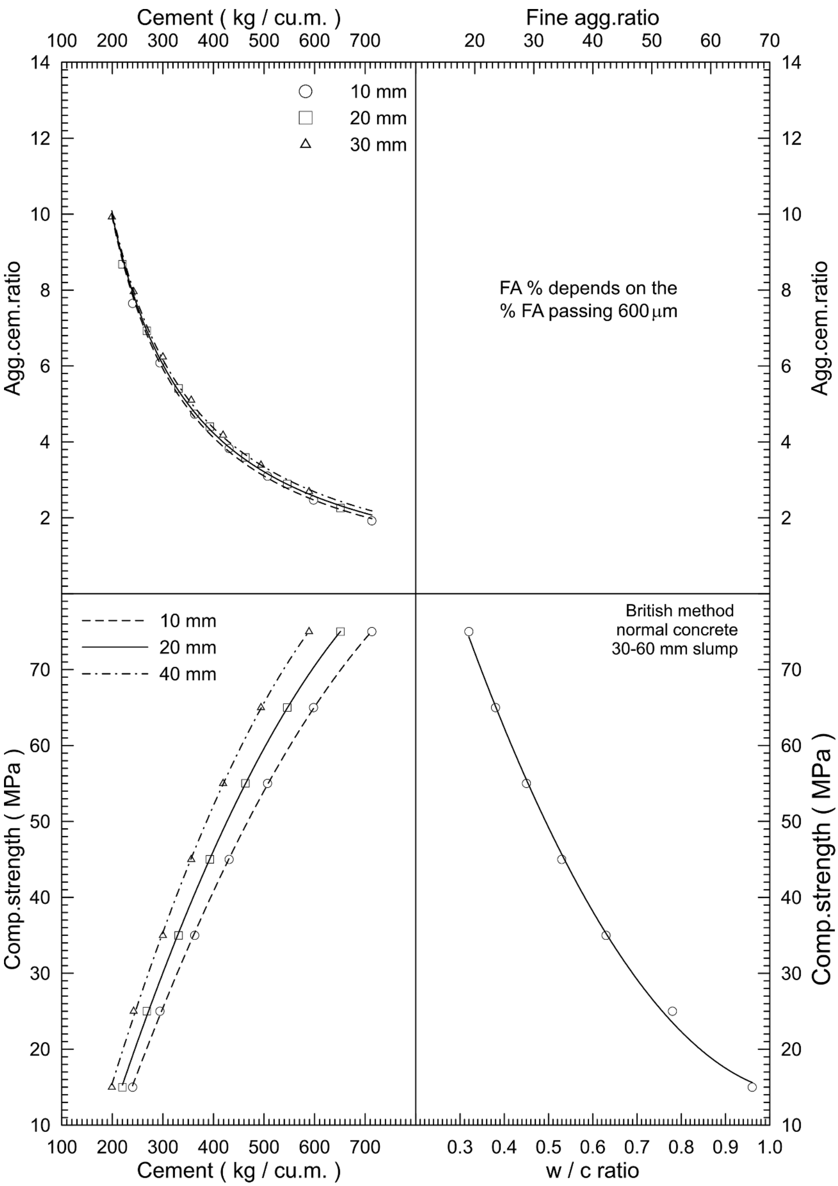

FIGURE 6.15
Typical nomogram for normal concretes (British).

simpler format. But considering the four different slump regimes that have to be addressed along with the possible modifications and aggregate characteristics, it was felt essential to present them clearly in the appendixes at the end chapter. Appendix BSN-6 (Figures BSN-6.1 to BSN-6.4) presents the variations in the constituents of normal concretes of different strength. Even so, the top right quarter which was earmarked for the fine aggregate quantity assessment was left blank as the number of possibilities for selecting that amount to a total of 20 lines, which is impossible to discern in any way in the graph.

An important factor in attempting to present the possibility of such nomograms in specific is the fact that it is possible to generate similar charts and nomograms for the day-to-day working and quality assurance purposes in ready mixed concrete plants or for very large construction projects that usually have a consistent supply of very closely regulated and similar material constituents to justify such an attempt. In such a case, the quadrant left without filling could also be appropriately calculated and presented.

6.8 Relevance and Potential for Practical Applications

The British regulations appear to be a comprehensive representation of the concrete mixture designs in all the various facets possible in general. Its important contribution is probably in accommodating the effect of age as a parameter in the concrete mixture design, which in general is not commonly available. It can also be said that the recent modifications seem to accommodate the cement strength characteristics as well. Naturally, by defining the wet density of concrete, it provides an insight into the effect of aggregate density on the concrete weight, paving the way for designing concretes of higher density required for the various practical applications—like counterweight mass for cranes, specific machine foundation requirements as well as nuclear applications. One surprising fact that probably needs some thought is that the different consistencies at which the regulations were attempted continues from 0 to 180 mm of slump. Maybe suggesting slump regimes of the close band (particularly the last regime of 60–180 mm) appears to be more of a necessity. Another important factor is the recognition that fly ash contents of up to about 50% and GGBS levels of as high as 70% are indeed a step in the right direction. Most of these will pave the way for an appropriate and effective utilization of the cementitious compositions in a large arena of concrete applications in practice.

Appendix LAB-6

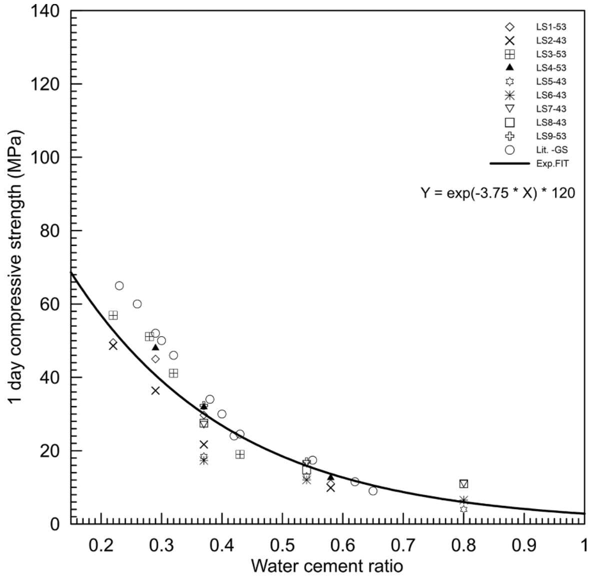

FIGURE LAB-6.1
Water cement ratio strength relationship (Laboratory, OPC, 1 day).

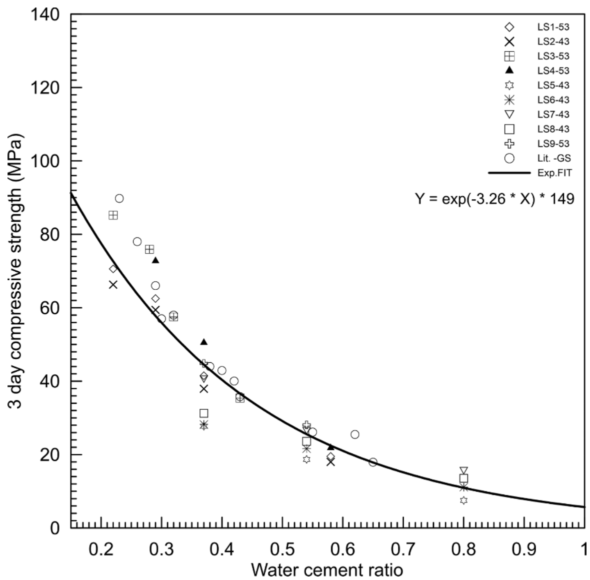

FIGURE LAB-6.2
Water cement ratio strength relationship (Laboratory, OPC, 3 day).

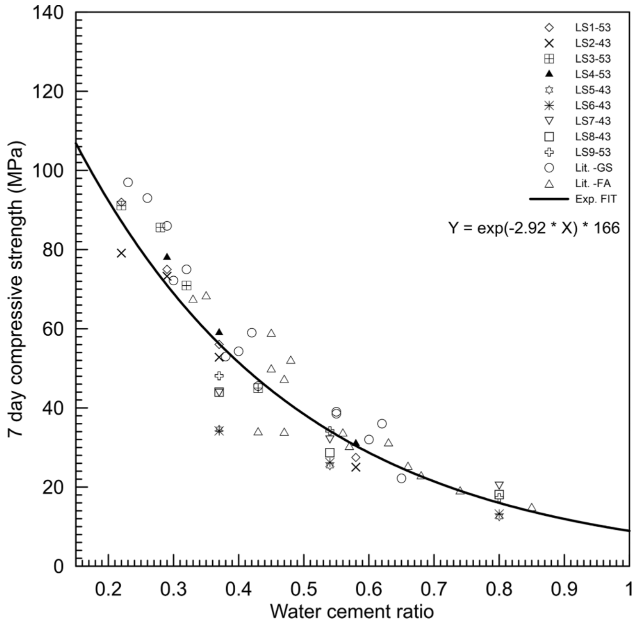

FIGURE LAB-6.3
Water cement ratio strength relationship (Laboratory, OPC, 7 day).

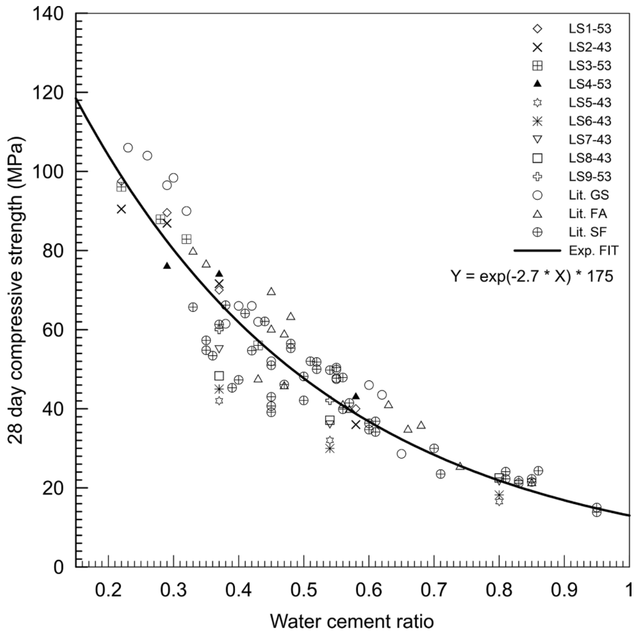

FIGURE LAB-6.4
Water cement ratio strength relationship (Laboratory, OPC, 28 day).

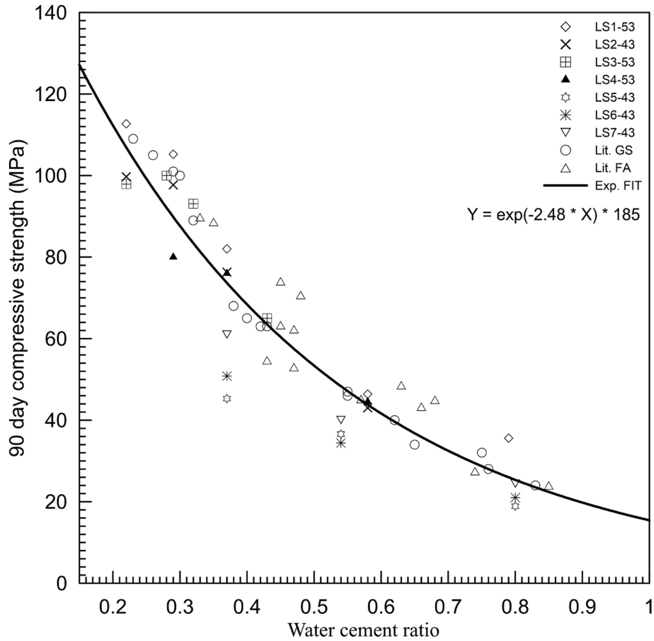

FIGURE LAB-6.5
Water cement ratio strength relationship (Laboratory, OPC, 90 day).

Appendix BSN-6

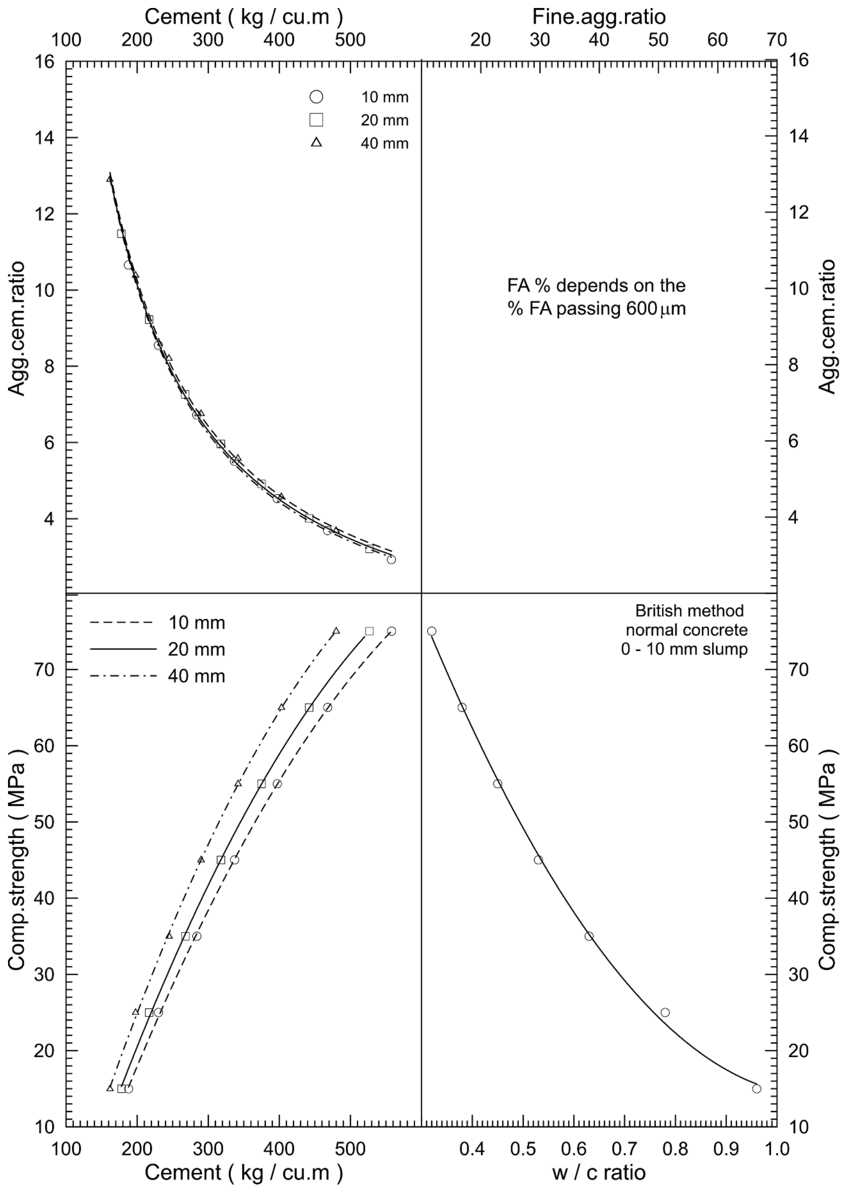

FIGURE BSN-6.1
Typical nomogram for normal concretes (British) (10, 20 and 40 mm aggregate, 0–10 mm slump).

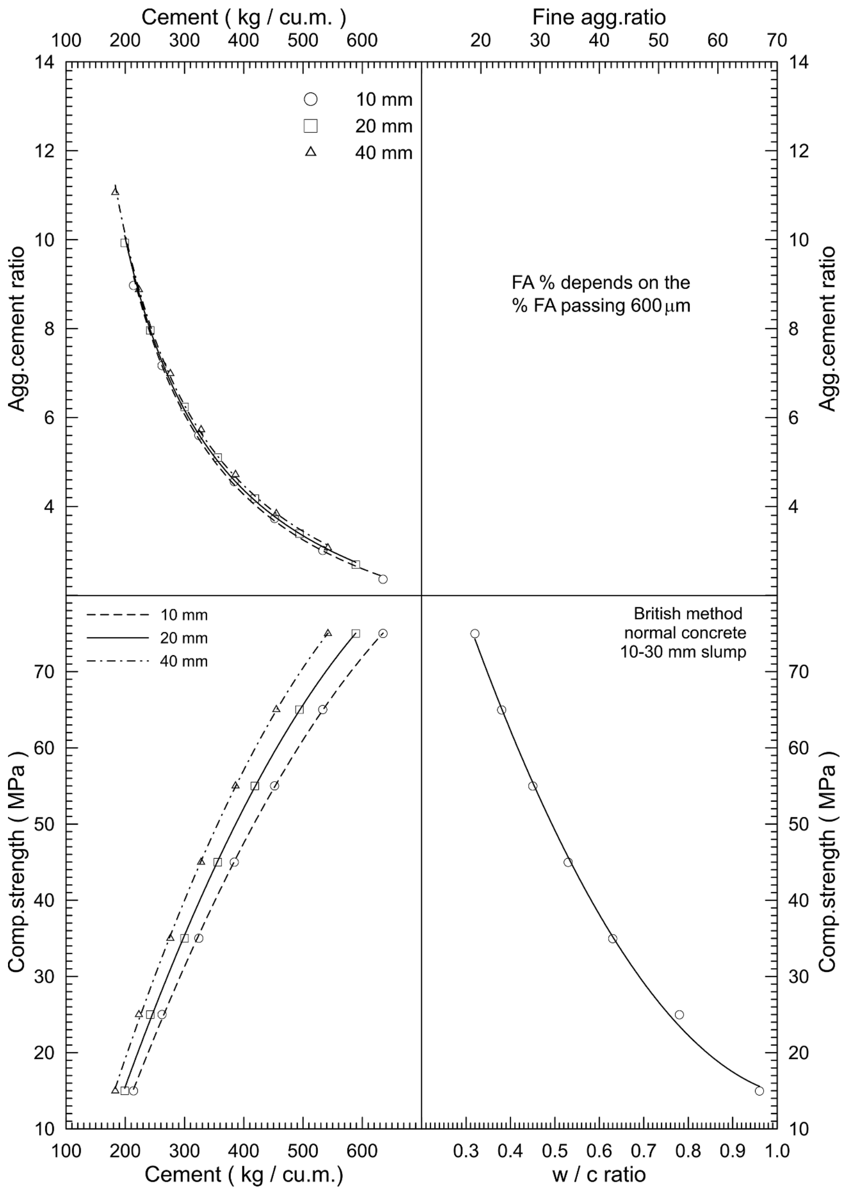

FIGURE BSN-6.2
Typical nomogram for normal concretes (British) (10, 20 and 40 mm aggregate, 10–30 mm slump).

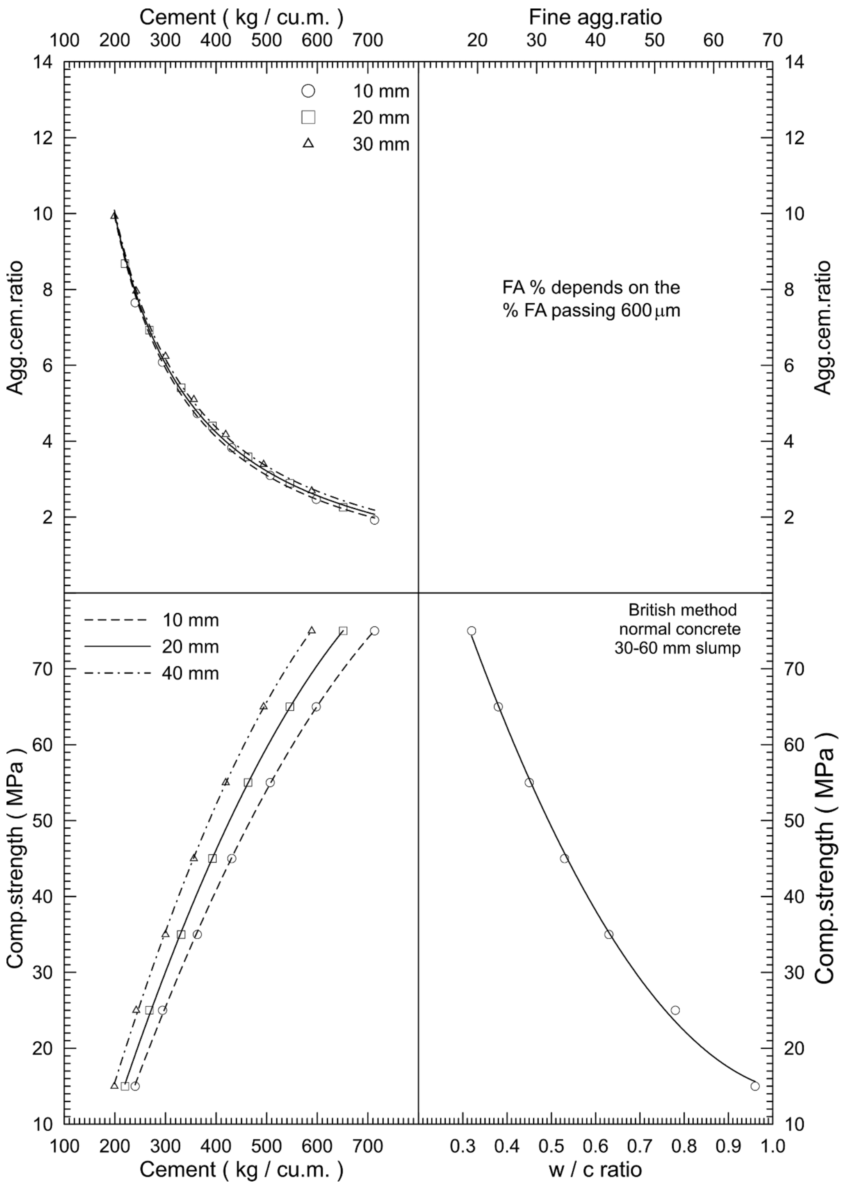

FIGURE BSN-6.3
Typical nomogram for normal concretes (British) (10, 20 and 40 mm aggregate, 30–60 mm slump).

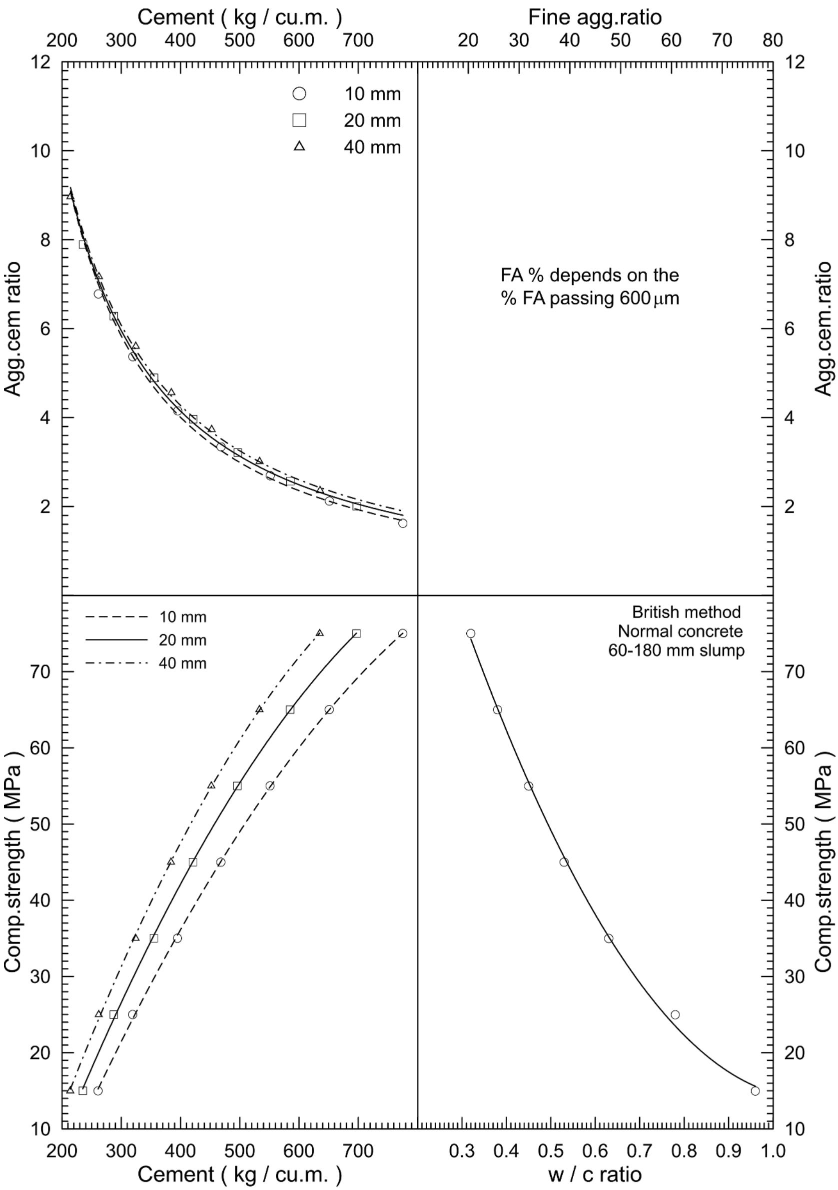

FIGURE BSN-6.4
Typical nomogram for normal concretes (British) (10, 20 and 40 mm aggregate, 60–180 mm slump).

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7

Euro-International Vision

7.1 Design Viewpoints

Starting from the earliest developments into the concepts of even the lime based cementitious materials, European thought has influenced the structural construction scenario in a significant way. Also, traditionally these come from the old school of thought and culture backed by millennia of background exposure of a fundamental nature. A very large number of mathematical models that exist all over the world in the various scientific and engineering regimes have their initiations from here. The several innovations and modulations in the cement and concrete scenario had the benefit of the developments from the divergent national standards with individual thought and experience. Most of the Euro standards of the present day have had a profound influence and also probably evolved largely from the earlier German DIN standards. The present chapter, while explaining the mix design principles of the Euro norms, tries to relate these to the others appropriately. Having presented these factors, the chapter also tries to look at the concrete compositions that will result from these recommendations. As is the primary aim of this effort, a later chapter details some of the mathematical formulations that can be proffered for the existing Euro norms in general. Having looked at the most prominent of the national recommendations that have influenced the thought, design and methodology from the three fundamental perceptions from the three different regions, it was felt that probably a brief overview of the recommendations of the other national bodies is only appropriate. In this context some of the recommendations from India and a few other countries are also reviewed. The consistencies as well as the inconsistencies in absorbing and assimilating the information available from various researchers at the recommendations of the previously described national bodies was also brought to the fore.

7.2 The German Norms

One of the most comprehensive reports containing the complete information along with the background for production of concrete according to DIN 1045 (1988) is probably the report by Walz (1971). Some of the concepts and the broad classification of cements of different strengths have already been explained in Chapter 4. In a way the discussions in this chapter explaining the concepts and research behind the cement strength classification form the basis for all the discussions in this part. To keep it focused and also to ensure clarity in terms of the norms that are prescribed by them, only some of the major aspects that could influence the normal concrete mixture design procedure are being looked at. Looking at the German specifications from a very broad perspective, one can always see that the overall concrete mixture design methodology articulated is probably in no way different from the earlier American and British recommendations. This being so, there is a substantial and quantum difference in terms of both the parameters identified to enforce recommendations and also the values that are associated with these parameters, making it one of the most specific while being the most direct form of all. To be explicit, some of these characteristics and the way they are enforced could be examined through the following broad outlines. Like in any of the other two concrete mixture design recommendations, the following basic steps could be first listed for an initial comprehension.

- The characteristics of the constituents have to be defined in the first place. This involves particularly the specifications regarding the strength of cement as well as the size and gradation of the aggregates.
- As in any other basic mix design methodology, the water cement ratio for the required concrete strength should be first ascertained for the cement being adopted.
- Based on the size and gradation of aggregates, the water content is prescribed, after ensuring the requirements of workability.
- Having already defined the combined gradation of both fine and coarse aggregates, the design of the concrete mixture is now fully defined.

The effectiveness of the German method is probably in ensuring that the characteristics of the constituents are enforced through the concrete mixture design process itself. The care with which these are handled is indeed the hallmark of the design.

7.2.1 Water Cement Ratio Strength Relations

The water cement ratio to strength relationship is defined in terms of the different strength characteristics of the cement itself. It is probably a matter of abundant caution and ease in enforcing quality that the color of the bag is also specified so that there is no ambiguity about the type of cement that is being used. As already stated in the earlier chapters, the water cement ratio to strength relationships are based on the earlier Walz roll curves (Walz, 1971), defined for four cement strength grades of Z25, Z35, Z45 and Z55, the number indicating the strength of cement. It is probably most appropriate and is also important to note that the Walz roll curves for concrete are indeed specified for the cement generally having a strength of about 10 MPa, tested as per the German standards as discussed in Chapter 4. Figure 7.1 presents these relationships for the different strength grades as already discussed. It is also important to understand that the Z25 grade cement is generally not adopted for a reinforced concrete and is used for massive applications mostly. The drooping part of the curves at the top part is indeed attributed to the compaction difficulties associated with each concrete and such low water cement ratios. The reason for the double curve for the Z45 and Z55 cements is also due to the possibilities of having different compaction procedures and maybe even a small amount of plasticizer. Incidentally, most of these regulations came into existence in the early part of the 60s when the present day superplasticizers had not come into existence, though some type of plasticizers were available for a very long time. One of the theoretical

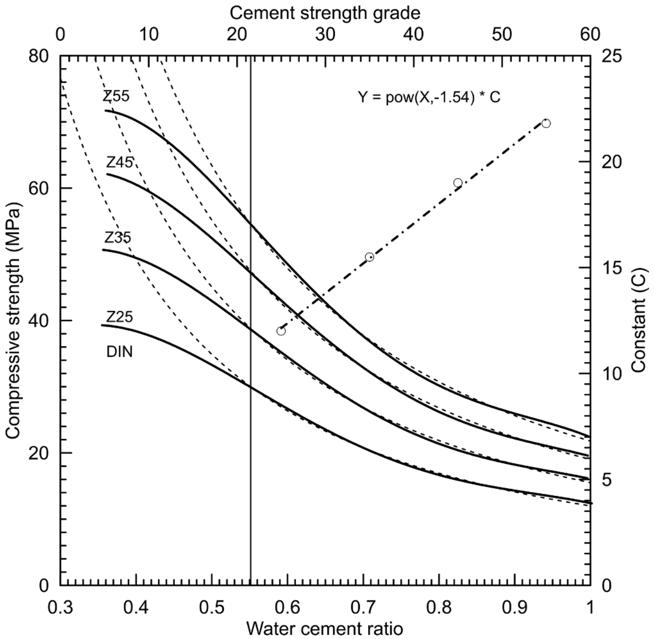

FIGURE 7.1
Water cement ratio strength relationships. (After Walz, 1971.)

attempts for the studies on high strength concretes often utilized these relationships, by projecting the part of the curve below 0.55 water cement ratio and extending it by using a power function, which appears to serve well for the Z45 grade most cements. It is obvious that the curves deviate from this particular point (from a water cement ratio of 0.55) onwards though a different point could be chosen if you want to include the data up to the lower water cement ratio level, and it will only bring down the compressive strengths at very low water cement ratios. An alternative that was attempted successfully is to choose an exponential relationship for the portion considered, which will have a more gradual development of the strength increase compared to the power relationships. This aspect of it will anyway be seen in the later part of this chapter while discussing the present Euro regulations. The possibility of appropriately modeling these power relationships with a single constant can also be seen in Figure 7.1. It is to be emphasized once again that these strengths are indeed possible if and if only the strength of cement at a water cement ratio of 0.5 conforms to the German standards and also that the desired combined aggregate gradation is strictly enforced.

7.2.2 Aggregate Grading and Grading Modulus

The water content for any specific consistency is actually dependent upon the aggregate size and gradation. Broadly, consistency regimes are classified as stiff (steiff-KS), plastic (plastisch-KP), soft (weich-KR) and flowable (fliessfahig-KF), each one of these being appropriate for specific construction practices. It is also noteworthy that the German specifications adopt aggregates of different maximum size compared to all the other regulatory practices—namely 8, 16, 32 and 63 mm. Even while specifying the intermediate sizes, the specification uses the multiplier 2 for the convenience of a mathematical representation. In fact, the combined grading curves as defined by the regulations have all been presented in terms of the size ratio with the maximum aggregate size (d/D) as given in Figure 7.2. It can also be said that the grading A can be approximated to the equation given in the Swiss code

$$Y = 50 * \left[\left(d / D \right) + \left(d / D \right)^{0.5} \right]$$

Also, the average grading between the grading is A and B, shown grading AB in the graph, and can be seen to be nearer to the Fuller's curve

$$Y = 100 * \left(d / D \right)^{0.5}$$

It is also generally stated that for ease of compaction and also an appropriate packing for higher strengths, the proportions that lie between the

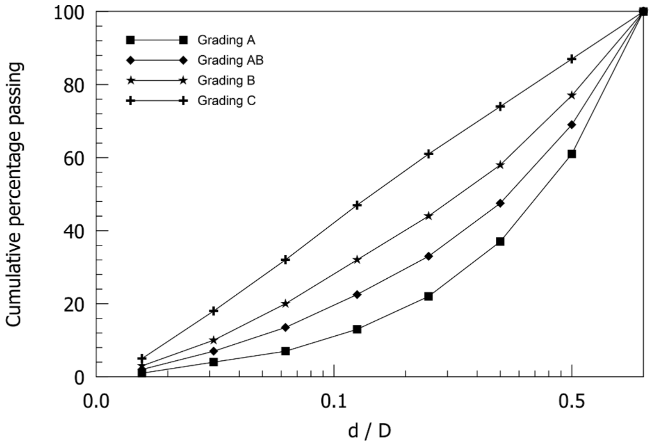

FIGURE 7.2
Combined aggregate grading curves (after DIN).

grading curves A and B are highly recommended. In fact, the aggregates never being perfectly rounded spheres, the gradation corresponding to their average (presented as grading AB) above was found to the most appropriate for ensuring the highest strength with enough loosening effect required for the production of the self-consolidating concrete compositions. The complete details regarding the design, assessment and modulations associated with the making of high performance self-consolidating cementitious composites was published earlier (Ganesh Babu, 2018).

7.2.3 Water Content and Consistency

Having got to know combined aggregate grading proportioning, the DIN specifications present the methodology for assessing what is termed as the combined grading modulus (k-value). This is very similar to the fineness modulus that is well known for representing the unified characteristics of sand. In the present context, the percentages retained on the various aggregates from 0.25 mm to the maximum aggregate size (say 16 mm) are all summed up, and the value as a percentage is represented as the k-value (kornungszifer). The required water content for the specified consistency is obtained based on this combined grading modulus, as presented in Figure 7.3. While the philosophy obtaining the combined fineness modulus of the all in aggregate is typical of the German regulations, the concept related to the maximum aggregate size to the water requirement by other national bodies (having accepted the grading regulations) is clearly similar to the present one. The one advantage in the present recommendation is that it not only takes the largest aggregate size as the controlling factor,

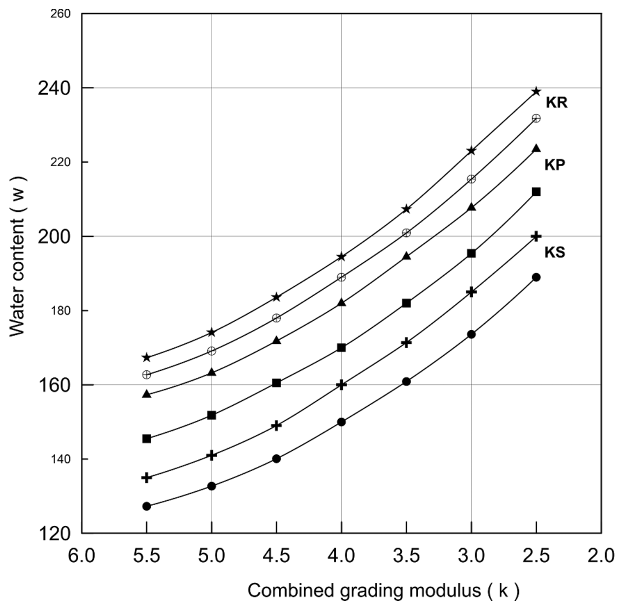

FIGURE 7.3
Water content to grading modulus relationship (after DIN).

but could adjust to the variations possible within the grading itself by recognizing what is known as the combined grading modulus.

Knowing the water content and the water cement ratio, the cement content can be determined. A typical nomogram presenting the details of the set of concretes mixtures of a plastic consistency, containing aggregates of DIN-A grading, is given in Figure 7.4. However, the ease with which it can be created makes presenting the complete range of nomograms for all the different grading distributions at all the consistencies even in an appendix rather unnecessary. The possibility of incorporating other mineral admixtures with an efficiency factor defined in the code itself is also available in the German regulations. In fact there is no need to talk about the coarse aggregate to fine aggregate ratios as the combined aggregate grading is already in place. The fact that the water cement ratio is related to the cement strength characteristics and the water content is related to the combined grading modulus makes the German regulations not only unique but could also be taken as most appropriate for considering the different characteristics of the material constituents. Apart from all these, the use of specific types of cement and regulations on the strength, the type of cement as well as the minimum cement contents for the different structures to be situated in the various environments are appropriately specified. A more comprehensive extension of this particular philosophy to arrive at the water contents required for the different aggregates was already presented earlier (Ganesh Babu et al., 1999).

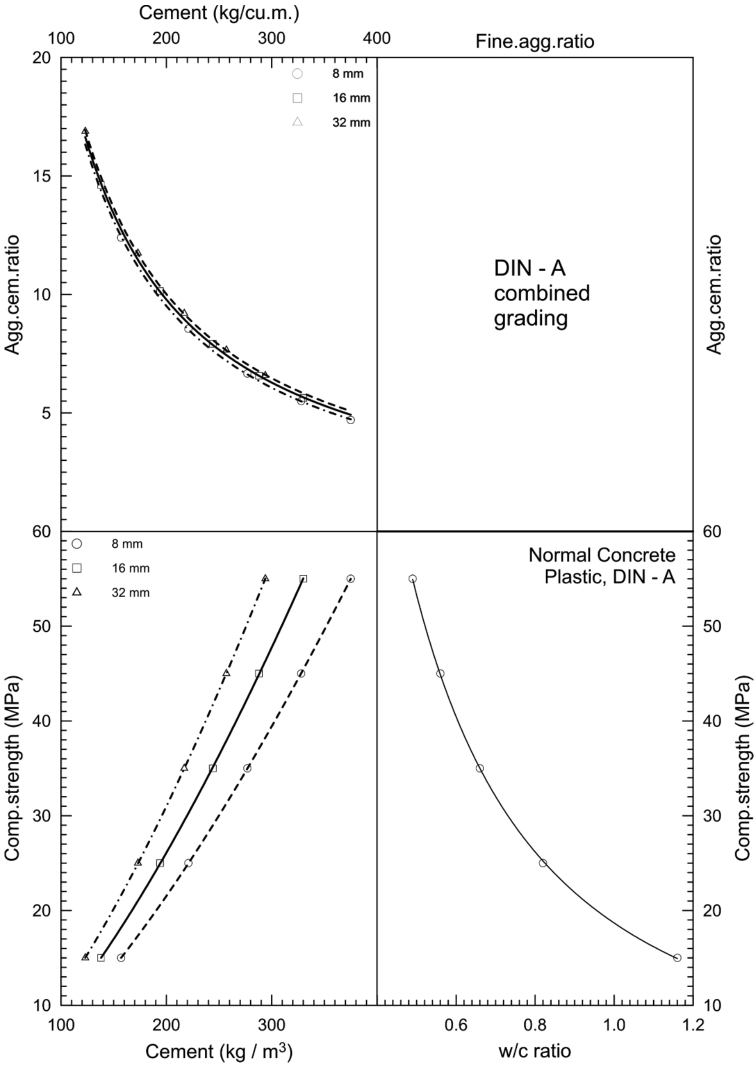

FIGURE 7.4
Nomogram for the design of concrete mixtures (DIN Norms).

7.3 Euro Adaptations

The provisions of the Euro code appear to be an appropriate modification of the German recommendations in more ways than one. It is recognized that the most important characteristic that sets apart the German recommendations with the other national recommendations discussed earlier appears to

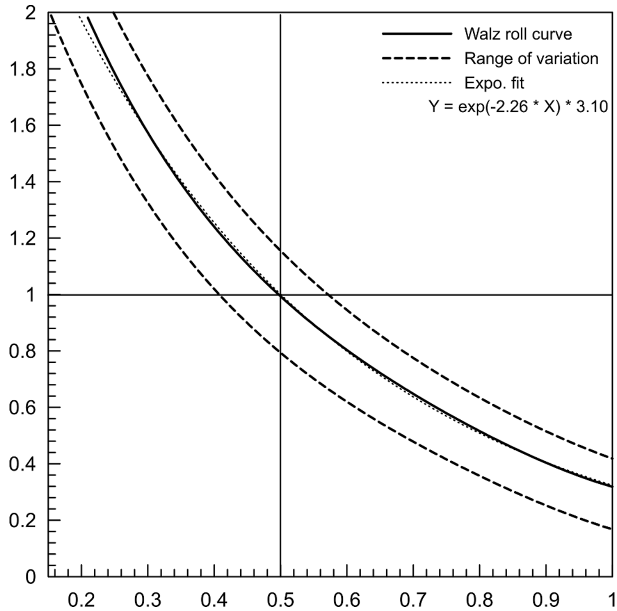

FIGURE 7.5
Walz roll curves for the Euro regulations. (After Sika, 2013.)

be primarily the fact that the water cement ratio to strength relationships are indeed different for the different strength grades of cement. The Euro regulations continue to adopt this particular philosophy with the modification that the relationships are extended at the lower water cement ratios to be continuously increasing (to avoid drooping portions of the curve earlier specified in the DIN 1045 (1988)). Even while doing this, the concept of the Walz roll curve was still adopted (Sika, 2013) as can be seen from Figure 7.5. The possible range of variation associated with it has also been shown in the figure. A very similar philosophy was proposed earlier in Chapter 4 while discussing the further acceptability of the Wall roll curve (Walz, 1971) through the extended data available from Hanke (1995) for the water cement ratio strength relationships (Figure 4.7).

The outcome of the modified Walz roll curve could be translated into the relationships for the cements of different strength grades ranging from 32.5 to 62.5. The change of the cement strength from 35, 45 and 55 MPa to the present 32.5, 42.5 and 52.5 could probably be related to the fact that the water cement ratio to strength relationships presently are associated with 0.50, instead of the 0.485 at which both the cemented concretes strengths are found to be nearly the same. In line with this, Figure 7.6 presents a comprehensive comparison of the earlier German relations with the present Euro specifications (EN 206-1, 2000). One important observation at this stage is that the relationships proposed appear to fit reasonably well with an exponential expression

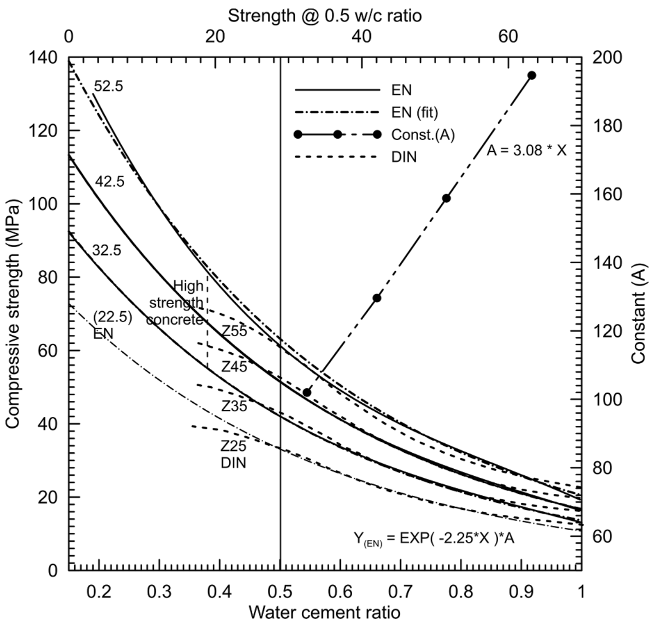

FIGURE 7.6
Water cement ratio strength relationships. (After DIN 1045; EN 206-1, Sika, 2013.)

instead of the power relationship chosen earlier while the DIN specifications were being looked at (Figure 7.1). It can also be seen that the relationships predict lower values at water cement ratios of 0.90 (which anyway is not a matter of interest for concretes required for most structural applications). Also, even with the minor deviations, the relationships appear to accommodate the strength values of the water cement ratio of 0.45 unlike the 0.55 suggested earlier in Figure 7.1. Also, for the different grades of cement, the high strength region proposed appears to indicate strengths in excess of 60 MPa, ranging all the way up to about a 120 MPa.

In this case also the proposed relationships for the Euro regulations can be summarized through one typical exponential equation with varying constants as presented in the figure itself. The Euro regulations also recognize an appropriate separation point at the water cement ratio of 0.35 for the high strength concretes. It is observed in literature that the rapid hardening cement (RHA) as referred to in the other national regulations could be treated as the 52.5 grade cements of the Euro norms presently. Considering this, the most appropriate relationship that could be universally adopted for the present day cements could be the expression derived for the 42.5 grade cement presented below for all practical purposes.

$$f_c = \exp(-2.25 \;.\!*\; X) \;*\; 159$$

It is only appropriate to suggest that this equation be used as a benchmark for the evaluation of any water cement ratio strength characteristics of particular cement. The fact that these values represent the cube strengths should also be specifically recognized. However, to suit the specific national recommendations already existing certain modifications of this maybe needed, which would be decided by the appropriate authorities. Also, the corporation at the correspondence of the relationships with some of the existing national courts is presented in a later chapter while discussing the modalities for achieving high strength, high-performance concretes.

7.4 The Indian Status

In contrast to the major international recommendations discussed till now, the status of the Indian cement and concrete mixture design recommendations appear to be, to say the least, fraught with several discrepancies. While it may not be possible and probably not even appropriate to discuss at length each of these, a few specific points have still got to be explained in brief. In the first place, the compressive strength of the Indian cement grades of 33, 43 and 53 for the ordinary Portland cements are all still evaluated by a very old test method (probably an old cement test of European origin). A comparison of the different as methodologies followed by the various national recommendatory bodies was already presented in Table 4.2 along with the grading distribution of sand used in each of them (Table 4.3). It can be clearly seen that all other things apart, the water cement ratio being used varies widely and the Indian standard appears to be using the lowest of them all. Even though the British regulations appear to show two different methods with widely varying water cement ratios for the cement strength, the fact is that the concrete mix design itself is always based on the strength to water cement ratio relationship corresponding to the water cement ratio to 0.50, which brings all the other three (American, British and Euro) to be necessarily using the same water cement ratio of concrete mixture design.

Furthermore, to look at the broad changes that have taken place over the years, the strength to water cement ratio relationship prescribed in Indian standards from time to time have all been compiled and presented in Figure 7.7. It can be seen that the average relationship prescribed in IS:10262 (1982) was perceived to be for the cement strength of about 48 MPa, considering the different curves (A to F) included in the code. The first revision of the IS:10262 (2009) tried to overcome this particular aspect by simply not presenting any specific water cement ratio to strength relationship, while the same was to be taken from the IS:456 (2000), actually a specification directed toward the plain and reinforced concrete. The table that

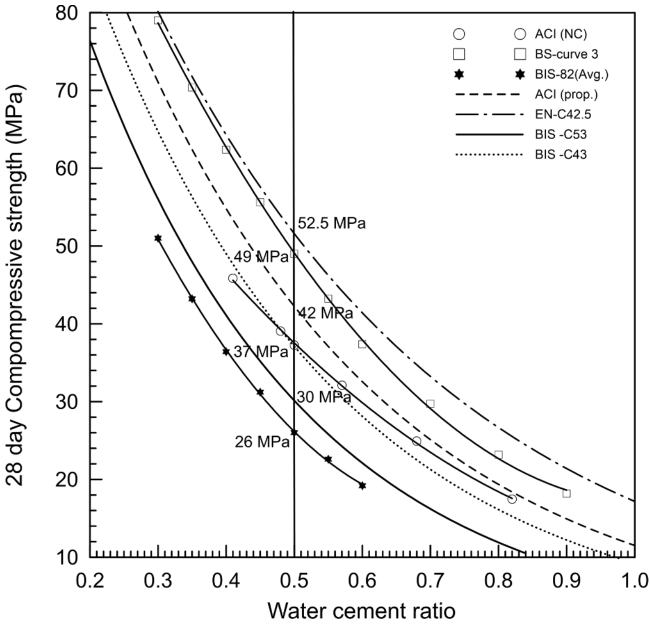

FIGURE 7.7
International perspective of the cement and concrete strength characteristics.

was recommended herein for this is one that talks about the minimum cement content, maximum water cement ratio and the minimum grade of concrete for the different exposure conditions. The latest proposed revision, which was a draft released for circulation in 2017 (a second revision of the IS:10262 viz. ICS 91. 100.30), presents the water cement ratio strength relationships for the three specific OPC cement strength grades of 33, 43 and 53. In order to have a clear perspective of the various regulatory bodies' recommendations at this point, Figure 7.7 also contains the appropriate relationships for the 45 grade ordinary Portland cement as specified in the ACI, BS and Euro standards. The proposed is the recommendation that was felt appropriate for concretes that include chemical and mineral admixtures in the earlier chapter on American recommendations as was also included in the figure.

Without going too deep into all the other factors, including the variations with water cement ratio, a cursory examination of the water cement ratio of each of these recommendations shows clearly how they are placed with respect to each other. To start with, the Euro code (also the earlier DIN code) requires a strength of 52.5 MPa, while the British standard's curve 3 (corresponding to the 28 day strengths) has 49 MPa. The values of the proposed relationship for the American standard and that for the normal concrete as given in the ACI 211.1 (1991), appearing to show 42 and 37 MPa respectively. In fact, it is to be recognized that the ACI recommendations present these for the cylinder strengths and not the cube strengths as in the BS and Euro norms. Finally, the earliest Indian standard IS:10262 (1982) shows only 26 MPa, while the presently proposed draft code appears to show 30 and 37 MPa for the 43 and 53 grade ordinary Portland cements as per Indian standards. It is only proper at this particular stage that these anomalies are recognized appropriately and comply to the international recommendations so that the nation's infrastructure needs are better served.

7.5 Other National Approaches

It is obvious that the manufacturing technology of cements in India is comparable to the most advanced anywhere in the world, particularly given the fact that most of the cement manufacturing technology and machinery as well as the know-how is invariably sourced internationally. Also, most cement manufacturing companies all over the world have participation of the best international players in cements and can certainly produce cements of international standards, if not even much better ones. At present, these recommendations lead to an enormous amount of wastage of cement and a consumer like the RMC industry could have a serious problem of viability if this continues. Apart from the aspect of wastage of scarce raw materials and natural resources, the emissions of CO_2 from the cement industry being the highest, the effects of carbon footprint are significant and far-reaching, suggesting an urgent need for an appropriate revision of the present code to ensure both economy and prudence. It is necessary that this should be viewed in the national perspective not only in the Indian context but also wherever an effort could be made to comply with the existing international recommendations.

Maybe it is only appropriate at this particular stage to look at the possible effects of the earlier discussions in relation to the cements produced in other countries. Having said this, it is in fact obvious that most of the recommendations in the various national codes originated from either the British or European thought in most Commonwealth countries. Countries in the south-east Asian region which have had strong colonial pasts mostly continue to live with the traditional British approach of yesteryears. Some of these aspects are slowly changing with the American influence due to their extensive research publications. Countries like Canada, Australia and New Zealand, which also have a strong background of research, have been continuously trying to modernize their cement and concrete recommendations. In fact, going one step further, it is the need of the hour to look for avenues to even further the capabilities of the present day cements, both by manipulating the physical and chemical characteristics along with the possible additives like supplementary cementitious materials to ensure sustainability of the cementitious compositions.

7.6 Mathematical Modeling

Looking back at the preceding discussions on the various concrete mixture design methodologies, the major national bodies along with the specific recommendations toward characterizing material constituents, one can easily say that it maybe possible to arrive at some conscientious set of recommendations that could make the entire design process much simpler and more practical. However, even if it is possible to bring forth a coherent methodology of concrete mixture design that has a reasonable level of acceptability of the different individual national bodies, with the prevailing industrial scenario it may not be possible to make it acceptable to the business community. This is because of the several difficulties associated with realigning all the relevant standards for both materials and processes associated with the production and processing of cement, aggregates and concrete apart from the ubiquitous chemical and mineral admixtures of the present day. Even so, it is only proper to consciously plan and articulate a possible scenario for the consideration of the several stakeholders, who can take it up from that point on and develop it into a viable proposition for the betterment of the existing scenario. In the succeeding chapters are indeed efforts to arrive at some common ground for the concrete mixture design process, after a careful consideration of the present status of the recommendations by the various national bodies.

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8

Perceptions of Performance and Sustainability

8.1 Introduction

There need be no two opinions about the fact that the performance and sustainability of constructed facilities is of utmost importance, particularly given the escalating costs in the built space. In fact there are several words like green, eco-friendly, etc. used synonymously with these, but for all practical purposes these claims appear to address a specific factor but not the complete perspective. Apart from this, there are several other forums that apparently promote sustainability through specific programs like LEED (Leadership in Energy and Environmental Design) certification promoted by the U.S. Green Building Council (USGBC). While the conceptual efficacy of these certifications and their rating levels have a certain perception, concrete use of Portland pozzolana cements or cements with some mineral admixtures as a part of these should be appreciated but yet should also be appropriately evaluated. Not going further into the aspects of the credibility of such assertions, the need for a clear understanding of the parameters defining the cement or cementitious materials performance and the aspects related to its sustainability characteristics need to be understood correctly. The inadequate performance of the concretes in the recent past necessitated a specific understanding of the performance of these concretes. Incidentally, the fact that the highly interconnected capillary porosity in concrete is significantly reduced at water cement ratios below 0.45 as observed initially promoted the perception that the higher strength concretes will indeed be the concretes of higher performance, which was seen to be a misnomer later. The higher cement contents associated with some of these higher strength concretes of those times obviously had high reactivity to the environment which led to deterioration.

The discussions associated with the following chapters after the concrete mix design procedures by various national codes are essentially perceptive and are not expected to be prescriptive and final. The main aim of the entire exercise is to clearly indicate the requirements as well as the avenues that govern the performance of the final concrete compositions possible within the domain of concretes adopted in most constructed facilities of today. However, there are classes of cement and concrete compositions which are certainly exclusive and have to be treated differently for an appropriate understanding, and these are not being attempted as a part of the present discussions.

Finally, it is only proper to recognize that concrete as the material of construction always kept pace with the fast changing, highly demanding requirements of the world. The ability to be able to modify its strength and reinforce its tension faces while being able to be produced in any form and shape along with its compatibility with steel and adequate fire resistance made sure that the several other contenders could not replace this construction material over the past couple of millennia. Probably the most attractive part of its ubiquitous presence is the fact that over 80% of its total volume most often is only locally available aggregates and even that manufactured component, cement, can be augmented with several supplementary cementitious materials as of today. In this journey of being universally approved in construction, concrete has almost reached the characteristics of steel if one chooses to make the appropriate modulations.

8.2 Perceptions of Environment and Performance

Efforts toward an understanding of performance both in the laboratory and field have always been a matter of significant discussion, if they are in any way representative of the actual degradation processes in the actual environment. Naturally, to have a handle on the possible deterioration levels with the different material constituents, concretes have been investigated in different ways to evaluate their performance characteristics in advance. These are invariably studies that invigorate the process of deterioration through certain accelerated methodologies that could show the effects with a reasonable span of time. For a much broader understanding, their effects on structures situated in such environmental regions are also studied in detail and are correlated to ensure a reasonable prediction of the performance characteristics of cementitious compositions.

The primary objective in developing concretes of a high performance was mostly to have adequate resistance to aggressive environments. In this regard, "high performance concrete" (HPC) is defined as that meeting the following requirements—essentially one regarding the strength and the other a durability criteria by Zia (1991).

1. A maximum water cement ratio of 0.35,
2. A minimum durability factor of 80%, as determined by ASTM C 666, Method A, and

3. A minimum strength criteria of
   * 3,000 psi (21mpa) within 4 hours after placement
   very early strength (VES), or
   *5,000 psi (34mpa) within 24 hrs
   high early strength (HES), or
   * 10,000 psi (69mpa) within 28 days
   very high strength (VHS),

Even in the above qualifications required for a HPC, (a) and (c) look at the strength only and (b) looks at the durability. However, the freeze-thaw test of ASTM C666 need not necessarily represent the performance of concrete to the environment it is subjected to. Even so, it should be conceded that these recommendations were certainly justifiable for constructed facilities of national and strategic importance involving very high cost or those having a high public utility value.

However, at this stage, one should consider if this definition and specifications could be universally applicable, particularly in situations where the early strength gain factor is not an advantage and/or the freeze-thaw stability is not a factor governing its performance as far as durability is concerned. In Prof. Zia's own words, these benchmark requirements were chosen to represent the durability considerations of concrete bridges of the federal highways which are subjected to freeze-thaw and salt spray apart from the need for the early strength for prestressing applications (Zia, 1992). Obviously the requirements could be totally different for an application involving higher impermeability as in pipes or even for concretes that are subjected to forces only after a long time like in dams, which also require only concretes of lower strengths, to name a few.

Also these requirements obviously appear to stem from the evolution of the concept of performance, that at water cement ratios below 0.45 the pore structure will become increasingly discontinuous and is recommended for concretes in marine environment by many codes of practice. However, the need of the hour is to recognize that the losses, due to the very common constructed facilities not functioning to the required levels of expectation, appear to be phenomenal by any national or international standards. Naturally, though it can be easily seen that this high performance need not necessarily be limited to only to the bridge structures, the performance requirement is universal.

In general, HPC can be defined as that concrete which has the highest durability (for any given strength class needed) for a particular application, of course with the understanding that it should be produced at an economical cost. This means that, with the available knowledge, one can always strive to achieve the most durable concrete required for a particular application. At this point the method for the assessment of durability may also have to be well defined, keeping in view the performance requirements of the concrete for the specific application and the environment in which it is expected to perform. Even so for the lifeline structures, the definition and the associated qualifications proposed by Prof. Zia can be taken as a benchmark at least to start with as they will be adequate in satisfying the performance criteria in most cases.

8.3 Performance and Sustainability Indicators

In principle strength is considered to be one of the major performance indicators in most construction practices. Concretes, based on the strength, can be classified into four categories, namely normal strength concrete, high strength concrete, very (super) high strength concrete and ultra-high strength concrete. Though there are no well-defined limits for this classification; the corresponding strength values can be taken as 20–60, 60–100, 100–150 and above 150 MPa respectively. The specifications for concrete mix design are only available for normal and high strength concretes. The high strength concretes and beyond require the use of chemical and/or mineral admixtures. In addition, the durability is ensured through recommendations in terms of the type of cement, minimum and maximum cement contents and the maximum water cement ratio depending upon the environmental conditions. Incidentally, it is felt that the increase in strength if any, due to the limitation on maximum water cement ratio and minimum cement content, could be made use of in the structural design calculations to achieve economy. An effective design for high performance requires a thorough understanding of the effect of the various constituents of concrete. The various material parameters and their influence on the design and performance of concrete are too much to discuss fully.

While the characteristics of the general constituents of concrete like the type of cement, coarse and fine aggregates and maybe sometimes even water could influence the performance, the most specific and appropriate modulations for achieving a suitable performance in the first place is governed broadly by the chemical and mineral admixtures associated with the concrete composition. The advent of chemical admixtures like superplasticizers or high range water reducing admixtures, accelerators (affecting set or strength), retarders, air entertainers (mainly for freeze-thaw resistance) and water proofers have facilitated several possible modulations to the concrete performance both in the green state as well as in the hardened state. In particular, superplasticizers have become an essential ingredient to help in bringing down the water cement and cementitious materials ratios significantly for producing concretes of higher strengths. This is more so while using mineral admixtures (either as pozzolanic materials or simple powder extenders) to counter the additional water required for wetting the increased surface area due to the associated fines. Pozzolans such as fly ash and silica fume are used either as replacements or supplements to the cement. The optimum amount of replacement or addition, the adjustments in water and aggregates (particularly the fine aggregate) are generally the important factors to be considered. In addition, superplasticizers are used generally with high volume fly ash to take care of the water demand and to increase the workability.

The performance indicators being what they are, the concept of sustainability is governed by an entirely different set of parameters related to the appropriate use of materials. This indeed could be the simple fact that the abundantly available local materials are used particularly as the aggregate constituents of concrete. It is possible that not always the local materials are admirably suited for utilization, and many a times there is a need to augment the matrix specifically to counteract the deficiencies. This part of sustainability is often looked down upon, while the use of industrial waste bi-products like fly ash, silica fume, GGBS and rice husk ash is only recognized as the benchmark for sustainability. In fact even an inappropriate utilization of these materials even at below par efficiency is considered sustainable, maybe because of their abundant availability. The methodology of their utilization and the consequent effects in terms of performance are also considered secondary.

One of the first concepts in terms of sustainability is to ensure that the use of such abundantly available waste materials be maximized, at least for the general-purpose applications that are omnipresent even in the semi-urban rural scenario. To cite an example, the high volume fly ash applications possible in highly advanced scenarios like prefabricated constructions have indeed never been fully appreciated. The possibility of enhancing the strength gain rate of the high volume fly ash compositions could be admirably modulated through the use of temperature. Particularly in the controlled conditions of prefabrication or even in the generally known countries with temperate climates, the advantages of the latent heat of solar radiation has not been effectively addressed. It is always possible to have a subsidiary system to supply the necessary heat from traditional sources as a standby to ensure continued production. Several such examples can be traced to have an effectively sustainable infrastructure program in many of the developed as well as the developing countries.

8.4 Concepts of Green and Sustainability

The further specific aspect that is often used as synonymous with sustainability is the concept of green and eco-friendly technologies. Maybe in a broad sense sustainability is associated with the conservation of resources while green and eco-friendly technologies are associated with a reduction in pollution relevant aspects. Sustainable also includes the life cycle cost of a structural facility. Looking, it is it is obvious that sustainable technologies could lead to a greener environment because of the use of local resources that avoids transport and the utilization of industrial wastes effectively that will lead to control of pollution. In its larger perspective, the chemical binding of some of the heavy metals associated with such industrial wastes also promotes the concept of an environmental safeguard.

One important factor associated with the utilization of fly ash and the other industrial wastes is that they are in fact supplementary cementitious materials and can help produce very high strength concretes. In fact, without the use of some of these high efficiency pozzolanic materials like silica fume it is not possible to achieve strengths in the range of 150 MPa and beyond. Obviously the use of such high strength materials inherently reduces the total volume of material required otherwise for constructed facility, which in itself is a saving leading to sustainability and green technologies. While the high volume utilization of lower efficiency pozzolanic materials leads to conservation of cement and even fine aggregates to a certain extent, the need for pozzolanic materials in conjunction with superplasticizers is obvious for the higher strength concretes. It is thus not just the adoption of some unspecified quantity of an industrial waste bi-product that makes the concept sustainable as advertised often but a prudent and justifiable utilization of the same to its maximum efficiency that should make it sustainable and green. Also, to be precise, there is as yet no specific mechanism by which these factors are appreciated and evaluated, other than the statement that so much material has been saved by the use of supplementary cementitious materials. The fact that there is no direct correlation either to the cementitious efficiency or to the paste extension capacity by their use of any specific application is probably obvious and needs attention. For this to happen there should be acceptable methodologies to make such an assessment.

Some of the present national recommendations do contain an average number for the efficiency concept and competition of the effective benefit; even so such averaged lower values will promote a much better appreciation and understanding of the contribution of these supplementary cementitious materials significantly. Apart from this, the effect of the contribution of other chemical admixtures in association with these in promoting appropriate methodologies for the production of concrete mixture compositions that are suited to the industry at the lowest cost should also be recognized in evaluating the sustainability and greener or eco-friendly characteristics of the concrete compositions that are utilized in the particular infrastructure facility. These can be specifically addressed by the supplier so that in evaluating the built environment the actual effect can be properly accounted for amongst all the other such processes leading to greener structures. The use of local materials in particular is probably the need of the day, which is not very much appreciated when they straitjacket the evaluation methodologies for certification. It may not be possible to exactly address these parameters overall, but to the extent possible the discussions highlight the need for an appropriate recognition of the various factors that contribute to sustainability and greener concepts.

TABLE 8.1

Effect of Cement Strength on Savings and Economy

S. No	Cement Strength (MPa)	Cement Content @ 0.5 w/c (kg/m³)	EN Concrete Strength @ 0.5 w/c (MPa)	Approx. w/c Ratio @ 45 MPa (kg/m³)	Cement Content @ 45 MPa (kg/m³)	Savings in Cement (kg/m³)/(%)
Assumed slump of 100 mm will require 200 kg/m³ of water.						
1.	25	400	35			
2.	35	400	45			
3.	45	400	55	BIS – 0.38	526	181 (52%)
				ACI – 0.48	417	72 (20%)
				BS – 0.54	370	25 (7%)
				EN – 0.58	**345**	---
4.	55	400	62			

Approx.w/c ratio @ 45 MPa and cement content @ 45 MPa are calculated for the Indian, **American (cyl.)**, British and European regulations.

To be more explicit and probably to address the problem at its root, the cement, one may be surprised that the upgradation of the cement characteristics in itself will lead to significant savings. The back of the envelope calculation associated with such a concept is presented in Table 8.1. The table actually focuses its attention on two factors in the cement strength (given in the second column) and the strength to water cement ratio effect through the approximate water cement ratio required for a 40 MPa concrete (given in column 5, calculated only for the cement strength grade of 45 MPa using Figure 7.7). It is possible that they could be minor variations in assessing the savings, but at the broader perspective the message is very clear. Incidentally, the ACI presents the cylinder strengths, and translated into the cute strength the actual cement saving may be only marginal. But this is because the competition was done not for the normal concrete as in ACI 211.1 (1997) but using the proposed relationship of the author. Even the BIS calculation was done for the curve using the proposed draft of 2017. It is obvious that the table speaks for itself in a clear and emphatic fashion why there is an urgent need for the gradation of cements not only in the interests of the industry and environment alone, but also in the interests of the national economy.

8.5 Design Methodology for High Performance

It should be obvious from your discussions that performance is specific to the application of the constructed facility and the environment in which it is to be operated. Notwithstanding this, a set of broad principles associated with performance and their operability in the design process is always necessary. In the first place and as a fundamental axiom, the use of minimum quantity of cement for achieving the required strength and workability while satisfying the requirements of durability helps in producing concretes of lower environmental reactivity, shrinkage and creep problems. In this perspective, a few typical and overarching directive principles for design can be listed as the following.

- Uniformity of structure and strength throughout the member,
- Choosing the appropriate maximum size of aggregate and the grading distribution,
- Maximizing the quantity of aggregate while minimizing the fines,
- Minimizing the quantity of cement to ensure a lower heat of hydration and economy,
- Maximizing appropriately the level of supplementary cementitious materials,
- Ensuring an adequate workability for the compaction process adopted,
- Utilization of appropriate chemical modulators like superplasticizers for workability,
- Above all these is the principal of ensuring adequate compaction.

Amongst all the above, assuming that the concrete design has a good handle on the various constituent's characteristics, maybe it is only appropriate to look for avenues for making concretes containing a combination of the chemical and mineral admixtures. In particular there have been several efforts to have a specific understanding of the overall cementitious capability of pozzolanic materials. It was seen that the pozzolanic materials' participation in concrete is characterized by two specific aspects, the pore filling and pozzolanic effects combined. With the availability of the pulverized fuel ashes from the modern thermal power stations, the characteristics of the materials like fly ash have become more uniform and their reactivity helped in enhancing the flash absorption capability of cementitious compositions of various strengths. This has promoted the use of fly ash in particular from about 20% of yesteryears to well over 50% in more recent times. However, a specific understanding of the efficiency factors with a reasonable level of reliability at the various replacement levels appears to be elusive. Evaluations of the laboratory experiments as well as the data from literature corresponding to such concretes have led to the formation of a methodology, termed as the "Δw method," which was similar to what was proposed by Schiessl and Hardtl (1991). After a careful evaluation of the available data, it was felt that a single efficiency number to represent the various replacement levels may not be in order. Thus the "overall efficiency factor" (k) at any replacement level was considered in two parts: the "general efficiency factor" (k_e) valid for all replacement levels (principally similar to what was being attempted and propagated by the researchers earlier) and the other termed the "percentage efficiency factor" (k_p), which is specific to each percentage level.

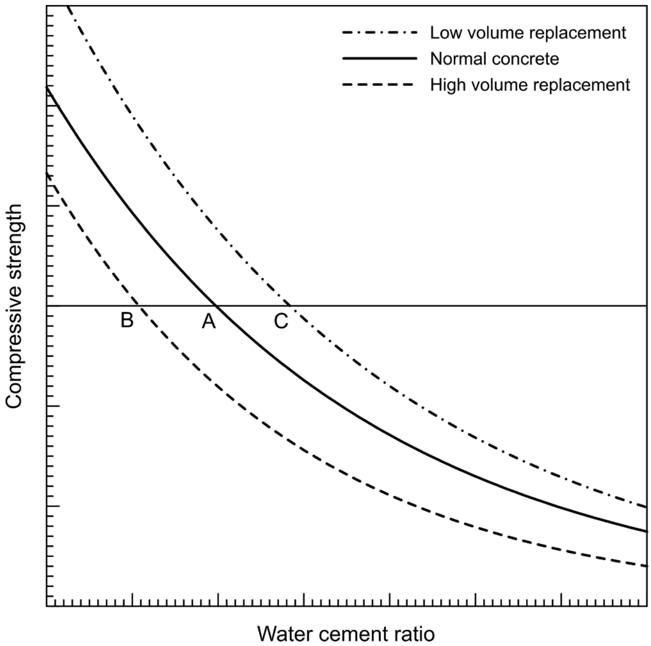

FIGURE 8.1
Methodology for assessing the efficiency of pozzolanic materials.

The combination of these could be seen to predict the overall efficiency of the cement composites effectively. To explain the theory in clear terms, Figure 8.1 presents the strength to water cement ratio relationship for a typical normal concrete. It is obvious that when fly ash is added (say 30% or above as in high volume replacements), there is a decrease in strength, and the corresponding water cement ratio strength relationship will be below the normal concrete relation. However, when only a very small quantity of pozzolanic material is added (below say 10% typically fly ash as in low volume replacements) the strength realized is generally higher, leading to a relationship that is above that of the normal concrete. The "Δw method" concept is an effort to correct the "total cementitious materials" to the "effective cementitious materials" to ensure that the concrete strength is represented by the original normal concrete relationship itself. In a way, the pine B and C are pushed to come to the point A in Figure 8.1, first by correcting both the low and high volume replacements by a single average efficiency factor (termed the general efficiency factor), and the discrepancies due to the variations arising out of the percentage replacements are corrected later through another factor (termed the percentage efficiency factor). Thus the well-known relationship involving efficiency of pozzolanic materials can be rewritten as the following.

$$w/c_0 = w/(c + kf) = w/(c + k_e f + k_p \cdot f)$$

The proposed concept and the methodology of the evaluation of the pozzolanic efficiency was indeed applied to several different lower efficiency as well as the higher efficiency pozzolanic materials like fly ash, silica fume, GGBS, metakaolin, RHA and zeolite etc. successfully through several research projects in the laboratory (Rao, 1996; Prakash, 1996; Sree Rama Kumar, 1999; Appa Rao, 2001; Surekha, 2005; Narasimhulu, 2007). There have also been several publications emanating out of these research efforts, and a few of them that could be effectively explained in detail and highlight this methodology could be seen (Ganesh Babu et al., 1992, 1993; Ganesh Babu and Surya Prakash, 1995; Ganesh Babu and Siva Nageswara Rao, 1996; Ganesh Babu and Sree Rama Kumar, 2000; Ganesh Babu and Chandra Sekhar, 2012). The above information effectively proves that the two factor efficiency concept proposed provides a reasonable assessment of the effect of the different pozzolanic materials reported apart from the simple powder extender, which has very small pozzolanic reactivity, namely limestone powder.

The design methodology for high-performance is enforced a bit indirectly by almost all national recommendations. ACI 211.1 (1997) specifies the maximum permissible water cementitious materials ratio 0.454 concrete in severe environment. Similarly, several of the national courts talk about the minimum cement content and maximum water cement ratios for concretes to be in contact with soils with the different sulfate concentrations. A comprehensive view on the environmental exposure conditions and the corresponding regulations has been an evolving subject for quite some time now. Different ideological subdivisions could be seen from different sources, particularly from the various recommendations of the national bodies including the CEB-FIP model code (1994). Also the design philosophy for durable concrete structures is systematically explained in the CEB-FIP design guide (1992). However, the one that is proposed in the DIN EN 206-1 as explained in detail by Grube et al. (2001) is indeed highly comprehensive. After a brief review of this, it was felt that there is a need for a comprehensive overview of the available recommendations and the corresponding specifications for the concrete in those environmental zones. In fact it looked obvious that there is a serious mismatch between the water cement ratios specified and the minimum strength and cement contents of the concretes proposed. Knowing that the water cement ratio strength relationships is already a known fact from the code itself, the concrete strength and the cement content at a reasonable water content for these concretes will indeed be obvious and should be evaluated. In line with this, simple effort was made to broaden the scope of the environmental zones as well as specify the minimum characteristics of the concrete that should be adopted in each of them.

Table 8.2 presents an appropriately extended environmental exposure scenario containing both the suggested recommendations of the Euro code (EN 206-1, 2000) as well as the possible or the necessary modifications

TABLE 8.2

Extended Scenario of the Environmental Exposure Classes and Suggested Recommendations for the Concretes Compositions (after EN 206-1, 2000)

Exposure Classes and Levels of Environmental Attack				Specifications for Concretes Recommended by EN 206-1			Modified Specifications for Concretes Evaluated (EN)		
Expo-sure Class		**Type of Environmental Attack**	**Severity of the Attack**	**Max. w/c**	**Min. Cem. (kg/m³)**	**Cube str. (kg/cm²)**	**Max. w/c**	**Min. Cem. (kg/m³)**	**Cube str. (EN) (kg/cm²)**
XO	--	Nil	None	None	None	8/10	None	None	10/20
XC	1	Carbonation — increasing order of severity	Dry	0.75	240	16/20	0.75	240	30/25
	2		Wet	0.75	240	16/20	0.75	240	30/25
	3		Moist	0.65	260	20/25	0.65	280	35/30
	4		Wet/dry	0.60	280	25/30	0.60	300	40/35
XD	1	Chloride ingress	Moist	0.55	300	30/37	0.55	330	45/40
	2		Wet	0.50	320	35/45	0.50	330	50/45
	3		Wet/dry	0.45	320	35/45	0.45	370	55/50
XS	***1***	***Ocean-Atmospheric***	***Highly humid** (85%+)*	***0.55***	***300***	***30/37***	***0.55***	330	45/40
	2	***Sea water***	***Wet***	***0.50***	***320***	***35/45***	***0.50***	330	50.45
	3	***Splash zone***	***Wet/dry***	***0.40***	***320+P***	***45/50***	***0.40***	420	60/55
	4	***Mud zone***	***Soil chemicals***	***0.55***	***300***	***30/37***	***0.55***	330	45/40
XF	1	Freeze-Thaw/ +deicing salt	Moderate saturation (wos)[a]	0.60	280	25/30	0.60	300	40/35
	2		Moderate saturation (ws)[a]	0.55+ae 0.50	300 320	25/30 35/45	0.55+ae 0.50	330 330	45/40 50/45
	3		High saturation (wos)[a]	0.55+ae 0.50	300 320	25/30 35/45	0.55+ae 0.50	330 330	45/40 50.45
	4		High saturation (ws)[a]	0.50+ae	320+P	30/37	0.50+ae	330	50/45

(Continued)

TABLE 8.2 (*Continued*)

Extended Scenario of the Environmental Exposure Classes and Suggested Recommendations for the Concretes Compositions (after EN 206-1, 2000)

Exposure Classes and Levels of Environmental Attack				Specifications for Concretes Recommended by EN 206-1			Modified Specifications for Concretes Evaluated (EN)		
Expo-sure Class		**Type of Environmental Attack**	**Severity of the Attack**	**Max. w/c**	**Min. Cem. (kg/m³)**	**Cube str. (kg/cm²)**	**Max. w/c**	**Min. Cem. (kg/m³)**	**Cube str. (EN) (kg/cm²)**
XA	1	Chemical attack—liquids & solids (soils)	Weakly corrosive	0.60	280	25/30	0.60	300	40/35
	2		Moderately corrosive	0.50	320	35/45	0.50	330	50/45
	3		Strongly corrosive	0.45	320+P	35/45	0.45	370	55/50
XG	1	***Chemical attack—gases***	***Weakly corrosive***	***0.50***	***320***	***35/45***	***0.50***	330	50/45
	2		***Moderately corrosive***	***0.45***	***320+P***	***35/45***	***0.45***	370	55/50
	3		***Strongly corrosive***	***0.40***	***320+P***	***45/50***	***0.40***	420	60/55
XM	1	Wear	Moderate	0.55	300	30/37	0.55	330	45/40
	2		Severe	0.45	320	35/45	0.45	370	55/50
	3		Very severe	0.45	320+P	35/45	0.45	370	55/50

Source: EN 206-1, 2000.

[a] (wos)—without salt, and (ws)—with salt.

to it considering the water cement ratio prescribed by the Euro code as the datum. In doing so the minimum cement contents are evaluated by considering a water content of 180 kg/m^3 as appropriate for water cement ratios up to 0.60, while for concretes of lower water cement ratios below that value the water content was taken to be 165 kg/m^3 (assuming that all such concretes also use superplasticizers invariably). Apart from that, the corresponding concrete cube strength for the water cement ratio proposed was also calculated for a cement of 45 MPa strength grade as was presented in Figure 7.7 in the earlier chapter. Such specific correlation between the specifications at the various regulations of a codal provision is not only essential, but will help in ensuring the clarity and integrity of the recommendations. It is clear to see from this revised or corrected estimate the minimum cement content and the strength of concrete to be used for concretes adopted in each environmental zone, and significantly higher end should be accepted as there are. However, a possible reduction of about 5 MPa is considered to accommodate possible variations in the cement and other constituent material characteristics.

8.6 Avenues for Green and Sustainability

After having a close look at the various factors associated with performance and sustainability of concrete composites in general, it may be appropriate to have a more specific understanding of the most utilized normal structural concretes to ensure a level of guarantee toward its strength as well as durability and performance. Being concretes of the normal strength range (similar to what was discussed in the ACI 211.1, 1997) have a very large applications range with various possibilities for the incorporation of both chemical and mineral admixtures while ensuring that the exhibit a high performance and even are self-consolidating if required. Table 8.3 presents a possible picture of the range of concretes that are useful for such general-purpose applications. It could be seen that only low-end pozzolanic materials (fly ash and GGBS) have been recommended as cementitious constituents though use of other lower end pozzolanic materials like even the limestone powder need not be ruled out. It must be remembered that the strength to water cement ratio in almost all these cases was taken to be the 42.5 MPa cement grade of the Euro standard. Such specific guidelines could also be created for concretes of other strength ranges after an appropriate consideration of the various concrete characteristics and how they can be grouped together to ensure a holistic vision of the complete range.

TABLE 8.3

Broad Outline Specifications for Concretes for General Purpose Applications

	1. General-purpose Concretes of Lower Strength Range with LEPs[a] (20–40 MPa; w/cm ~ 0.50–0.70; LEP only; 25 mm graded aggregate)					
S.No.	**Nomenclature**	**%—Pozzolan Combinations (%)**	**Slump/Slump Flow* (mm)**	**Total Cementitious Content (Kg/m^3)**	**Super-Plasticizer[b] (%)**	**VMA[b] (%)**
1.1.	OPC concretes	0	Extremely Dry–150			
1.2.	Plasticized concretes	0	50–150			
1.2.	Pozzolanic concretes	30-F/50-G	Extremely Dry–150	250–450	0–1.0	0.0
1.4.	Flowing concretes	30-F/50-G	150–200			
1.5.	HPC	30-F/50-G	100–200			
1.6.	SCC	30-F/50-G	500–650*	350–450		0.5

Note: All aggregates should be appropriately graded to ensure good packing characteristics.

[a] Low-end pozzolans (LEP)-F-fly ash (35%), G-GGBS (50%).

[b] Superplasticizer content as a percentage of the total cementitious materials.

8.7 Performance Quality Indices

The requirement for enforcing quality never need be overstressed in any engineering activity that proposes to ensure a sustainable product. Even so, given the highly competitive industrial scenario that tries to enforce a very low cost of production, the quality aspects in general are only given a go by and is probably the first casualty. In this perspective, it is absolutely essential that the most important factors that govern the behavior of concrete not only in terms of its strength but also its performance have to be appropriately identified and may also have to be ranked to ensure the correct product in place. While a separate chapter is given over to the actual performance regulatory efforts needed for ensuring the quality, it is necessary to recognize the major factors that enforce quality. It is to be noted that though one can list a significant host of parameters that can be identified with quality in general, it is essential that the cornerstones for the realization of quality be identified in specific to be enforced realistically. The preceding chapters have indeed dealt with some of these parameters in great detail for the concrete mixture design methodology and maybe at this stage it is only appropriate to delineate them in crisp and readily identifiable parameters, even without going into why and how these have been chosen as such discussions have all been presented earlier. In this process it is also possible that maybe some parameters that have a more direct and appropriate connection with certain specific processes of concrete construction have been left out, and it is essential to revise or at least incorporate other such parameters every time a new project is being considered.

- The strength of the cement at a water cement ratio of 0.50,
- The combined aggregate grading curve or the individual grading that represent reasonably the combined aggregate grading curve,
- The water cement ratio limitation from the environmental aspect and the corresponding strength and cement content,
- The consistency requirements from the size and shape of the structural member,
- The transport, placement and compaction as well as curing regimes, and finally
- The strength of the concrete at regular intervals.

The actual tests that have to be enforced are probably more appropriately discussed in the later chapters.

8.8 Concepts of Reliability

Notwithstanding all the precautions that one takes to ensure quality in terms of the materials, production, placement and compaction, curing, etc. in putting together a concrete mixture of the desired quality, the fact that the processes are associated with a certain degree of variability is obvious. In a way it is this variability that has always been the reason for almost all the national codes suggesting or even specifying that the concrete mixture design be verified through a trial mix. Even after this, the inadvertent variations in the constitutive materials could result in a certain variation from batch to batch in the construction process. Without going into the theory of reliability and its evaluation by ascribing partial reliability factors to each material and process, the variations associated with the concrete in place are monitored many a time through its strength characteristics. While this may be the final test for a specific product quality, appropriateness and reliability of the processes adopted, the actual strength result of the concrete in place is only available at the end of 28 days. As an ideal observer of the concrete process, maybe it is possible to set reliable guidelines for observing the intermediate behavior of the concrete, more so in the green state and early age so that appropriate remedial or corrective measures could be put in place. These intermediate observations can also be correlated to the final 28 day strength value, and it may be possible to have an adequate understanding of the final resultant product well before the 28 day period. Looking at the variability of a few specific parameters that have a bearing on the characteristics of the concrete that is required for the particular application (not necessarily just the strength value of it) may not only support the quality assurance aspects required but will also ensure that the final concrete will have all the attributes that are desired for a satisfactory performance in the given environment.

Naturally, it is important that such intermediate stages where observations can be made (in most cases are anyway already available) are identified for each particular operation (as some of them could be even operation specific). However, in a broad sense the following may be ideally suited for being considered as the intermediate process results, which can be correlated to any of the final quality assurance parameters desired. These could be briefly listed as the following.

Observations on green concrete

- Excessive bleeding and its influence on the water cement ratio,
- Segregation and its effects on pumping and consolidation,
- Slump retention and effects on consolidation,
- Initial hardening time through penetration test,
- Effect of the heat of hydration up to 24 hours at regular intervals.

Observations on hardened concrete

- One, three and seven day strengths for assessing strength gain rate,
- Initial drying for understanding curing needs,
- Normal NDT tests from time to time.

In fact there are several other nondestructive tests that could be a part of such quality assurance procedure, each of which could be representing some parameter of interest, and one of the most appropriate amounts could be chosen with the particular constructed facility in mind. The most important aspect as aside from reliability is that no single test or even two will seriously be able to predict with reliability the parameter considered most appropriate for the situation. It is always essential that no less than three parameters should present a coherent outcome with reasonable reliability. This is also a fact even when considering the other aspects of the concrete behavior like the strength or other durability and corrosion parameters.

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9

Very High Performance and Sustainable Compositions

9.1 Introduction

A specific understanding of concrete compositions that are sustainable while they could exhibit a very high performance is always the most sought after by the entire community associated with built space. The previous chapter actually deals with a very specific aspect of trying to look at methodologies for producing concretes that could serve as general-purpose materials used most commonly. These are essentially materials that could interpret very large quantities of low-end pozzolanic materials for ensuring a sustainable product of medium strength. However, with the advent of superplasticizers and the high efficiency pozzolanic admixtures, the possibilities for realizing concretes of high strength as a high performance which would still be products of admirable sustainability have increased enormously. In simple terms, with a judicious choice of the constituents that include chemical and mineral admixtures, it is possible to realize concrete mixtures that could have almost the strength of steel at least in compression. The journey of concrete from its humble beginnings over the millennia is an interesting one to be traced, and as exact appreciation of the various factors and modulations that contributed to the performance of concrete in reaching levels of such excellence is to say the least highly fascinating. It is probably not within the realms of possibility of a simple chapter like this to go through the various machinations and modulations even without such a chronological trace. Naturally, to be in focus with the requirements of understanding the concrete mixture design procedures, the following few paragraphs explain broadly the salient aspects of arriving at concretes of higher strength, performance and sustainability.

The need for adequate flexibility of the green concrete to fill the mould appropriately, even while is being adopted for its compaction, far outstrips the water needed for hydration of cement in the concrete mix. In fact, the porosity created by the water remaining in the concrete skeleton immediately after the final set reduces with time due to the hydration products of cement enhancing the strength of the concrete. However, the void space that is remaining in terms of its porosity in general and the permeable porosity in particular that influences both the strength and performance (in terms of environmental ingress and the resultant degradation) is the subject of discussion at all levels in concrete technology. Incidentally this also explains the reason for the effectiveness of the strength to water cement ratio relationship, as it is increasing volume of this additional space occupied by water that could not be filled with the hydration products that leads to the lowering of strength and higher water cement ratios. While it is one of the primary objectives to reduce the water content to the extent possible to improve strength, the need for an appropriate workability or consistency forces an increasing of the water content. The consistent efforts to balance the dichotomy through various methods, be it vibration and pressure or be it the use of the materials like superplasticizers to release the water locked up in the cement flocculation to be available for the necessary flexibility of such concretes, essentially makes up the entire technology and modulations in the cementitious compositions. While the contributions with chemical admixtures is one facet of the concrete's development over the years, the pozzolanic and pore filling contributions of the supplementary cementitious materials contributed to the strength gain in the short-term, and the long-term has been a long and exalting story stretching over the past couple of millennia. The full impact of the possibilities are associated with the modulations possible in terms of making near homogeneous defect free cementitious materials, though the constituents and the production, compaction and effective curing are still being investigated.

Also, the fundamental reason for the normal concretes exhibiting considerably lower strengths could be traced to the possible weak zones in the normal concrete compositions which have to be addressed during the efforts toward the making of very high performance sustainable concrete compositions. It may not really be appropriate at this particular stage to recapitulate some of these aspects through a different perspective to ensure that we understand the need for such modifications in the composition and characteristics of the constituents and process on concrete mixtures.

9.2 Concepts of Concrete Fracture and Propagation

The failure and fracture characteristics are best understood in a system through the appropriate identification of the possible defects present in it. In the case of concrete, fundamentally one can say that the shrinkage and temperature effects produce a large number of micro cracks that could influence the failure characteristics. The effects of the capillary pores and voids (not considering imperfections due to inadequate compaction like honeycombs) could still be a crack initiator during the review process. Apart from this, the interface between the aggregate and the mortar matrix, what is known as the interfacial transition zone (ITZ), which always presents a weaker link in the matrix, is another point at which a crack can initiate. While discussing the ITZ in particular, the possibility of water lenses associated with the bottom sides of the aggregate suspended the matrix which entrap the bleed water should also be recognized. In fact, a very large quantity of the calcium hydroxide associated with the hydration of cement is precipitated in these water lenses at the bottom of the aggregate and also on the surface of the aggregate where initially the wetted surface presents itself as a highly accommodating location. Figure 9.1 presents a brief view of these water lenses which tend to present the weaker surfaces due to the low strength calcium hydroxide precipitated in them and the higher the water cement ratios associated with the region. These are indeed the potential crack initiators while the propagation is continued through the shrinkage and thermal cracking as well as other porosity related defects associated the concrete's internal structure.

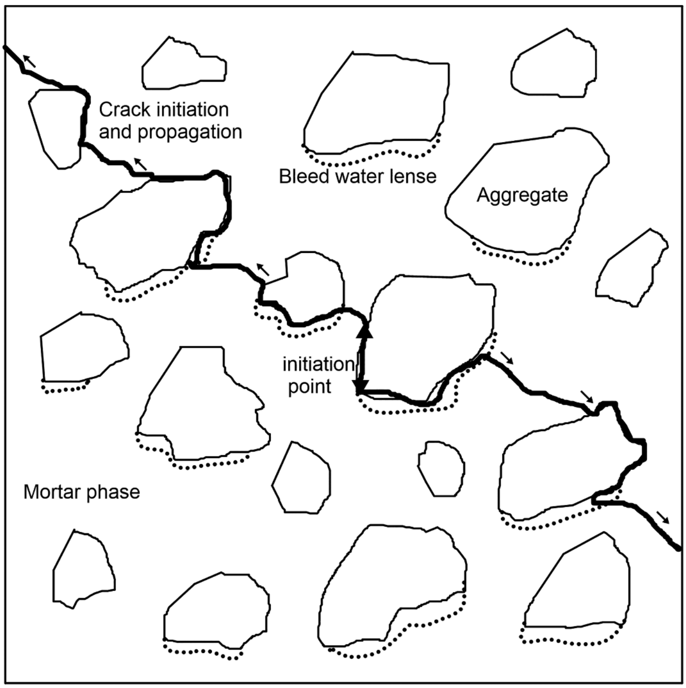

FIGURE 9.1
Effect of water lenses on the failure process.

The broad sequence of events that constitute the failure of the specific material is well understood through its stress strain relationship. Naturally, compressive strength being the most all pervasive material property, the stress strain characteristics of concrete should be better understood to have a handle on the modifications required to ensure both a higher strength and performance. Not being seriously concerned with the effects of platen restraint on the laboratory experimental investigations associated with the compressive strength testing of concrete at this point, a typical stress strain relationship of the normal concrete specimen could be represented through Figure 9.2. Figure 9.2 presents the entire stress strain behavior in which the following stages and the characteristic internal microstructural behavior of the concrete specimen can be seen. These observations on the internal microstructure are all based on the experience of several experimental investigations using direct methods like x-ray techniques or even indirect methods like lateral expansion due to Poisson's effect, etc.

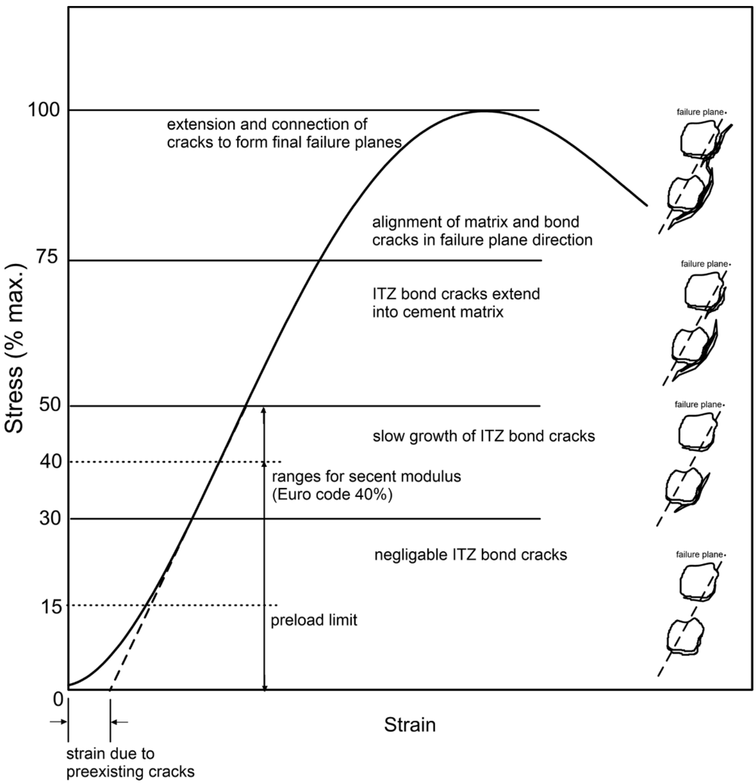

FIGURE 9.2
Effects of internal cracking and propagation on stress strain curve. (After Glucklich, 1965.)

- To start with, the initial effects of compression due to the closure of the cracks perpendicular to the line of stress present a specific nonlinearity, reflected through the strain offset in the stress strain relationship.
- Corrected for the strain due to the pre-existing cracks, the stress strain relationship will look almost linear for almost about 50% of the maximum concrete is strength, though in principle the stress strain curve is never really linear in any portion. The fact that this apparent linearity is used in most codes provisions that the slope of the backwards extended linear segment up to 40% is chosen to be the secant modulus of the particular concrete. Some researchers have even extended this limit to 50% in the computation of the secant modulus.
- Also, maybe it can be presumed that there are negligible bond cracks in the ITZ regions up to a level of about 30%, and any minor opening of the existing cracks is indeed compensated by a corresponding closure of the few in the transverse direction as discussed earlier.
- Between the 30% and 50% stress levels, the bond cracks in the ITZ region start not only to open up but could extend a little beyond their original size leading to 2 year non-recoverable strain which will make the stress strain curve non-linear. However, any removal of stress at this particular point may allow these crack extensions to close, showing an apparent linearity in the behavior of concrete. This can be seen in the small representative diagram presented on the right-hand side in Figure 9.2. In fact similar representative diagrams for each particular zone can be seen therein.
- After this zone, further stress will not only extend these ITZ bond cracks but the extensions will also be influenced by their joining with the matrix micro-cracks, which will continuously make the stress strain behavior more and more non-linear. This may continue up to about almost 75% of the strength of the matrix. However, the matrix is still intact and a large portion of the strain can still be recovered. It may be at this stage that the failure planes and their orientations get defined to a large extent.
- The last zone will be defined by the extension of these ITZ bond and internal micro-crack combinations to align themselves by joining and forming the final failure planes. At this stage, the system is potentially unstable initially, and loading it further will lead to the totally unstable mechanism situation at about 90%. In fact, the system will fail even if there is no further loading due to creep itself. The reviewers on formation in extension in the various zones as described can be seen diametrically in the figure itself as already stated.
- After reaching the ultimate strength capacity of the concrete specimen, the continuing connectivity of the system will lead to larger strains and deformation which cannot be sustained by the loading mechanism, and an apparent drop in the concrete stress strain curve is obtained as can be seen in the figure.

9.3 Recent Outlook in Design Methodologies

In light of what has been discussed in the earlier few paragraphs and the other aspects covered in the previous chapters, one can present a broad outline of the methodology for achieving higher strengths and performance without sacrificing the ultimate goal of achieving the reasonable sustainability of the material concrete. These can be viewed generally in relation to the characteristics of the constituents, cementitious materials and aggregate and probably the mixture design methodology associated with it. Without going through a detailed discussion on each of these aspects, the following few lines present the salient points as a quick review of the various aspects covered earlier.

9.3.1 Cementitious Materials

The strength characteristics of the cement could be significantly improved. For normal constructions, the 42.5 MPa strength grade cement could be used (with a guaranteed strength of 52.5 MPa at 0.50 water cement ratio in a 1:3 mortar as recommended in the Euro standards). For very high strength concretes, cements of 52.5 MPA strength grade (with a guaranteed strength of 62.5 at 0.60 water cement ratio) could be adopted.

Knowing the fact that the strength of concrete is directly related to the strength of cement, this would help in reducing the cement consumption significantly, naturally resulting in very large savings.

The possible use of superplasticizers will help in further reducing the cement consumption yet making concrete constructions significantly homogeneous and defect free.

The use of supplementary cementitious materials could be promoted to improve the ITZ. The efficiency of the pozzolanic materials in conjunction with superplasticizers used for the time being could still be as specified in the Euro standards, though for effective testing these values should be further perfected.

The possible values for of efficiency of a few of the pozzolanic admixtures like fly ash, GGBS, silica fume, RHA, metakaolin, zeolite and even lime stone powder have already been suggested through experimental investigations in the laboratory and could be used with the appropriate modulations.

The use of lower efficiency pozzolanic admixtures will help in ensuring economy in concretes of lower strength grades. A minimum cementitious materials content of about 350 kg/m^3 may be advised for ensuring cohesive mixes even at the lower strengths.

The higher efficiency pozzolans could result in the materials of higher performance as well as high strength. It may be appropriate to suggest minimum total cementitious materials content of about 450 kg/m^3 for concretes of strengths beyond the 70 MPa (10,000 psi).

In fact, there is no necessity for such a clear demarcation between the higher and lower strengths, and one could appropriately choose the cementitious materials content for concretes up to the 100 MPa strength grades, not to be beyond the level of 550–600 kg/m^3.

9.3.2 Aggregate

The maximum size aggregate size could be retained at 20–25 mm for the lower strength structural concretes (strengths below 60 MPa) from the general economic considerations.

For structural concretes of strengths beyond 50 MPa it is prudent to make the maximum aggregate size smaller and in fact a continuous reduction (16 mm for strengths up to MPa; 12 mm for strengths beyond) is ideal.

The smaller aggregate will help in reducing bleeding and segregation apart from making concrete homogeneous while simultaneously reducing and also distributing the bleed water lenses at the bottom of the aggregates.

It is also preferable to suggest the continuous combined grading of aggregate for all concretes irrespective of the strength grade to avoid gaps in aggregate grading which will necessitate higher fines and thus higher water contents reducing the strength of concrete.

All the above suggested values are generally as perceived through an understanding of the different national and international standards available today and could be modulated appropriately wherever necessary to ensure the highest economy in terms of the total costs of the constituents and their availability for each project.

9.4 Modern Mathematical Propositions

The possible avenues suggested as the recent outlook in design methodologies while generally present in the guidelines do not clearly propose a specific methodology for achieving them directly. It may not be possible to entirely delineate the procedures and processes for ensuring or realizing some or all of them, but it is necessary to project how to make them operational in a broad sense. One of the first requirements probably is to look for the appropriate strength to water cement ratio relationship that could be adopted. Naturally the available strength to water cement ratio relationships from the Euro code presented earlier for the 42.5 and the 52.5 cements strength grades could be shown as the most appropriate presently. To be explicit and to give a clear picture of the strength to water cement ratio relationships from both the cement strength grades suggested, it is necessary to look at them more closely and to relate them to the existing recommendations of the various national bodies as of today. This will help in adopting the existing regulations in the various national bodies without much of a change and will also be an enormous matter of comfort or the practicing community that is already attuned to the existing norms. Even so, it is also suggested that the expectation from these regulations could be slightly downgraded (maybe up to about 5%) if it was felt that the existing cements of the present national scenario will not be able to accommodate it immediately. However, the following discussions clearly show that what is being recommended and sought is in no way different from what exists already in the various national codes, and the recommendations only try to put it in probably simpler terms to ensure clarity.

It was seen in the earlier chapter on Euro regulations that the proposed relationships in the Euro code (EN 197-1, 2000; Sika, 2005, 2013) could be summarized through the exponential equations presented in Figure 7.6. The euro regulations presented at concretes at water cement ratios below 0.35 constitute the high strength structural concrete grades. In fact, the strength to water cement ratio relationship for present day 42.5 grade cements was seen to be the one below.

$$f_c = \exp(-2.25 * X) * 159$$

It is also to be reiterated that literature suggests that the 53 grade cement of the Euro standard is almost akin to the rapid hardening cement (RHC) as referred to in the national regulations in several countries. This actually provides an avenue for defining the strength to water cement ratio relationships of these concretes without having to explicitly recognize even the strength grade concept.

In a way, for reasons of simplicity and for ease in understanding and memorizing, this expression could be simply replaced with the following without any major deviations that is very similar to the one that was presented during the discussions on the ACI recommendations.

$$f_c = \exp(-2.20 .* X) * 155$$

It may be noted that the proposed ACI relationship was arrived at considering water cement ratio to strength relationship given by ACI 211.4, for high strength concretes (with both high range water reducing admixtures and pozzolans) containing 20 mm maximum size aggregate, which is once again given below for an understanding and ready reference.

$$f_c = \exp(-2.60 * X) * 155$$

It is only appropriate to recognize that the present Euro relationship is also for structural concretes containing concretes with similar materials. To be more explicit and to have a very clear picture of the strength to water cement ratio recommendations from the various major national bodies, the

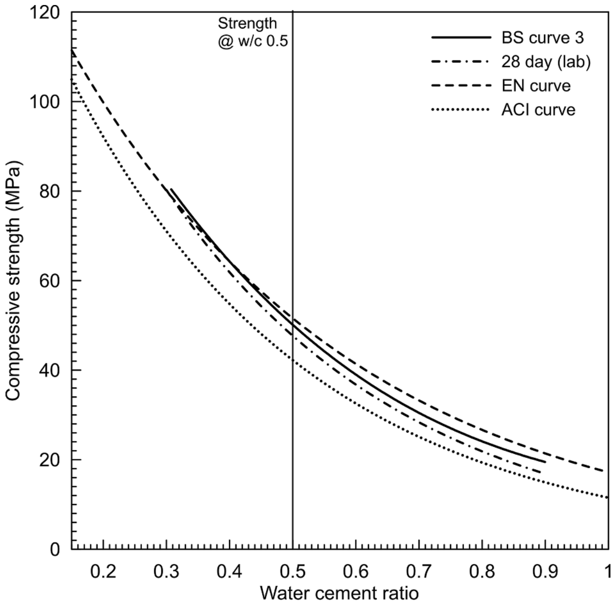

FIGURE 9.3
Comparison of the water cement ratio to strength relationships (BS, EN, ACI and Lab).

comparison of the 28 day strength characteristics as perceived is presented in Figure 9.3. It is evident from this figure that the British and Euro recommendations are indeed very close to the 28 day laboratory values presented. However, the ACI relation appears to be certainly below the others. Knowing that, the difference between the strength characteristics presented by the ACI and Euro norms is that the standard specimen for testing in the case of ACI is a cylinder while the same for the Euro specifications is a cube. Naturally, by considering the cube to the cylinder strength ratio (as given in EN 206, 2000), the present ACI relation will almost coincide with the relation proposed for the water cement ratio relationship for Euro 42.5 cement. These observations indicate that the general-purpose cements produced in the recent years (mostly 42.5 MPa cement grade) should invariably be resulting in almost the same strength the world over. To be more precise, the concretes produced with the normal cements as manufactured today (using almost the same type of machinery and the same advanced manufacturing standards) should be able to result in a strength of 52.5 MPa at a water cement ratio of 0.50 as required for the 42.5 cement of the Euro standards. Even if one has to accept the possibility of a very bad aggregate grading and also an inadequate production capability, the corresponding concretes should have strengths a little above 45 MPa at the water cement ratio of 0.50 under any circumstances. This could be used as an acid test for the acceptability of the quality standards of the cements and concretes manufactured internationally.

Following up with characteristics of the constituents and the method of enforcing quality standards through the mathematical modeling procedures, one should look for appropriate avenues for understanding the specifications that could help in producing high strength, high-performance concretes in general. Naturally, the need for regulating the aggregates to arrive at an appropriate packing to reduce the cement content ensuring flexibility is a matter of primary importance. One could also look at the possibility of making the grading of both coarse and fine aggregates mandatorily comply with a much closer set of variations at each aggregate size, given the significant variations allowed at the various sizes.

It is obvious that aggregates constitute the bulk of the total concrete volume. The characteristics of the coarse aggregate which influence the behavior of concrete are its type, size, shape, surface texture and gradation (Ganesh Babu et al., 1992, 1999). In a well-designed concrete mixture, the different sizes of aggregate are expected to be bound by the cement paste. Also, the cement content expected is a small percentage of the total concrete (300–600 kg/m^3) with the aggregate cement ratios generally varying between 3.0 and 6.5. Naturally it is essential to have an appropriate grading of these aggregates to give a concrete with minimum voids that helps in producing concretes of high strength and economy. The various codal provisions follow essentially two different methods of either the overall grading of all in aggregate or the grading of the individual coarse and fine aggregate separately, which are later mixed to form the total filler. In both the cases, the maximum size of aggregate is defined based on the dimensions of structural member and the reinforcement spacing. The water contents required for any specific workability will depend on the total surface area to be wetted. An increase in the finer proportions will make the mix more cohesive but require a larger water content, ultimately affecting the cement content. Thus it is required to find an optimum solution for this problem. Probably the most highly detailed account of the various characteristics of aggregates overall is presented by Popovics (1978).

It can be seen that the combined all in aggregate grading is recommended by in a few codes like CEB-FIP (1994) and DIN (1988). However the American (ASTM C 33, 1986), British (BS 882, 1983) and the Indian (BIS, 1973) codes look at grading of the coarse and fine aggregate separately, mixing them in an appropriate proportion based on the type of finer material used (fineness modulus of sand as in ACI and particles below 600 microns in the latest British specifications). It is obvious that an increase in the finer fractions of aggregate can ensure a better packing and also a better flexibility to the concrete. The increased fines content in self-consolidating concrete compositions essentially stems from this particular perspective. But this increase in fines content will also mean a higher surface area required to be wetted and will need higher water contents resulting in higher cement contents at the same water cement ratio for a given strength.

It is known that as the maximum size of the coarse aggregate increases, the mix becomes economical as the cement content decreases (Neville, 1971). But in practice, the dimensions of structural members and the spacing and distribution of the reinforcement will have a restraint on the maximum size of the aggregate. Moreover, mixes with smaller size aggregates yield higher strengths in comparison to mixes with relatively larger size aggregates (ACI 363, 1984). These things have to be borne in mind while designing high strength concrete mixes that are essential for tall and long span structure and for structures in an aggressive environment. It is clear that in most codes the allowable range of variation is of the order of 40% at some of the sizes. Experience in the laboratory is that it is very difficult to maintain the required slumps with such a wide variation allowed in the grading for both coarse and fine aggregates. This problem is highly accentuated for high strength concretes (of low water cement ratios) with or without admixtures. Presently, with the availability of the weight batching plants, the required grading for the coarse and fine aggregates or even the combined aggregates can be easily obtained within a very narrow range. As a corollary, the consecutive sieve sizes for establishing the grading requirements of coarse aggregates can be chosen nearer. This obviously means that there is an urgent necessity for a relook into this aspect.

The DIN specifications (DIN 1045) present the combined grading modulus (k) for the all in aggregate grading. This value is based on a total of 9 sieves starting from 63 mm to 0.25 mm. This is similar to the fineness modulus of the fine aggregate as considered by the ASTM C 136 (1995). The ASTM considers only the cumulative percentage of the material retained on the sieves: 0.15 mm, 0.3 mm, 0.6 mm, 1.18 mm, 2.36 mm and 4.75 mm for calculating the fineness modulus of sand which influences the water requirement most because of this is the finer fraction in the mix. To have a clear picture, the grading curves for coarse aggregate (of 20 mm maximum size) and fine aggregates as given by ASTM C 33 (1986) are presented in Figure 9.4.

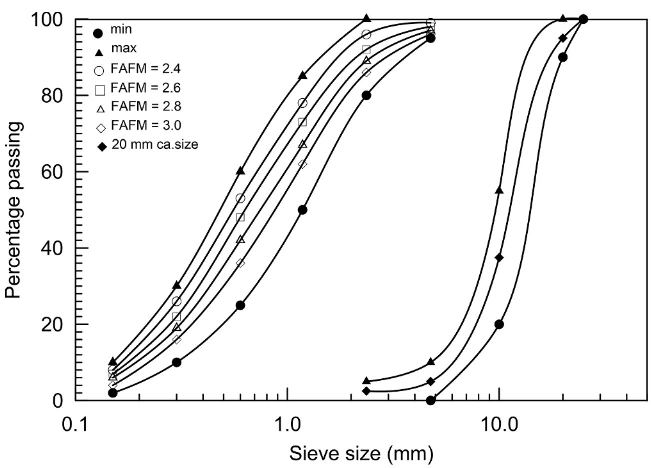

FIGURE 9.4
Grading of fine and coarse aggregate as per the ASTM.

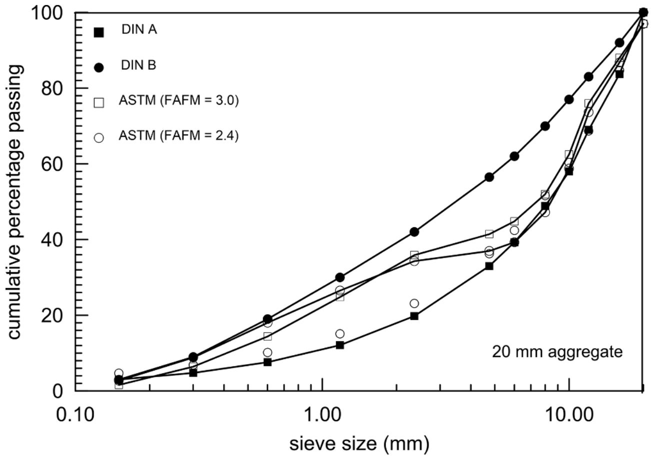

FIGURE 9.5
Comparison of the combined grading as per DIN and ASTM.

Assuming that the grading of fine aggregate follows the best possible distribution for the different fineness moduli (2.4–3.0), these are also presented in Figure 9.4. Considering the maximum size of aggregate to be 20 mm and also considering the two extreme fineness moduli (that is considering the proportions of fine and coarse aggregate by the ACI 211.1 (1991), the resulting combined grading proportions are calculated. To have a clear understanding of this ASTM distribution as compared to the one specified by DIN (modified for 20 mm maximum size aggregate) is presented in Figure 9.5. This clearly shows that there is a significant deviation from the distribution A of DIN (as followed by the coarse aggregate) toward the distribution B of DIN in the fine aggregates of the ASTM combined grading. Though this falls in the good distribution region of DIN, between A and B, The sand content is significantly higher, requiring a much larger amount of water content for wetting.

9.5 Review of Data and Compliance

After a critical evaluation of the various national recommendations for the design of normal concrete mixtures and the associated correlations and comparisons possible from such an understanding, it may be appropriate if indeed the presumptions made over the last few chapters can be reasonably verified with some independent data. It is obvious that already an effort in that direction was made by comparing the laboratory data (along with some of the experimental investigations in literature on normal concretes) with the different strength to water cement ratio relationships proposed in the

British standards (Figure 6.10). The various laboratory relationships evaluated through the data appear to be almost in line with the British strength to water cement ratio relationships. These effectively prove that the British regulations were formulated based on the strength variations with age as was originally done in the Road Note No. 4 as discussed in Chapter 6.

Even after having established that such an excellent correlation exists not just for the mature strength relations at 28 days, but across the board at all ages (1, 3, 7, 28 and 90 days) with the British relationships, it was felt appropriate to see if these correspond to the data available from other sources. In this context amongst the several datasets looked at, the first one by Yeh (1998) was a reasonably large one with over 1000 datasets having details of the constituents. Yeh utilized this data set, and he attempted to model the strength of high-performance concrete through artificial neural networks. A close look at the average curves for the dataset along with the possible maxima and minima have all been evaluated and compared with the appropriate relationships from the BS code. It will be sufficient to say that most of these relationships appear to be slightly below the BS code relationships as was seen from the laboratory data earlier. However, the relationships for the possible maximum values have all surpassed the BS code predictions at almost all water cement ratios. Figure 9.6, as can be seen, presents the same

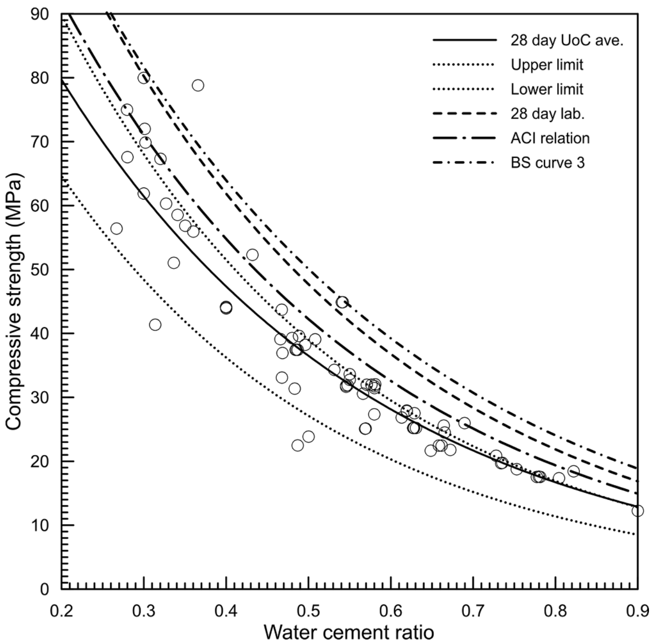

FIGURE 9.6
Comparison of w/c relations with a dataset. (After Yeh, 1998.)

for the 28 day strength relationships with this dataset. Another important factor that should be remembered is that the BS relationship is as already known a servitude strength while the experimental results of the dataset are all for the cylinder strength. Without even bothering for the necessary correction it can be said that the BS code relationships are indeed applicable for this dataset also as was the case with the earlier laboratory dataset. To be brief, the remaining correlations and comparisons of the data with the British code relationships are not being presented herein.

Apart from this, comparison of the dataset available from an entirely different continent was chosen to look at the suitability of the predictions of the BS code relationships for the strength to water cement ratio relationships of concretes at the different ages (Tomosawa, 1993). The available datasets at the age of 3, 7, 28, 90 and 180 days have all been replotted to understand the strength to water cement ratio relationships and were compared with the British code (Figure 9.7). In fact this dataset contains over 3000 concrete compositions that contain a host of different constituents, and only those corresponding normal concretes were analyzed as was the case previously too. Once again a typical dataset of the 28 day strengths is only being presented to be brief, though all the other data at the other age levels were also provided appropriately and compared the BS code. It was seen that a lot of the results of the dataset are above

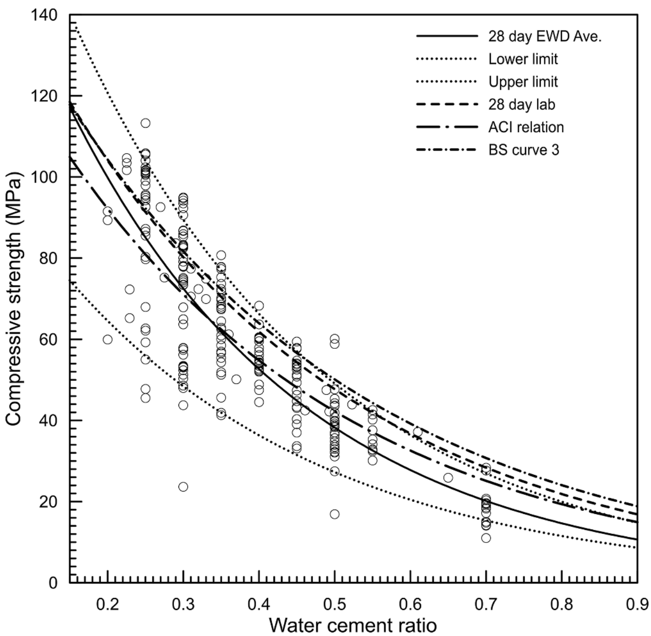

FIGURE 9.7
Comparison of w/c relations with a dataset. (After Tomosawa, 1993.)

the predictions of the BS code. However, the average relationship for the data appears to be just below that of the BS predictions. Notwithstanding this, one can see as already stated a large portion of the data is above the BS predictions. This probably indicates that the BS relationships as was compared with the laboratory relationships in Figure 6.10 can be taken to be the appropriate relationships for the various ages discussed earlier. Apart from this, the equations proposed above for the strength to water cement ratio relationships at 28 days could be taken to be appropriate, even though there are several indications that the predictions from this equation could be well exceeded.

Apart from establishing the appropriate water cement ratio relationship for at least the 28 day strength, to have a reasonable and effective way of ensuring that is to have some control on the grading distribution of the coarse and fine aggregates. In the light of what was already discussed, it can also be said that the combined grading distribution is probably the most appropriate. In the light of this, a brief discussion on the present Euro status, even if it were to be confusing a little by deviating from what has already been said to be the most appropriate, is presented in the next few lines.

A more apt discussion on the grading regulations, the possibilities of combining the aggregates in the broader perspective can be had through a look at a comparison of the present Euro norms (EN 480-1, 2006) and the earlier DIN (DIN 1045, 1988) regulations presented in Figure 9.8. While presenting the aggregate composition for the reference concrete, EN 480 has actually specified the grading distribution limitations as given in Figure 9.8 which is at variance with the earlier DIN specifications. However, it is recognized that the specification continues to adopt a combined grading curve of the coarse and fine aggregates. In an effort to delineate the appropriate proportions of the aggregates of different maximum size to arrive at this distribution, the SIKA Corporation as an example presented that this could be achieved with the combination of 20% of 18–32 mm, 20% of 8–16 mm, 12% of 4–8 mm gravel and finally 48% of 0–4 mm sand. This combination resulted in the approximately average distribution curve shown in the figure. In an average setting if one is not careful and uses only 32 and 16 mm maximum size aggregates with sand (generally expected to be below 2 mm), the portion of aggregate sizes that could be missing can be clearly seen in the figure marked. Even if the 4–8 mm size aggregates are utilized, in all likelihood the aggregate sizes between 2 and 4 mm could still be missing. Also aggregate sizes that are at the lowest end (below say 150 μm), if present in larger quantities of almost 10%, may require additional water for wetting. It may also be noted that in spite of all these aggregates combined to arrive at an appropriate grading distribution, the EN 480 recommends a combined grading curve well above both the DIN A and B grading curves. These aspects have to be further considered and evaluated for an specific judgment on the appropriate grading distribution that could be suggested concrete.

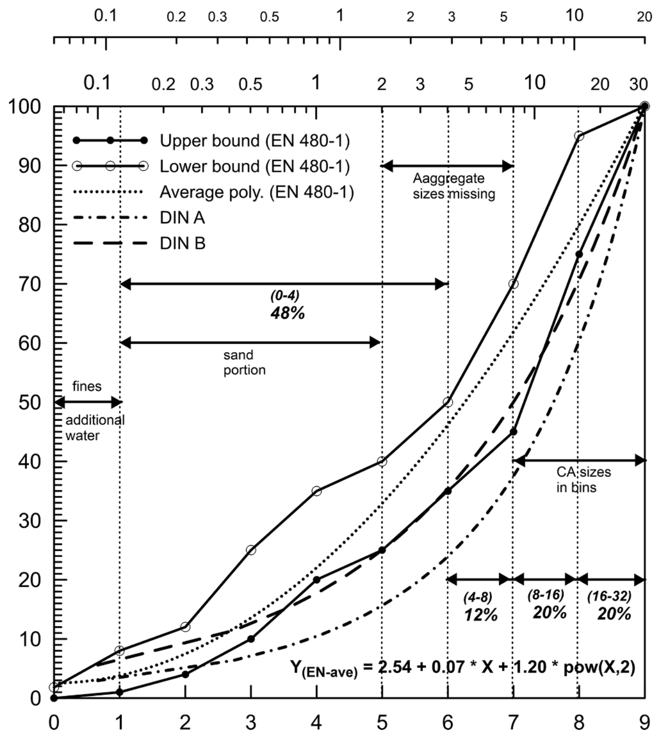

FIGURE 9.8
Comparison of the combined grading regulations. (After EN 480-1 and DIN.)

9.6 Concepts for Very High Strength Compositions

The need for very high strength compositions appears to be in increasing demand, with the advancements in the construction practices as the constructed facilities being proposed to accommodate the increasing stress on urban infrastructural needs. Obviously it is not possible to exactly specify and enforce a set of regulations without understanding the structural configurations and the environmental interaction. However, a broad set of guidelines could still be mandated to effectively ensure the realization of very high strength compositions.

- The first one is the choice of the cement itself, and it is advanced that the Euro 52.5 grade cement is recommended. Naturally, in the first place it reduces the amount of cement that is required for the expected strength grade, which incidentally also reduces the required water content. As a corollary, taken as a percentage in most cases, the amount of chemical and mineral admixtures associated with the proposed concrete mixture will also reduce. This makes the concrete certainly less reactive to the environment while at the same time achieving the engineering perspective of economy.

- The second end of the more fundamental aspect is to recognize the fact that the water cement ratio strength relationships proposed by Euro standards are indeed appropriate and effort should be made to realize this both through an effective cementitious materials combination along with chemical admixtures.
- In simple terms the last aspect is that for achieving the expected strengths as per Euro standards; it is still required that the aggregate gradation should be appropriate and it is suggested that a combined aggregate grading curve lying in between the DIN A and B curves is the most appropriate.

9.7 Effect of Chemical Admixtures

On the above recommendations and level of assurance, the need for a relook at the chemical admixtures being planned is also essential. Firstly, the compatibility of each one of the admixtures with both the semester as well as the mineral admixtures if any should be established. If there are two or more admixtures planned, the synergistic effects normally associated with such combinations could be effectively exploited. However, it should not be confused with the increase in the total water content influencing the workability in particular. In fact the simplest recommendations could be that all the liquid chemical admixtures quantity should simply be added to the water content for calculating the water cementitious materials ratio or water cement ratio. Apart from all this, a change of brand or source in the cement or the admixtures could result in serious consequences in terms of both workability and strength apart from performance. There is a need to establish the acceptability of each of the materials in the concrete constituents to ensure high strength as well as performance.

9.8 Effect of Pozzolanic Materials

While there are indeed several different pozzolanic materials available to the concrete designer, the utilization of a particular supplementary cementitious material should be based on not just availability but also on its effectiveness and the resulting economy. It is obvious that for high strength high-performance concretes to be sustainable it is necessary to use high-end pozzolanic admixtures like silica fume, metakaolin, etc. One of the first aspects as a precaution is never to consider pozzolanic additions or replacements at levels below 5% for them to be effective. However, any addition beyond 15% should be viewed with caution as the increased super fine material in the system will demand much higher water content for wetting generally. Also it can be safely assumed that in no case are high efficiency pozzolans at levels beyond 20% generally as efficient, and this will only cause problems with additional water requirement and the highly stiff and sticky mixture that is obviously difficult to compact. Experience in the laboratory has clearly shown that even in the case of ultrahigh performance concrete with silica fume, addition is never normally beyond 20% for the effective utilization of its potential. Apart from this, the variations in the characteristics of the high efficiency pozzolanic materials could have a significant influence on the strength characteristics of the concrete which is not immediately realized.

9.9 Thermal Effects and Appropriate Utilization

The effects of thermal gradient and even a huge increase in the heat of hydration are generally not associated with structural systems containing high efficiency pozzolanic materials in general. This is primarily because the larger strength characteristics of the material is obviously a factor that was desired to keep the concrete sections essentially smaller. However, in the highly stressed zones, the specimen dimensions could be significant to warrant an appropriate evaluation of the heat of hydration as well as its dissipation over time. In fact, one of the primary observations in this regard is that the exposed surfaces of the concrete members tend to become relatively dry too soon and any strength loss due to inadequate hydration resulting could hamper the further strength gain, even securing program sets in later. This obviously is not very easy to recognize but can be effectively addressed by misting the surface once the surface water due to the bleed if any evaporates and the concrete is hard enough to walk on. It detailed evaluation which, followed by an effective set of guidelines for ensuring adequate surface moisture required for hydration, is an essential part of the use of high strength concrete compositions effectively.

9.10 Integration, Applications and Limitations

It can be seen that the discussions in this chapter specifically relate to an effort to bring together the relevant information that paves the way for arriving at the high performance sustainable compositions after understanding of the perceptions of performance and sustainability earlier. In this chapter the effort is to look for performance and sustainability of a group of relatively lower strength compositions through the use of lower end pozzolanic materials. This chapter also looks at extending further the concept of high performance in terms of the higher strength materials even. One should remember that the sustainability and the performance characteristics associated with them are not exclusive and could be the sides of the same coin. The only aspect that distinguishes both of them is a fine line between the conventionally used normal strength compositions that drive the economy to a large extent and their counterparts which are absolutely essential for relatively high-end applications, be it high raise buildings, long span bridges or other important industrial facilities reaching up to the most critical requirements of nuclear applications. One of the factors that probably needs to be articulated, explained and driven home should be that the high strength compositions that have an abnormally low permeability will have serious limitations when exposed to high temperature. The fact is that even the small quantity of the internal water trying to evaporate at higher temperatures will not have the pathways in the pore system like in the lower strength concretes and thus leads to pop-ups and blistering of the surface of the concrete. In particular, the first recommendation is the limitation on the use of silica fume, a material that should be totally and unequivocally avoided in such high temperature applications or even possible locations. As a further level of caution, it is extremely important that high-strength silica fume concretes should be mandated to be avoided at all nuclear applications, other than those that require waste encapsulation and binding. In fact, for nuclear waste encapsulation, one of the best alternatives is to look for such very low level of permeability so that the internal moisture is not released to the environment thus causing unacceptable pollution through runoff or other means.

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10

Performance Regulatory Efforts

10.1 Introduction

The previous chapters present an effort to understand the concrete mixture design regulations of the various national bodies and extend the basic design philosophies to arrive at high performance cementitious compositions that has the flavor of a comprehensive international regulation. It is obvious that any such effort without an appropriate regulatory enforcement will certainly not be completed in ensuring the performance characteristics expected of the concrete mixture. The present chapter is given over to present a brief outline of these regulatory efforts required for ensuring performance broadly.

At the very outset, it is to be appreciated that while the aspects related to the improvements in strength can be realized through design which is based on appropriate mathematical relationships and the interconnectivities, performance cannot be consigned to such mathematical precision. The complexity involved in the structure and the environment make performance regulations require not only the characterization materials and processes involved in planning, design, execution alone but transgresses the boundaries of engineering to enter into the realms of form, shape, constructability in architecture and even human behavior. It is certainly not possible to propose an accurate and perfect procedure to enforce quality and performance standards. It can even be said that in each individual construction, the region of location, the environment in which it is supposed to perform, the expected life period, and the quality of maintenance will demand specific and probably different regulatory provisions to ensure performance. The present effort is only to highlight a few of the major aspects and present the possible avenues for achieving the required performance in the constructed facility.

10.2 Regulatory Authorities and Certification Efforts

The regulatory effort in envisioning and creating the constructed facility large or small will essentially need an understanding of the functional utility, performance effectiveness and above all the cost (necessarily the life cycle cost) and economics. It is obvious that as the facility becomes more complex, the number of associated organizations and individuals responsible will increase, naturally with the accompanying complexity of their interactions. It is but natural that such a complex and interactive process needs an organizational setup that is coordinated and controlled through well delineated tasks and responsibilities including the time periods for each particular operation in the overall scheme of construction. A complete review of the associated entities and their hierarchy in the complex structural construction scenario is certainly not in the realm of the discussions planned herein. At present only a specific aspect of the key issues and associated regulatory requirements through the organizations responsible in the construction of a facility with concrete as the primary building material is being looked at. Even so, how it integrates into the broad structure of the overall responsibility of constructing the facility is also a matter that needs a clear delineation and acceptance. It is essential that there is a certain structure to this enforcement mechanism, which will look at not just the progress that also the quality of materials and work that goes into this progress. A typical outline of the possible structure for this effort can be probably best explained by an organizational chart (Table 10.1) that has the responsibility both to the construction and the facility owner or operator.

While the above table is expected to be nearly self-explanatory, it may be appropriate to highlight a few of the aspects that are enshrined within but have a much larger significance in the overall quality and performance assurance scheme. In fact it is the introduction of the roles and responsibilities of these few that augment, enforce and maybe even deliver the final product in the way what it should be. As can be seen, these aspects are even highlighted in the table itself, but to be more specific, they are explained for clarity in the following few lines.

- In the first place, the client should actively look for an appropriate consultant with the right vision and a clear perception and understanding of the facility being planned. He is the one that directs the complete construction of the facility on behalf of the client, and should have the overall responsibility from concept to completion.
- With a view to ensure the appropriateness and the economy of the construction, the need for a design proof check through a competent person or persons (certainly not just for the reason that they are in a reputed organization) is essential.
- In a similar way that the quality assurance program with a third-party is almost the order of the day, it is obvious that because of the

TABLE 10.1

Organizational Setup for Quality Enforcement in Concrete Construction

Role	Responsibility	Evaluation Strategy	Enforcement Mechanism	Remarks
Overall planning	Client Consultant Contractor Engineer	Final coordinating authority	Evaluation of milestones and modifications	Responsible for a comprehensive review
Engineering design	Consultant Engineer	Facility design	Construction feedback	Ease of construction
Proof checking	Consultant Competent external agency	Design efficacy	Consultant and client reports	Alternative solutions
Materials management	Engineer Contractor	Quality of materials, storage and delivery	Quality assurance team reports	Materials sourcing
Concrete production	Engineer Contractor	Plant upkeep and concrete quality	Quality assurance team reports	Productivity
Transport and placement	Engineer Contractor	Delivery schedules	Quality assurance team reports	Timeliness
Compaction, curing and finishing	Engineer Contractor	Finish quality	Quality assurance team reports	Effectiveness
Quality assurance	Engineer Contractor Third party	Record of the total activity	Quality audit report	Accuracy of records
Quality audit	Consultant and competent external agency	Periodic inspection	Consultant and client reports	Appropriate feedback
Maintenance and upkeep	Consultant Contractor Client	Operational assurance	National and regional regulatory bodies	Operational quality

continuous presence in the day-to-day operations, the concentration to its quality is often neglected in the interests of maintaining an appropriate and exhaustive record. The quality audit of the design and construction by an off-site organization that could make periodic, yet an unannounced appearance to verify the validity and the appropriateness of the construction progress as well as the quality will be a great help.

- Lastly, enforcing a clause that there is a performance guarantee to the structure for at least 10% of the short lifetime of the structure (or maybe a minimum of five years alternately) is certainly a reason for the entire construction team to perform. Making the consultant and the contract along with the client responsible for this will certainly promote a measure of compliance in delivering an appropriate structure of the right quality.

The various aspects concerning premature degradation of concrete structures was also addressed by several organizations, amongst which the CEB guide to durable concrete structures (CEB, 1992) presents a simplistic view of the degradation mechanisms in fair detail. It also speaks of the aspects like quality assurance and quality appraisal mechanisms of the total concrete construction scenario.

10.3 Historical Efforts Toward Assurance

The concept of quality assurance is well known presently in the construction arena. With the projects becoming larger day by day and more complex involving several specialized agencies, the planning and management of the sequence of events that need to precede and mash with all the succeeding processes has enforced the evolution of an entirely new branch of engineering, construction management. The entire gamut of speed and efficiency of the construction in progress, management of materials and manpower, integration of the different facets involving civil, mechanical, electrical and even communication requirements and above all the quality assurance are each a mammoth task. In principle, each of these is essentially turned over to the respective agencies performing the actual work and probably loosely overseeing the progress in terms of delivery. The internal quality assurance of each of these aspects is the responsibility of the subagents responsible, which obviously means that there is no supervisory control over the total process. This naturally led to efforts to delineate responsibilities to agencies that have an exclusive domain of operation in terms of quality assurance, but these have remained largely recording stations with no major effect on progress or quality. Over the years, several different methodologies have been suggested to keep the roles of each of these organizations involved in line with the objective of achieving the fastest construction with highest quality standards. Incidentally, it is necessary to realize that each project, if looked at closely, will have intricacies and differences that are quite challenging, and naturally a set table of routines will have difficulty in addressing appropriately the aspects concerning such intricacies. In a way, while there could be a broader overall guideline, the need for re-engineering the process to suit the needs of a specific project is probably the need of the hour.

10.4 Quality Evaluation, Assurance and Audit

In the construction scenario involving concrete as the primary structural material, knowing the sequence of operations associated with concrete, production, delivery and placement, etc., the broad stages at which such an assurance process is viable and appropriate could be listed as the following.

- Production
    - Sourcing material for construction
    - Processing and storage
    - Recovery for production
    - Mixing
- Transport
    - Transport and transit mixer
    - Site delivery schedule
    - Delivery quality
- Placement
    - Casting
    - Compaction
    - Leveling
- Curing
    - Method of curing and frequency
    - Surface crazing cracks
    - Deeper structural cracks
    - Surface finish, air voids, honeycombs
    - Minor rendering if required

It is obvious that this list is neither exhaustive nor directs the complete picture of the requirements but is often quoted as the outline for effective quality assurance. Amongst these major operations, it is probably appropriate to list some critical aspects that may have the largest say on the quality assurance operations.

1. Quality of cement, particularly strength
2. Grading of aggregate, compliance with combined grading curve
3. Efficiency of supplementary cementitious materials
4. Concentration and water content in chemical admixtures
5. Efficiency of mixing, transport through quality of material delivered
6. Effective placement, compaction and curing

A broad check to enforce a reasonable regulation with a well-defined variation allowance will make the concrete reflect desired performance. Each one of these stages could be monitored at different times and frequencies to facilitate easier compliance and faster construction.

10.5 Methods of Evaluation and Efficacy

After having broadly understood a comprehensive perspective of the quality assurance requirements in concrete construction along with the critical operations that have a larger say on quality, it is only proper to concentrate exclusively on the qualities of concrete itself that need be established and ensured. In fact, it is mandatory that some of these qualifications are complied with for allowing it to be utilized in any part of the structure. It is only through this process that an impeccable assurance of the concrete quality can be guaranteed. The prequalification requirements of different materials and the mixing, transport, placement and compaction assurances have been no further considered for discussion and are supposed to be in order. In most cases these parameters need necessarily be checked and approved either monthly or whenever there is a change in the material, process or equipment associated with the operation. At this stage only the final quality of the concrete is being considered for a relook. However, the quality of the concrete is not just to be ascertained at the point of delivery and placement but at least at the following stages of its delivery.

1. The first stage of assurance check is immediately after mixing
2. The second is immediately after the transit mixer arrives on-site
3. The third stage is to evaluate and the placement location

It is not necessary that all the associated press be done at every one of these points, and a judicious mix as well as repetition of these along the supply chain will go a long way in ensuring quality of the concrete delivered resulting in an excellent performance.

Table 10.2 presents a broad outline of the various quality inspection and acceptance criteria tests that are relevant to most concrete constructions. It is not mandatory that all these tests will be done, and there could be a bouquet of tests that are probably the most appropriate for each particular construction scenario depending on the structural facility and the environment which it will be subjected to. This is very clear from the table itself, as it includes a separate segment of tests that are possible and may be necessary in a specific scenario. The choice and the frequency of the testing and maybe even the test methodology could be discussed and delineated between the concerned parties with the understanding that finally the consultant will choose to prove them.

Notwithstanding the fact that this entire quality assurance program and the acceptance criteria are in place, it is best and probably most appropriate to have an audit party that verifies the program, procedures, methodology and the results along with the consultant periodically. In fact there

TABLE 10.2

Concrete Quality Inspection and Acceptance Criteria

Parameter	Test Method	Frequency	Approval Criteria	Remarks
Initial mix proportions	Weigh-batching records	Every batch	As specified	@ All stages
Concrete condition	Visual inspection	Every batch	Bleeding, segregation and consistency	@ All stages
Concrete temperature	Temperature probe	Every batch	Temperature values and variations	@ All stages
Consistency	Slump	Every batch	Specified ± 25 mm	@ All stages
Flow	Slump flow	Every batch	Specified ± 25 mm	@ Stage 3
Air content	Entrainment meter	Every 100 m^3/ Daily @ noon	Specified ± 1%	@ Stage 3
Density	Weighing	Every 100 m^3/ Daily @ noon	Specified ± 3%	@ Stage 3
Water content	Appropriate tests	Every 100 m^3/ Daily @ noon	Specified ± 2%	@ Stage 3
Cement content	Appropriate tests	Every 100 m^3/ Daily @ noon	Specified ± 2%	@ Stage 3
Final mix proportions	Site evaluations	Every 100 m^3/ Daily @ noon	Specified ± 2%	@ Stage 3
Curing effectiveness	Visual and periodicity	Daily @ start, noon and close	As specified	@ All locations
Exposed finish quality	Visual and photographic	Every member and joint	As specified	@ All locations
Strengths	Compression	Every batch/ Every 100 m^3/ Daily @ noon	Specified ± 4 MPa	1, 3, 7, 28 and 90 day for each day
Further tests at specified intervals as desired by the consultant				
Rebound test	Rebound	At important locations and on the control specimens made from the corresponding batch	Specified ± 2 %	On the structure or on control specimen
UPV	UPV			
Resistivity	Res. meter			
Potential	Pot. meter			
Alkalinity	Conc. sample			
Chloride content	Conc. sample			
Water absorption	Absorption test	At specified intervals or location		
Air/Water permeability	GWT meter			
Chloride diffusivity	Diffusivity test			

should be no specific periodicity (that it takes place a particular day of every month) so that there is no prejudice to the assessments being made. However, a monthly review at very short notice is probably the most appropriate to ensure that the results associated with the quality assurance program are authenticated appropriately by the audit team. It is also necessary that the audit team is charged with the responsibility of suggesting appropriate and viable solutions to the discrepancies and shortcomings in the construction scenario which is approved by the consultant for implementation.

10.6 Perceived and Achieved Quality

There is no doubt about the fact that the specifications of concrete for any application should always be decided based on the functional characteristics of the structural member as well as the environmental characteristics to which it is exposed. Also, the structural shape and size will influence the dissipation heat of hydration, which could be an advantage if appropriately perceived but could lead to catastrophic failure if not controlled. This aspect is generally addressed in terms of the type of cement utilized and by restricting the sectional thickness of the concrete pour.

The compaction and curing regimes have to be specifically addressed to ensure a dense mass that is not deprived of hydration water for achieving the expected strength. Incidentally, while there are excellent recommendations and specifications for achieving the required objectives, a laxity in implementation at the various levels, which may by themselves look extremely insignificant and small if at all, finally aggregate to a significant effect on the resulting concrete performance. The so-called quality assurance systems that are in place apparently many a time are considered insignificant and cumbersome procedural practices and are effectively sidestepped. One very specific practice is not to enforce the frequency of inspection or to simply observe and record without making the appropriate tests mandated. Unfortunately the idea is not to implement the system as planned, but to increase the pace of the construction in view of the progress expected by all concerned, be it the facility owners, planners, designers, contractors or consultants that are associated with the project. It is this aspect that leads to enforcement through quality audit, which facilitates taking stock at regular intervals of the problem and progress in construction and if necessary look for ameliorative or curative measures to put the project on rails.

10.7 Legal Framework

The financial stresses and strains associated with the construction activity obviously lead to logjams in several situations, which forces the parties concerned to seek legal redressal. However, a prudent practice in most cases is an arbitrator who can study the problem from the perspective of both the parties and suggest possible compromise solutions. In the first place, the arbitrator should be a person with enough knowledge associated with construction, not just in terms of experience as in some local, state or federal body, but should have a much bigger perspective in terms of construction, quality assurance, testing and evaluation for understanding the techno-legal aspects of the problem while at the same time be regarded as a person of impeccable character. A few examples of the situations on the experiences in the laboratory include the problems associated with acceptable compressive strength variation, the acceptable deviations in finish, the acceptable deviations in cover and many more. In each case, the first attempt was to look for what is required rather than what was prescribed to come to a reasonable solution that could be proposed. In several situations, while there is a marginal shortfall in the expected outcome of any particular test on the concrete, the actual requirement is much less and the shortfall could be accommodated with reasonable safeguards. However, to enforce quality there needs to be a small yet prudent mechanism by which such shortfalls could be appropriately penalized. Also, continued shortfall at several levels on a continuum basis could lead to a very serious compromise on the overall structure quality at any time. A very critical appraisal of some of the problems associated with concrete and their legal connotations have been broadly discussed by Neville (2006). There are also several other aspects to the dispute resolution methodologies without the extreme recourse to legal and techno-legal avenues. In a way, the need for a subject expert even in the legal scenario is normally required. But with the compartmentalization of the so-called professional bodies, the operational aspects of most of the possible resolution methodologies are very much fraught with uncertainties.

10.8 Concepts for Localization

One of the possible avenues for a reasonable and acceptable quality assurance methodology is to evolve systems locally, through professional bodies or individual groups, to be able to generate confidence in the quality of materials, products and even machinery locally. In any case, the qualities of good construction always stand out in public and will certainly be appreciated, even if it were to be only gradually. Apart from this, it is probably only appropriate to have a systemic, community approach in the construction scenario so that experience, expertise and even equipment could be shared, so that the overall capital costs are reasonably low and the quality assurance tenets can be adopted even in much smaller levels of construction activity. In any case, there is a need for a substantial if not a sea change in the outlook and perceptions of the public itself to appreciate the advantages and adoption of quality assurance routines in the construction scenario. It is only proper to move these aspects to the fore particularly at the local level to see that could quality practices are indeed appreciated and adopted.

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11

Future Prospects and Potentials

11.1 Introduction

It is well known that there have been several alternative materials that were actively promoted as being a viable alternative to the pride and position occupied by concrete over the last 100 years. Serious efforts were indeed made to even replace the cement that forms the basic binding component in the concrete arena. At the end of over 100 years, it is indeed well recognized that concrete as the material of construction for structures subjected to even extreme environmental forces is still the only viable alternative. This stems from two factors, firstly that one of the largest components of concrete, namely aggregate, is essentially made up of local materials, and secondly the raw materials for the production of cement itself are also abundantly available around the globe compared to any other possible prospective contestant for its replacement. A few other factors that are not so often acknowledged or appreciated include that concrete with its high alkalinity is the best protection system for steel reinforcement, which is obviously a part of a reinforced concrete to counteract the inadequate tensile capacity of concrete itself. Another factor that makes concrete the most viable alternative is its flexibility in the fresh state that accommodates it being molded and formed to the requirements of total capacity and strength. The advent of reinforced and prestressed concrete has been consistently modifying itself to cater to the diverse and demanding needs of the modern construction industry at all times.

It is also recognized, as was already seen in the initial chapters of this particular compilation, that the cement itself has undergone several changes in both its chemical and physical characteristics over the last 100 years, and several efforts are on to upgrade it in more ways than one even presently.

The latest Euro recommendations suggest a plethora of 27 different cementitious compositions based on several supplementary cementitious materials. They also suggest the different strength grades for cement (32.5, 42.5 and 52.5 MPa) apart from other higher grade cements that are not available off the shelf from reputed manufacturers. Also, there are a host of special cementitious recipes that are only available as proprietary and even sometimes patented materials that are necessary for the production of ultra-high strength cementitious compositions.

Also, apart from reinforcing the weaker segments of concrete members appropriately with either reinforcing and prestressing steels, the advent of discrete fibrous reinforcement (fiber reinforced concrete) as well as continuous mesh reinforcement (the age-old technique of Ferro cement) have transformed the modern day concrete compositions significantly in their application and use. The possibility of polymer modifications like polymer cement concretes and polymer impregnated concretes have also had their say in making concrete and material with a difference even for the most aggressive and harsh environments. Some of these modifications have also made it possible to achieve not only improvements in compressive strength but have facilitated a significant increase in the tensile strength. More importantly, the possibility of immensely improving the energy absorption capabilities and post cracking behavior of some of these ultrahigh strength high-performance cementitious compositions is also noteworthy. These developments have even produced materials like strain hardening cementitious compositions akin to their steel counterparts. Efforts are on to modulate cementitious compositions to emulate nature by appropriately tailoring the compositions through chemical and mineral admixtures and additives, which are still at the workbench in several advanced research laboratories. At the same time, efforts are on to understand the intrinsic behavior of these compositions to facilitate tailoring of substances that are specific to an application itself. It may not be possible to illuminate and explain each of these paths that concrete has taken or is taking presently in a short text as envisaged. However, the possibilities and prospects of the enormous potential of the concrete compositions should still be recognized, appreciated and acknowledged appropriately and fully by the construction industry.

It is important to understand that there is a lot of information available around us from the past over 100 years regarding the performance of appropriately designed concrete mixtures. In fact the idea of this entire book is to bring together a few glimpses of that knowledge to ensure high performance cementitious compositions of various strength levels required. At this point maybe it is important to realize that even the doyen of concrete technology, Prof. Neville, while talking about the future improvements in durability opined that "We have at our disposal a whole gamut of good cementitious materials, as well as admixtures: what we need is a judicious and intelligent use of these materials and good quality execution of the concreting operations" (Neville, 2001).

11.2 Envisioned Objectives

Even after having said that, the incomplete panorama of the available concrete compositions cannot be summarized or explained in detail at present; the broad outline of the normal concrete mixtures starting from those that are used for general-purpose applications to the high strength high-performance concrete compositions that could be used in major construction activity could still be delineated as presented in Table 11.1. In fact, the general-purpose concretes compositions of marginal strengths were already explained in Chapter 8. Continuing from this particular level, the possible material compositions for producing higher and higher strength concretes along with the supplementary cementitious materials and chemical admixtures have been presented briefly in the table. The primary aim in the making of this table is to clearly present certain general limits on the complementary materials for producing concretes that are not only of higher sustainability but also that ensure a significant economy through experience in laboratory studies and field practices in the experience of the author. Also the strength characteristics detailed for each of the concrete types is the cube strengths probable. The limits of pozzolanic combinations are designed actually to ensure the highest efficiency at that particular strength grade in consonance with the lowest superplasticizer content while keeping the total cementitious materials within limits. It is presumed that the table is self-explanatory and needs no further detailed

TABLE 11.1

Probable Classification and Characterization of Structural Concretes

S. No.	Nomenclature	%—Pozzolan Combinations (%)	Slump/Flow[d] (mm)	sp[b] (%)	Total Cementitious Content
1. General-purpose concretes of lower strengths (20–40 MPa; w/cm~ 0.50–0.70; LEP[a] only; 25 mm graded aggregate)					
1.1.	OPC concretes	0	Dry–150	0–1.0	250–450
1.2.	Plasticized concretes	0	50–150		
1.3.	Pozzolanic concretes	30-F/50-G	Dry–150		
1.4.	Flowing concretes	30-F/50-G	150–200		
1.5.	HPC	30-F/50-G	100–200		
1.6.	SCC	30-F/50-G	500–650[d]		
2. Medium strength concretes (40–60 MPa; w/cm~ 0.40–0.50; LEP[a]; 25 mm gr. agg.)					
2.1.	Plasticized concretes	0	50–150	1–1.5	300–450
2.2.	Pozzolanic concretes	30-F/50-G	50–150		
2.3.	Flowing concrete	30-F/50-G	150–200		
2.4.	HPC	30-F/50-G	100–200		
2.5.	SCC	30-F/50-G	500–650[d]		

(*Continued*)

TABLE 11.1 (*Continued*)

Probable Classification and Characterization of Structural Concretes

S. No.	Nomenclature	%—Pozzolan Combinations (%)	Slump/ Flow[d] (mm)	sp[b] (%)	Total Cementitious Content
3. High strength (performance) concretes (60–90 MPa; w/cm ~ 0.035–0.45; LEP/HEP[a]; 20 mm gr. agg.)					
3.1.	Plasticized concretes	20-F/G; 10-S/R/M/Z	50–150	1–2.0	450–550
3.2.	Pozzolanic concretes	20-F/G; 10-S/R/M/Z	50–150		
3.3.	Flowing concrete	20-F/G; 10-S/R/M/Z	150–200		
3.4.	HPC	20-F/G; 10-S/R/M/Z	100–200		
3.5.	SCC	20-F/G; 10-S/R/M/Z	500–750[d]		
4. Very high strength (performance) concretes (90–120 MPa; w/cm ~ 0.25–0.35; 12 mm gr. agg.)					
4.1.	VHPC	10-F/G; 20-S/R/M/Z	100–150	2.0–3.0	500–600
4.2.	Flowing concrete	10-F/G; 20-S/R/M/Z	150–200		
4.3.	SCC	10-F/G; 20-S/R/M/Z	500–650[d]		
5. Super high strength (performance) concretes and SIFCONS (120–150 MPa; w/cm ~ 0.20–0.25; 4 mm gr. agg. + fiber/pressure/heat)					
5.1.	SHPC	20-S; (20-powder[c])	100–150	3.0–3.5	600–700
5.2.	Flowing concrete	20-S; (20-powder[c])	150–200		
5.3.	SCC	20-S; (20-powder[c])	500–650[d]		
6. Ultrahigh strength (performance) concretes (150–250 MPa; w/cm ~ 0.20–0.25, 2 mm gr. agg. + micro fiber/pressure/heat)					
6.1.	Flowing concrete	20-S; (20-powder[c])	100–200	3.0–4.0	700–1000
6.2.	SCC	20-S; (20-powder[c])	500–650[d]		
7. Projected future composites (>250 MPa; w/cm ~ 0.18–0.20; 0.5 mm gr. agg. + gr. micro fiber/pressure/heat)					
7.1.	Flowing concrete	20-S; (20-powder[c])	100–200	3.0–5.0	1000–1200
7.2.	SCC	20-S; (20-powder[c])	500–650[d]		

Note: All aggregates should be appropriately graded to ensure good packing characteristics.

[a] Low-end pozzolans (LEP)—F-fly ash (35%), G-GGBS (50%), P-powder (20%) and High-end pozzolans (HEP)—S-silica fume (20%), R-RHA (20%), M-metakaolin (20%), Z-zeolite (20%).

[b] Superplasticizer content as a percentage of the total cementitious materials.

[c] The powders are basically micro fine silica or substitutes of similar nature.

[d] The values given are the slump flow band width.

explanation. Even so, a few of the aspects may need a specific explanation, and only these are explained in the ensuing paragraphs.

11.3 Cementitious Modifications

It is felt appropriate to look closer at Table 11.1 to explain some of the projections in terms of the higher strength cementitious compositions. It can be said that concrete composites at the level of very high strength and performance (up to about the 120 MPa level) can be achieved without any major inputs from the research and developmental activities that are on the anvil. The available materials, particularly the 52.5 grade cements or maybe even 42.5 grades, with some difficulty along with a smaller size aggregate of 12 mm in conjunction with an appropriate pozzolanic material can produce almost the 120 MPa concrete with the present production, transport, placement and curing technologies available. The availability of the fourth-generation superplasticizers like poly carboxylic esters has made this prospect even simpler while this was possible even with the sulfonated melamine formaldehyde or sulfonated naphthalene formaldehydes available earlier (Rao, 1996; Prakash, 1996; Sree Rama Kumar, 1999; Appa Rao, 2001; Surekha, 2005; Narasimhulu, 2007). The use of higher efficiency pozzolanic materials and poly carboxylic esters will reduce significantly the cementitious binder and thus the above chemical and mineral admixtures themselves. While with careful proportioning this is possible even with the supplementary cementitious materials of the lower efficiency, the prospect of using larger cement contents and larger plasticizer contents will drive the user to consider the higher efficiency SCMs or a sensible alternative in the present-day context. The possibility of using these supplementary cementitious materials through alkali activation as geopolymers could also be produced in the laboratory predominantly by a similar approach (Satya, 1993).

Apart from this the cement industry itself is proposing and promoting cementitious compositions that could achieve a 120 MPa concrete using suitably graded aggregate along with the poly carboxylic superplasticizer. There have been attempts to extend some of these combinations in recent times. Apart from this, concretes of this class have been used in a few outstanding and prestigious engineering facilities all around the world in recent years. Also with the advent of newer generation superplasticizers and specially graded and processed aggregate concretes of higher strength, even up to the 150 MPa mark could be achieved.

11.4 Fibrous Incorporations

Conventional fibrous additions in concrete will not significantly alter the effective compressive strength of the concrete composition substantially, while it could impart significant ductility to an otherwise highly brittle matrix, required particularly at the high strengths in which these additions should be preferred. Incidentally, the concept of fiber reinforcement was advocated to bridge structural cracks in reinforced concrete and to improve the ductility (Romualdi, 1963; Swamy, 1979; Naaman, 1985). Primarily steel fibers of about 0.4 mm in diameter and length of about 100 mm resulting in an aspect ratio of 80–120 were adopted. The possibilities of enhancing the ductility of an otherwise brittle material as we go in for higher strengths has invigorated research in this area for quite some time now (Raja, 1993). The limitations on the fiber absorption capability of concretes (with the general limit of around 2%–2.5% above which the fiber interactions lead to the phenomenon of balling or rejection) necessitated other avenues like slurry infiltrated fiber reinforced concrete (SIFCON) wherein it may be possible to increase this percentage to around 12% (Balasubramanian, 1992). The possibility of using several other types of fibers for improving specific characteristics of concrete behavior was also recognized apart from the efforts to arrive at appropriate mixtures with specific application potential (Pavan kumar, 2005). However, most of these attempts were apparently toward addressing the structural and progressive failure cracking of the concrete composites once the cracks have started forming an opening as a result of the increasing loads. Incidentally, some of the earlier concepts of interpreting polymer fibers to reduce the shrinkage cracking in concrete surfaces prompted the idea of bridging even the micro cracks that are formed during the initial hydration process itself, like thermal, chemical and drying shrinkage effects. Given the micro defect free cementitious compositions coupled with the efforts toward reinforcing these micro cracks through very short and very thin microfibers (essentially 0.15 mm in diameter and about 6–12 mm length), researchers were able to produce cementitious compositions that have strengths in excess of 150 MPa (almost reaching the 300 MPa mark). These compositions primarily avoid the use of coarse aggregate in total while using significant quantities of cementitious materials (almost 800–1,000 kg/m^3, which includes a higher efficiency pozzolans like silica fume) and appropriately graded sand in conjunction with polycarboxylate superplasticizers (Chandrasekhar, 2017). It is obvious that the technology toward the development of ultra high strength high performance cementitious compositions and their various application possibilities for ensuring very sleek, aesthetic and yet highly functional structural combinations is still at its nascent stage. It is also to be recognized that the possibility of combining these materials with very high strength reinforcement could empower the structural designer with several different options. Some of these materials were also seen to be of a strain hardening the nature, hitherto unthinkable in cementitious compositions.

11.5 Macro Material Management

In principle the use of fine materials in an essentially hydrating cementitious composition requiring water poses the problem of higher wetting water requirements for the increased surface areas associated with the finer particles. The advent of the more efficient superplasticizing admixtures like poly carboxylic esters was able to address this problem to a certain extent, though use of nanomaterials is still a problem. Various methodologies are being looked at to ensure an appropriate mix that will lead to the best pore filling and pozzolanic effects without significantly increasing the water content. Special mixing and curing techniques to ensure the most defect free system that could result in the highest strengths possible are on the anvil in several research laboratories. The reactive powder compositions or micro defect free material formulations that have started a while back are now becoming more and more often the possible contenders for even large structural applications. Add the fibrous reinforcements as discussed earlier and may even reinforced appropriately with the several different possibilities available presently, these systems could lead to significant improvements in the performance of the cementitious compositions as well as the structures that are built with these materials.

11.6 Application Based Visions

While efforts are on to build enhanced and special properties into the cementitious compositions of yesteryears, the possibility of trying to look for the methodologies for achieving specific properties for applications that need to perform in a specific environment or with a specific role in the structural configuration are also being actively pursued. Some of these could be applications related to specific joints that require very high rotation capacities and performance active hinges without any significant distress, or materials that could withstand very highly corrosive exposure conditions like acidic waters and industrial effluents, etc. These efforts have also promoted the thinking of making smart materials with shape memory characteristics that could potentially change the construction scenario significantly, particularly in earthquake prone regions. It is realized that there is no simple solution where a single material can perform the desired objective and that appropriate combination of the several different possible formulations may be able to address at least some of the major requirements of the vastly advancing and highly intricate construction scenario evolving day by day in recent times. It is probably not possible and is also not even in the scope of the present effort to discuss the relative merits and demerits of these efforts.

11.7 Education and Training

In principle, the intuitive germination and advancement of the ideas and concepts toward the advancements in science and engineering primarily start in the academic and research organizations with the requirements of the industry in its broad perspective during their interactions. However, in an effort to be competitive or even to update several of the efforts, conventional academic institutions appear to be pursuing a more traditional approach of continuing with the quest to understand the existing cementitious compositions. Professionally or even personally it would be a worthwhile effort of any organization to look a little farther ahead to enhance the available knowledge without dissipating their energy on repetitive confirmatory efforts. Even so, some of the repetitions may still be required to ensure confidence in being able to appropriately utilize the present knowledge as a part of the effort toward training and education. Notwithstanding this, it is obvious that there is a phenomenal amount of repetition as well as inconsequential and maybe even irrelevant efforts the world over done in the name of research and development that can be easily avoided. In most cases these fill the pages in documents and publications or will be directed toward the promotion efforts of individual companies associated with them. Maybe these are strong views and should not be aired in public, but in the interests of promoting competitive research efforts toward the advancement of science and technology of the most ubiquitous cementitious composites it is probably essential to recognize the present status. In continuation to what has been said, maybe there is an urgent need that the appropriate national and international bodies as well as government institutions advocate and advance more appropriate and preferential research efforts that could benefit and cater to the needs of local and provincial requirements. Apart from these, some of the possible deviations that can be associated with local materials can be appropriately positioned through research methodologies like round-robin testing of specific parameters. These will also inculcate a sense of belonging and competitive spirit to contribute to the national effort directly or indirectly by the research community. Apart from the aspects of education, training and research and development on these most commonly used materials construction, there is an urgent need and responsibility to explain and delineate the various advanced research needs more efficiently. It should also ensure an equitable participation of as many stakeholders as possible to see that the different viewpoints as well as avenues for advancement are all utilized fully.

11.8 Innovative Concepts

Incidentally, there are two main limbs on which the entire development aspects could depend, firstly the sustainability and environmental aspects and lastly the utilization of cutting edge scientific developments to the advancements in cementitious compositions. While it may not be possible to exactly present the possible scenario wherein such activity is relevant immediately, the development of ultrahigh performance concrete compositions has shown a way forward in this direction. These materials and their modifications have given rise to a host of new structural concepts that were hitherto the domain of structural steel formulations. Apart from these efforts, several individual research groups are looking at an aspect that focuses on reinventing some of the old and probably forgotten technologies that were capable of withstanding the test of time for many centuries. The possibilities of unlocking some of these by investigating appropriately existing structures as well as relics still standing is a science that is still not understood nor probed in depth. There is certainly an urgent need for coherent scientific efforts toward unlocking the mysteries of some of these unexplained scientific facts through both professional and governmental bodies. Another aspect in the realms of engineering excellence that is often talked about but not much addressed appropriately is the facets relating to the methods of emulating nature. There are a lot of potential advantages in understanding the axioms of nature and deploying them with a scientific thought into their formulation materials, including those related to construction like the cementitious compositions. Without going into further details, it is enough to say that there should be an appropriate body that looks at several of these innovative concepts and supports the advancement in a holistic fashion.

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