Concrete

ULLMANN'S ENCYCLOPEDIA OF INDUSTRIAL CHEMISTRY

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1. Introduction

Concrete is an artificial stone in which natural stones of well-graded sizes are bound together by a cement matrix, thus providing strength. Although this principle of manufacturing building materials or structures can be traced back as far as 5000 B.C. to ancient cultures in the Middle East, Turkey, Greece, and then to the Roman Empire, it was later neglected for centuries. Concrete regained importance in the 1800s, when methods for large-scale production of modern cement were developed [14, 15] (see → Cement, Chap. 2.).

Concrete is a brittle material, but reinforcing with steel bars (reinforced concrete) or with prestressed tendons (prestressed concrete) has greatly expanded its applicability. It is now one of the most important building materials because of its structural, physical, and chemical properties and its economics. Furthermore, it can be considered an environmentally friendly material [16]. Fresh concrete can easily be shaped, and most concrete is poured in place on the construction site. However, there is increasing use of concrete elements or concrete products that have been prefabricated in plants.

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In 2004, ca. 2136×10^6 t of cement was produced worldwide to manufacture ca. 7×10^9 m^3 of concrete for the construction industry. Therefore, concrete represents the second largest commodity traded in industrialized countries. Ten countries, namely, The People's Republic of China (43.7%), India (6.1%), the United States (4.6%), Japan (3.2%), South Korea (2.5%), Spain (2.2%), Italy (2.1%) (2,1%), Russia (2.1%), Turkey (1.9%), and Mexico (1.6%), consumed more than 70% of the world production of cement and concrete [17].

Concrete is one of the less energy-intensive building materials. Concrete based on Portland cement has a total energy content of only ca. 1250 MJ/m^3 [18], and even less when waste materials or industrial byproducts such as fly ash, silica fume, or ground granulated slags are incorporated. Table 1 gives a comparison of total energy content and total energy content per unit of strength of different building materials [18–20].

The supply of natural concrete aggregates of good quality is not guaranteed worldwide, and because of continuous consumption, a shortage of suitable material is observed in some locations. Aside from more sophisticated methods of recovery or treatment, the use of low-quality aggregates for special applications as well as recycling of old concrete, other building materials, or waste products must be considered in the future [21]. Corresponding regulations are available on a national basis, e.g., [22, 23] or are under preparation by CEN TC 154 on a European level. Recommendations have been established by RILEM [24].

Aside from its composition, the properties of a structural concrete depend to a great extent on its age and curing history as the controlling factors of cement hydration. Therefore, physical and chemical properties must be tested by standardized procedures both before and during the construction process. National standards, as well as international standards or recommendations given by the International Organization for Standardization (ISO), Comité Européen de Normalisation (CEN), Comité Européen du Béton (CEB) – now Fédération International du Béton (fib) after merging with Fédération Internationale de la Précontrainte (FIP) –, or Réunion Internationale des Laboratoires d'Essais et de Recherche sur les Matériaux et les Constructions (RILEM), cover quality control of concrete raw materials, as well as that of the concrete itself. Additional guidelines may be specified by the purchaser.

For the Common Market of the Member States of the European Union, the EFTA and associated states, CEN has prepared harmonized regulatory documents also for construction with concrete. EN 1992-1 (Eurocode 2) [25] specifies requirements for the planning and design of structures made of plain, reinforced, or prestressed normal-weight concrete, heavy- or lightweight concrete. Eurocode 2 is supported by product standards, i.e., European standards for the required materials such as concrete, namely EN 206-1 [26], as well as standards for concrete making materials such as aggregates, mixing water, chemical admixtures and additions. On a further level, a set of standards specifies test methods and procedures for quality assurance of products and materials. Also the execution of concrete works must follow given specifications, e.g., EN 13670 [27]. In national annexes to these harmonized standards, the Members States have the opportunity to introduce supplementary requirements in order to account for local conditions.

Table 1. Total energy content of some building materials

Material	Mean strength, MPa	Total energy content, MJ/m^3	Total energy content/strength
Steel	370*	237 000	640
Aluminum	320*	730 000	2280
Clay brick	25**	4200	168
Sand lime brick	25**	1220	49
Polyethylene		92 800	
Concrete	35*	1242	35.5

*Tensile strength.

**Compressive strength.

2. Materials

Basic materials for the production of concrete are cement, aggregates, and water. Up to certain limits, additional compounds – concrete additives – may be used to control some properties of the fresh or hardened concrete. These materials must meet specifications set forth in standards or in approval documents. The compatibility of all of the compounds used must also be considered.

2.1. Cement(→ Cement)

The hydraulic binder cement reacts with water to form a highly dispersed cement paste matrix in which the aggregates are embedded. This cement matrix normally constitutes ca. 25% of the volume of concrete. Different types of cement can be distinguished according to cement standard compressive strength, chemical composition, kinetics and heat of hydration, or resistance to chemical or physical attack [28–31]. Economic considerations may influence the choice of the type of cement, depending on the local supply of raw materials for cement production or concrete aggregates.

2.2. Aggregates

The remaining 75% of the volume of concrete is made up by aggregates, which act as inert fillers and give concrete the properties needed in a structural building material (e.g., volume stability, limited crack development, modulus of elasticity, wear resistance, ductility). The mechanical and physical properties of the aggregates may differ considerably from those of the cement paste. They are reflected in the properties of the hardened concrete but not necessarily in proportion to the concentrations of the aggregates. Concrete aggregates can be categorized according to their origin as natural or artificial aggregates; according to their density as light, normal, or heavyweight concrete aggregates; or according to their composition as mineral, metallic, or organic materials. The last two types are used only for special concretes.

Grading of Aggregates. Aggregates used in producing high-quality concrete have a particle-size distribution in the range 0.01–100 mm. The finer fraction is classified as sand, which comprises particles up to 4–5 mm in diameter; larger particles are called coarse aggregates. As a general rule, the size distribution of aggregates is selected to maximize their concentration in the concrete while maintaining sufficient workability of fresh concrete with a low water content. Therefore, the total surface area of the aggregates should be kept as small as possible [32].

The particle-size distribution of aggregates is determined by sieve analysis, which subdivides a sample into fractions. Within each fraction, particles of sizes between a lower and an upper limit are present, depending on the mesh sizes of two consecutive sieves. For two consecutive sieves, these mesh openings are normally increased by a factor of two, however, intermediate sieve sizes may be used for certain applications, e.g., road pavements. Specifications for sieves, as well as procedures for sieve analyses, are given in various national and international standards or recommendations [23, 32–34].

After subdivision of the aggregates into fractions, grading is based on the specific surface area, water requirement factor, average particle size, fineness modulus, etc. The grading curve is a graphic presentation of the cumulative percentage retained on or passing through successive sieves.

In general, specifications or recommendations of limiting grading curves for the aggregates as a whole, or for the sand only, are commonly used [35, 36]. The maximum aggregate size is usually specified. Concrete aggregates must not contain compounds that inhibit the hardening of the cement paste or that are vulnerable to chemical or physical degradation. Therefore, the permissible contents of organic or expansive compounds, soluble sulfates, silt, and clay are limited. Aggregates to be used in reinforced or prestressed concrete must not contain soluble compounds, such as chlorides, that attack steel [23, 36-38]. Aggregates that contain reactive silica, e.g., opal or certain flints, demand special, low-alkali cements to prevent expansive alkali–silica reactions in the hardened concrete [39–43].

Other characteristics of aggregates, such as modulus of elasticity, hardness, density, porosity, thermal conductivity, thermal expansion, and resistance to wear and frost action, must be considered in many applications.

2.3. Water

The mixing water added in the preparation of fresh concrete serves to hydrate the cement and assures the workability of the fresh concrete. Although only 20–25% of the mass of cement must be water for the chemical reaction with cement, additional water is needed to achieve complete hydration, as well as good workability.

Impurities in the mixing water, such as sugar, organic compounds, oil, carbonic acid, sulfates, or other salts, may affect the hardening of the concrete or reduce the concrete strength. The concentration of dissolved chlorides is restricted for reinforced and prestressed concrete. Doubtful cases should be subjected to chemical analysis, but normally hints of excessive amounts of impurities can be derived from the color, odor, taste, turbidity, or formation of bubbles or foam. Guidelines for permissible impurities can be found in [32, 44], and a European Standard EN 1008 [45] is pending. In concrete plants wastewater from cleaning of production equipment from remains of fresh concrete may be re-used with certain restrictions [46].

As a general rule, potable water is suitable as mixing water, but also spring water and water from rivers or lakes if not contaminated. Sea water must not be used for reinforced or prestressed concrete because of the dissolved chlorides, which may induce the corrosion of the reinforcement. In case of doubt, a trial mix with the water should be prepared and the development of concrete strength compared to that of a control mix. A trial mix is also important because the effect of impurities on concrete properties may depend on the type and amount of cement used.

2.4. Admixtures

Compounds may be added to control specific properties of the fresh or hardened concrete. These additives are either water-soluble (mainly organic) compounds in low concentrations or finely divided mineral material in higher concentrations. The classification of additives with respect to their effect is arbitrary, because in most cases several concrete properties are influenced simultaneously; specifications or guidelines can be found in [47–50]. The majority of additives function to control setting and hardening, workability, or concrete porosity.

2.4.1. Setting and Hardening Admixtures

In some instances, the setting and hardening development of concrete must be accelerated or retarded to meet the needs of a construction job. Set-retarding agents are used to prolong the period of workability during hot weather, to avoid discontinuities in subsequent placements of fresh concrete, or to reduce crack formation due to deformations in an early stage. Accelerators are used when concrete is placed under cold weather conditions or when there is need to strip the formwork earlier than normal. Use of high concentrations of accelerators in shotcrete (see Section 4.4) leads to rapid development of strength only seconds after mixing.

2.4.2. Workability Admixtures

Many types of additives exert a significant influence on concrete workability while also affecting other properties such as the setting time. The main objective of using such additives is to improve concrete workability. These plasticizers or superplasticizers reduce the amount of water needed and are the most commonly used additives, because they facilitate the placing and compacting of the concrete. Because they permit the use of lower water-to-cement (w/c) ratios, the strength and durability of the concrete is improved [51].

2.4.3. Porosity Admixtures

The resistance of concrete to frost and deicing salt can be improved substantially by the use of air-entraining additives that form spherical pores with diameters considerably less than 0.5 mm [15]. To prevent frost damage, these pores must be closely spaced and uniformly distributed in the cement paste matrix of the concrete. The necessary volume of entrained air depends on the mix proportion of the concrete and is normally 2–6% by volume of the concrete [52]. Foam-forming additives are used to make concrete with fine aggregates and a cellular structure. Such special lightweight concretes are primarily used for thermal insulation.

Air-removing additives are also available, and are often added to plasticizers.

2.4.4. Other Admixtures

Other additives are used for special applications, for example, expansion-producing agents; corrosion inhibitors; fungicidal, insecticidal, or germicidal agents; damp-proofing and permeability-reducing additives; bonding agents; or pigments. Their total consumption, however, is low [32, 48].

Much experience and careful control of concrete properties is required when additives are used because their effects may depend on many parameters, such as concrete composition, type of cement, the sand fraction of the aggregates, and temperature. The simultaneous use of more than one additive may lead to problems because of interferences and to undesired concrete properties. In such situations a trial batch is mandatory.

2.4.5. Fine-grained Material and Polymers

Fine-Grained Material. The main groups of fine-grained mineral solids used as additives are powdered unreactive rock, such as limestone or quartz or finely divided pozzolanas, which are either natural or industrial byproducts. Unreactive rock material is an inert filler that can improve the workability of the fresh concrete, especially when the available natural aggregates lack fines. Pozzolanas may increase the strength and reduce the permeability of the hardened concrete because of chemical reactions with hydration products of the cement. These reactions consume a part of the calcium hydroxide formed during the hydration of Portland cement clinker. Accordingly, excessive amounts of pozzolanas may lower the alkaline reserve of the concrete.

Reactive Minerals. Natural pozzolanas include volcanic ashes, opaline shales, and cherts that contain reactive compounds of silicon or aluminum. Specifications for natural pozzolanas are given in [53, 54]. Among the synthetic pozzolanas, pulverized fuel ash (fly ash) is the most important additive and is used in large quantities. Its requirements as a concrete additive are specified in standards [53, 55–57]. Aside from improving certain concrete properties, the use of fly ash can reduce the amount of energy-expensive cement and save natural resources by recycling waste material [58].

Silica fume — a pozzolanic waste material in silicon and ferrosilicon industries — has opened new areas of application for advanced cement-based materials. Owing to its small particle size (ca. 0.1 μm) silica fume acts as a microfiller in the cement paste, thus reducing the total porosity considerably. Compressive strengths exceeding 250 MPa have been reported for concretes containing silica fume. For special applications, the new material can be substituted for cast iron, other metals, ceramics, or polymers [59]. Requirements for the properties of silica fume are given in [60].

Metal Oxide Coloring Agents. Coloring additives are generally alkali-resistant oxides of iron, titanium, or chromium. A uniform coloring effect is best achieved when such additives are used in combination with white cement. Coloring agents must be resistant to the high alkalinity of concrete [61].

Polymers. A considerable increase in concrete strength and durability under severe conditions is achieved by the addition of certain polymers to concrete (polymer cement concrete, PCC). However, the properties of polymer-modified concrete may deteriorate on continuous exposure to high humidity [62].

3. Production

3.1. Definition of Concrete Properties

Advances in concrete technology have established the basic rules for making concrete with desired properties in both the fresh and hardened states. Although the desired properties of the fresh concrete must be deduced from the working conditions and equipment at a particular construction site, the requirements for hardened concrete are determined by the expected service conditions. Strength, physical properties, and durability must be considered. A careful analysis of all required concrete properties is necessary before a selection of materials and their proportions is made.

In many instances, the need for concrete durability may lead to more stringent requirements for materials selection and proportions than those for the desired strength. Therefore, in national and international standards and guidelines or recommendations on the production and use of concrete and reinforced or prestressed concrete, the expected service conditions are sumarized in exposure classes and requirements on the concrete composition are set, e.g., on maximum water-to-cement (w/c) ratios, type of cement, and minimum cement content or the use of particular aggregates or additives [26, 25, 63]. Expected chemical attack of the hardened concrete, e.g., by sulfates, may require the selection of sulfate-resistant cements. Anticipated exposure to severe weather and deicing salts requires the preparation of air-entrained concrete. Alkali-sensitive aggregates should be used only in combination with low-alkali cements [43, 64]. In all cases where external attack is expected, a concrete with a dense pore structure and low permeability should be used. In reinforced concrete, corrosion protection of the steel reinforcement must be assured by a low w/c ratio. Therefore, for moderate service conditions, the w/c ratio is limited to a maximum of ca. 0.650, whereas severe conditions may require w/c ratios not above 0.4 [26, 63–65]. Other uses may require similar restrictions for the w/c ratio, type of cement, or cement content, as well as the selection of suitable aggregates and beneficial additives (see Section 7).

In [26], the exposure conditions and the associated risk for corrosion of either the concrete itself or the embedded reinforcement are classified in 7 categories as described in Table 2.

3.2. Proportioning of Materials

The selection of the concrete-making materials and their proportioning may be specified by the purchaser of the concrete or the owner of the structure to be built, or it is in the responsibility of the concrete producer or contractor [26]. The basic concrete materials and additives must be proportioned in such a manner that all desired properties of the concrete are achieved.

There is no general approach, but rather empirical methods for determining the proper mix proportions, based on either volume or density considerations. The volume or mass of the individual concrete constituents is determined in consecutive steps, which in general lead to a first trial mix for evaluation.

Only for low-grade concrete with a characteristic strength $f_{\mathrm{ck}} < 20$ MPa (cube strength) are suitable mix proportions presented in the tables given in [26]. High-grade concrete or concrete containing additives require a thoroughly detailed mix design for the first trial batch. The mix design may be changed after the properties of the trial mix have been tested. Guidelines and methods for proportioning of concrete mixes can be found in [14, 15, 32, 65].

One of several possible approaches to obtain a first estimate of the mix proportions is presented below. The concrete quality is specified by its characteristic compressive strength, which normally is determined after 28 days on cubes or cylinders [66–69].

Because of variations in the strength of concrete, the mean strength f_{cm} of a set of test samples must exceed the required characteristic strength f_{ck} by a certain amount, which can be derived by statistical methods [26, 63, 70, 71].

For normal aggregates and a given type of cement, the strength of completely compacted concrete is a function of the w/c ratio. Approximate values of this ratio for achieving different strength levels are given in Table 3 for non-air-entrained and air-entrained concretes [65]; these values can be obtained from diagrams for different types of cement [72], such as Figure 1 for non-air-entrained concrete.

The content of mixing water required to achieve a certain consistency of the fresh concrete depends mainly on the maximum size and

Table 2. Exposure classes and associated corrosion risks

Exposure class	Exposure condition	Severity levels
XO	No corrosion risk (applies to plain concrete only)	
XC	Reinforcement corrosion due to carbonation of concrete cover	XC1, XC2, XC3, XC4
XS	Reinforcement corrosion due to chloride ingress from sea water	XS1, XS2, XS3
XD	Reinforcement corrosion due to chloride ingress other than sea water, e.g., deicing salt	XD1, XD2, XD3
XA	Concrete corrosion due to chemical attack	XA1, XA2, XA3
XF	Concrete corrosion due to freeze-thawing with/without deicing agents	XF1, XF2, XF3, XF4
XM	Concrete corrosion due to abrasion and wear	XM1, XM2, XM3

Table 3. Relationship between w/c ratio and compressive strength of concrete cylinders [65]

	Water : cement ratio	
Compressive strength, MPa	Non-air-entrained	Air-entrained
45	0.38	
40	0.43	
35	0.48	0.40
30	0.55	0.46
25	0.62	0.53
20	0.70	0.61
15	0.80	0.71

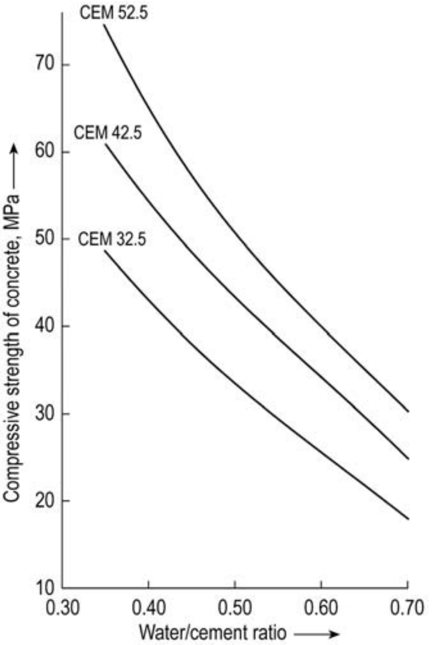

Figure 1. Characteristic compressive strength f_{ck} of concrete cylinders for cements with different standard compressive strengths as a function of the w/c ratio

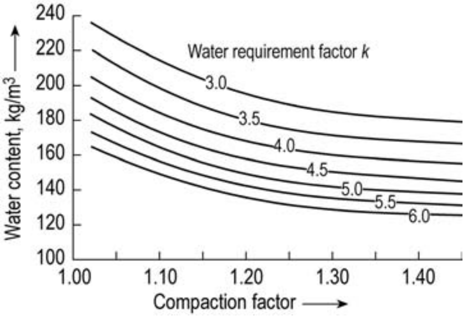

Figure 2. Water content of fresh concrete as a function of the compaction factor for different water requirement factors [74]

the grading of the aggregates. As a general rule, more sand or fine particles and smaller maximum aggregate size require more mixing water. For angular coarse aggregates, Table 4 gives maximum quantities of mixing water as a function of aggregate size and consistency as described by the slump (see Section 4.1) of the fresh concrete.

Table 4. Approximate water content (in kg/m^3) of fresh concrete [65]

	Maximum diameter of aggregate, mm				
Slump, mm	10	12.5	20	25	40
30–50	205	200	185	180	160
80–100	225	215	200	195	175
150–180	240	230	210	205	185

The amount of water required for a concrete of given consistency may also be estimated from the parameter *k*, the water requirement factor, which is defined as the sum of the percentages of aggregate retained on 9 standard sieves (0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 31.5, and 63 mm mesh), divided by 100:

$$k = \frac{1}{100}\sum_{1}^{9} R_i$$

where R_i is the percentage of material retained on each of nine sieves, each of which is charged with the complete range of aggregate sizes.

In Figure 2 the water content of concrete with rounded aggregates is shown as a function of *k* for various ranges of consistency as described by the compaction factor *v* (Section 4.1).

If consistency is measured on a flow table as the spread of concrete or by the compactability the water content of fresh concrete may also be calculated for various consistencies according to Table 5.

Table 5. Water content of fresh concrete for various consistency classes as given by the flow F or compaction C and water requirement factors *k*

Consistency F, C	Water content w
C0	$w = 1000 / (k+3)$
F1, C1:	$w = 1100 / (k+3)$
F2, C2	$w = 1200 / (k+3)$
F3, C3	$w = 1300 / (k+3)$
F4	$w = 1400 / (k+3)$
F5	super plasticizer required
F6	super plasticizer required

The amount of water added to the mix may need to be corrected for the amount of water adsorbed on the aggregate surfaces, particularly for the sand fraction when stored in open bins or bunkers. After the water content is estimated, the cement content of the mix is determined from the w/c ratio. The amount of aggregates can be calculated by considering the absolute volume of the various concrete constituents contained in 1 m^3 of compacted fresh concrete. Then, a typical mix for a standard concrete may contain ca. 300 kg/m^3 of cement, 150 kg/m^3 of mixing water (w/c= 0.5), and up to 1950 kg/m^3 of aggregates.

In this example, no restrictions on the w/c ratio or cement content are considered, which may be necessary to achieve a sufficient durability or workability. Furthermore, the results obtained by any method of mix design will give only a first estimate of the concrete composition. Necessary corrections to the individual parameters are determined by trial batches. Trial batches are mandatory whenever additives are used because the effects of the additives cannot be reliably predicted and may depend on the temperature, intensity of mixing, and composition of the concrete.

3.3. Production Process

For the production of uniform concrete of high quality, adequate storage facilities for the individual components must be provided. The cement should be protected from moisture to prevent partial prehydration. Fine and coarse aggregates stored in separate fractions must be handled carefully to avoid segregation. Sand, if not stored in protected bins, should be drained to avoid excessive water adsorption. Liquid additives must be protected from freezing and thoroughly mixed before use.

All solid materials are measured by mass; liquids can be measured by volume. All measuring devices should be calibrated regularly to operate accurately within 1–3% [26, 73]. On large construction sites or in ready-mixed concrete plants, measurement of the components may be automated at the bin discharge. The materials are carried to the mixing station by conveyor belts. Automatic sensing of the surface moisture of the aggregates allows for the correction of the amount of water to be added to the mix. Solid additives are added to the mix with the cement, whereas liquid additives are preferably mixed with the water. Some types of superplasticizers are effective for only a limited period of time. Therefore, they are added to the fresh concrete in a second mixing step immediately before placing the concrete.

To achieve a thoroughly mixed and homogeneous fresh concrete, the materials are charged into mixers which generally consist of revolving drums equipped with blades, stationary or revolving pans in which blades rotate on vertical shafts, or horizontal drums in which spiral blades operate on a rotating horizontal shaft. The necessary mixing time depends on the intensity of mixing, as well as on the batch size, and normally ranges from 30 to 120 s. Truck-mixed concrete may require up to 100 revolutions of the truck-mounted drum rotating at mixing speed [15, 26, 73, 74].

4. Fresh Concrete

4.1. Workability

The term workability describes several characteristics of fresh concrete which are of particular importance for its placement, consolidation, and finish. These characteristics include flowability, resistance to plastic deformation, compactibility, cohesiveness, and tendency to bleed or segregate. There is no single test method for evaluating all aspects of the workability of fresh concrete. Accordingly, test methods commonly determine either the flowability, expressed in terms of consistency, or the compactibility, which may be described by different compaction factors.

A widely used method for evaluating the consistency of fresh concrete is the slump test, which is specified (with minor differences) in various standards [75, Part 2, 76-78]. In principle, in this test a frustum of a cone which serves as a mold is filled with concrete in a standard manner. After the mold is removed, the subsidence of the concrete cone is measured to determine the slump classes S (Fig. 3).

In [75, Part 5], the spread of a cone of fresh concrete is determined on a flow table, which is dropped in a standard manner (15 times

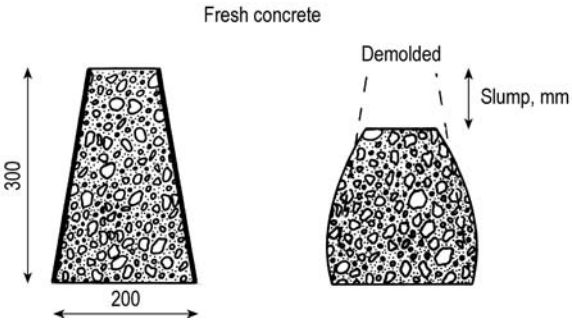

Figure 3. Test setup for the determination of the slump of fresh concrete [77]

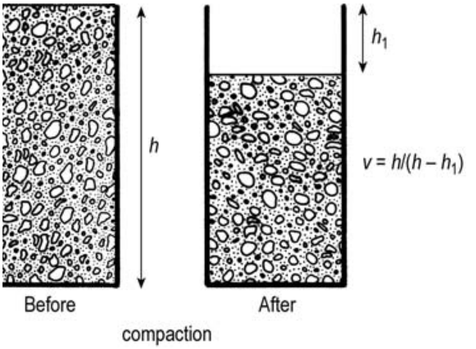

Figure 4. Test setup for the determination of the compaction factor v of fresh concrete [75, 81]

within 15 seconds, one side is lifted 40 mm and dropped) to agitate the fresh concrete to determine the consistency classes F. In the Vebe test, a cone of fresh concrete is remolded to a cylindrical shape by standard vibration. The time required to achieve complete remolding describes the workability of the fresh concrete in terms of Vebe seconds [75, Part 3, 79-80], which indicate the consistency classes V.

Tests for the compactibility of fresh concrete are specified in [81]. In general, a mold is filled with concrete in such a manner that any uncontrolled compaction is avoided. After the mold is filled, the fresh concrete is consolidated by vibration. Compaction factors are then derived from density measurements or a comparison of the original volume (height) of the fresh concrete to the volume (height) after compaction. The compaction factors indicate the consistency classes C. The test setup is shown schematically in Figure 4.

There is no strict correlation of the results obtained from the different methods for evaluating the workability of fresh concrete, and no single test method is universally applicable. Although plastic concrete mixes can be characterized by the slump or spread, the compacting tests are more appropriate for stiff and dry mixes. The different methods of testing workability are correlated in Figure 5 [74].

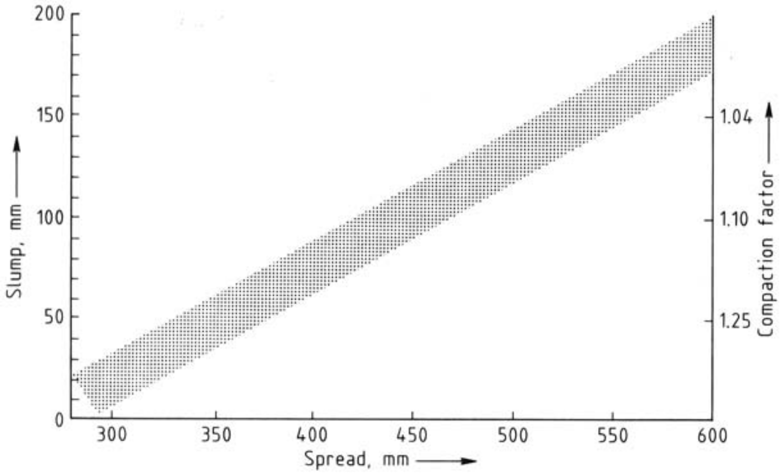

Figure 5. Approximate correlation of the slump, spread, and compaction factor of fresh concrete [74]

4.2. Placement, Consolidation, and Finish

After mixing, the concrete must be placed in its final position, consolidated, and eventually surface-finished within 1–2 h and before the initial set. The method of placing concrete into the form works depends on its consistency and the equipment available at the site. Separate placement of single batches by buckets or buggies, as well as continuous placement by concrete pumps and hoses or conveyor belts, is successful if care is taken to avoid separation of the concrete constituents. To prevent cold joints, subsequent layers must be placed while the first preceeding layer is still plastic and while knitting of the two layers can be achieved by vibration.

Consolidation of the fresh concrete after casting removes entrapped air, allowing for a monolithic and densely packed concrete structure. The reinforcement must be embedded thoroughly to provide a good bond with the concrete and to be protected from corrosion.

Fresh concrete is consolidated by vibration, which is usually provided by poke vibrators inserted into the concrete. Vibrators mounted on vertical formworks of thin concrete cross-sections or surface vibrators are also used. The vibration energy necessary for complete compaction decreases as the workability of the fresh concrete increases. Excess vibration can cause segregation [74, 82].

Plasticizing additives may substantially reduce the necessary consolidation work, and concrete containing superplasticizers and an appropriate fraction of mineral fines may not require any consolidation. Self-compacting concrete may increase the quality of the concrete placement and, at the same time facilitates the work and increases the efficiency on the site [45, 83, 84]. Concrete may benefit from a second vibration after the initial setting to repair cracks that have developed due to settlement, early shrinkage, or deformations of the formwork.

The top surface of fresh concrete can be troweled or screeded. The durability of horizontal concrete surfaces, such as pavements and parking garage decks, is increased by vacuum processing of the fresh concrete surface. Partial withdrawal of the mixing water results in lower porosity and higher strength of the surface region [15, 74, 82].

4.3. Curing

The development of concrete strength and impermeability requires favorable conditions for hydration of the cement. In addition, crack formation should be avoided. Curing of concrete, therefore, comprises all measures undertaken to protect the hardening concrete from drying and to control the temperature across a section [86].

Early loss of water from the young concrete may prevent further hydration of the cement, especially in the surface region, resulting in insufficient strength development and high permeability. Furthermore, premature drying causes extensive shrinkage, which will lead to random cracks in the surface layer. Protection against moisture loss is normally achieved by covering the concrete surface with water-absorbent materials such as burlap or straw, which are kept wet under damp-proof plastic sheets, or by the application of membrane-forming curing compounds. The last-named compounds contain wax or resins and are sprayed or brushed on the concrete surface; however, they do not provide sufficient protection for hot weather concrete curing [85].

Control of concrete temperature may be necessary when concrete is placed at low ambient temperature. Because the hydration of cement proceeds only slowly or even ceases at temperatures $< 5\,^{\circ}\mathrm{C}$, thermal insulation of the concrete surface is used to prevent rapid loss of the heat of hydration. Thermal insulation also prevents excessive temperature gradients in a concrete cross section and protects the young concrete from freezing [87]. Thermal insulation is particularly important for massive concrete sections.

Interior sections of a concrete member are less affected by curing than the surface regions. Adequate curing is, therefore, essential for achieving the required durability of a concrete structure.

Aside from the expected exposure conditions for a concrete member, the required curing period to achieve a sufficient concrete majurity in the surface near zone depends primarily on the ambient climatic conditions during the hydration period as well as on the hydration kinetics of the cement used; it may vary from one day for rapidly hardening cement under moderate climatic conditions up to more than 14 days for massive concrete structures and / or severe exposure conditions. Guidelines can be found in [26, 86].

The accelerating effect of elevated temperature on the hardening of concrete is used in the prefabrication of concrete elements; however, curing temperatures exceeding ca. 60 °C may reduce the final strength of the concrete. Steam curing at atmospheric or high pressure is applied in the preparation of certain concrete products such as pavement units, masonry units, and precast elements [88, 89].

4.4. Special Methods

A variety of special methods have been developed to simplify or increase the efficiency of preparing, transporting, placing, consolidating, and curing concrete.

For repair work, for strengthening existing structures, or for special applications, shotcrete may be superior to conventional concrete placing practice. In shotcrete, concrete is transferred pneumatically in a hose and projected through a nozzle onto a rigid surface at high velocity; consolidation is readily achieved by impact [90–94]. Dry and lean concrete mixes for road sub-bases or bearing courses as well as concrete in dams are placed as roller-compacted concrete (RCC).

In construction of large concrete elements such as dams or for concrete placed under water, grout may be injected into the voids of preplaced coarse aggregates to produce concrete [73]. Similar methods are applied to pre-packed steel fibers to produce fiber-reinforced concrete with high fiber concentrations. [95].

Special procedures also exist for the production of concrete products such as masonry units, concrete pavements, or concrete tubes [88, 89].

5. Mechanical Properties

The most important design characteristics of concrete needed for structural analysis are the compressive strength and the modulus of elasticity of the hardened concrete; in many instances the tensile strength is not a design parameter. For concrete sections subjected to tensile stresses, a fracture mechanics approach is recommended because the tensile strength of concrete is controlled by such material defects as voids, pores, or microcracks. Structural design also requires information on dimensional changes due to creep, shrinkage as a result of moisture migration, or temperature variation.

5.1. Crack Development

The mechanical behavior of concrete is controlled by defects or microcracks, which are caused by the nature of the hydrated cement paste or which are generated during the hardening of concrete. The cement hydrates continuously, thereby dissicating the matrix and causing it to shrink. Additional shrinkage is due to evaporation of water from the concrete surface. Because the stiff aggregates restrain the shrinkage of the cement paste, microscopic cracks are formed in the interfaces between mortar and coarse aggregates. Crack propagation continues from these defects when the concrete is subjected to stress. Tensile stresses and compressive stresses cause different types of crack propagation [96].

When concrete is loaded in compression, microcracks start to propagate when the stress exceeds ca. 40% of the maximum stress. With an increasing stress level, crack growth proceeds mainly along the interfaces between coarse aggregates and the matrix. At ca. 80% of the maximum stress, the cracks start to extend into the mortar matrix. Frequently cracks are arrested at aggregates, which results in branch cracking. As a consequence, the nonlinearity of the stress–strain diagram increases substantially. The predominant orientation of the cracks is then parallel to the axis of loading. At high stress, microcracks join to form longer cracks. Thus, the cracks reach a critical length, and unstable crack growth can only be avoided by reduction of the stress. As long as crack propagation remains stable, the strains continue to increase and the stress–strain relationship shows a descending part (stress $\sigma =$ force/area, strain $\varepsilon =$ change in length/original length).

If the load is kept constant at a strain greater than the strain at maximum stress, a continuous fracture plane is formed, causing the complete collapse of the concrete [97].

Concrete loaded in tension behaves like a brittle material. Initiation of crack growth takes place at preexisting microcracks, but multiple crack growth and branch cracking are much less pronounced than when under compression. Crack propagation is usually limited to one section. Nevertheless, a *process zone* is formed in front of a propagating crack, thus increasing the energy dissipation. At tensile failure stress, unstable crack growth forms a fracture surface perpendicular to the axis of applied tensile stress. Sophisticated testing procedures can detect some stable crack propagation, which is more pronounced for larger amounts and sizes of aggregates [98].

5.2. Strength

5.2.1. Compressive Strength

The compressive strength of normal concrete is in the range 10–100 MPa (N/mm^2), depending on the composition and preparation procedures. High-strength concrete (HSC) can be produced with selected types and grades of aggregates, mineral fines, and superplastizers to allow very low w/c ratios, and compressive strengths exceeding 250 MPa have been reported [99, 100]. The compressive strength of most concrete placed, however, is in the range 25–50 MPa. The most important parameter controlling concrete strength is the w/c ratio [101]. Other factors are the type of cement, curing conditions, moisture content, degree of hydration of the cement, and the grading and shape of aggregates. If sufficient water is provided, the hydration of cement will continue over a period of several years, and concrete strength may increase continuously during this time [14, 15]. It is customary to classify concrete according to the compressive strength attained after a standardized curing of 28 days. In certain cases, however, the compressive strength after shorter or longer curing periods may be specified.

On the basis of f_{ck}, EN 206-1 [26] categorizes structural concrete into discrete strength classes according to Table 6. In the denomination of the strength classes the first number indicates the characteristic strength as tested on concrete cylinders with a diameter of 150 mm and a height of 300 mm, whereas the second number stands for results obtained from testing cubes with a side length of 150 mm.

Lightweight concrete can be reinforced or prestressed similar to normal weight concrete. Concrete with strength classes lower than C16/20 may not be reinforced.

Table 6. Strength classes for concrete according to EN 206-1 [26]

Normal and heavyweight concrete	Lightweight concrete
C 8/10	LC 8/9
C 12/15	LC 12/13
C 16/20	LC 16/18
C 20/25	LC 20/22
C 25/30	LC 25/28
C 30/37	LC 30/33
C 35/45	LC 35/38
C 40/50	LC 40/44
C 45/55	LC 45/50
C 50/60	LC 50/55
C 55/67	LC 55/60
C 60/75	LC 60/66
C 70/85	LC 70/77
C 80/95	LC 80/88
C 90/105	
C 100/115	

Because of inevitable differences in the properties of concrete components, preparation procedures, handling, consolidation, and curing, the strength of any particular type of concrete varies within a range. For the classification of concrete strength, therefore, a characteristic strength f_{ck} is defined, below which only a certain percentage, usually 5%, of the entire population of data falls. This value of f_{ck} defines a 5% defective concrete [66, 26, 70]. Assuming a normal frequency distribution of the individual strength values, the mean strength f_{cm} associated with a certain 5% defective for a given standard deviation s can be estimated:

$$f_{\mathrm{cm}} = f_{\mathrm{ck}} + 1.64\, s$$

Even if good quality control is maintained during the production process, a standard deviation s of at least 3 MPa must be assumed. If a sufficient number of individual strength data are available, the standard deviation can be computed from the observed frequency distribution of individual strength results [26, 102]. In quality control during concrete production, the conformity of a given concrete with the respective strength requirements must be judged on the basis of a limited number of test results. EN 206-1 [26] defines conformity criteria for the mean values of the observed compressive strength as well as for individual values [103].

In general, the strength of concrete is determined by testing separately cast companion specimens [66], which are either cured under standard laboratory conditions or are exposed to the same curing conditions as the ultimate structure. Because the test results depend on the size and slenderness (i.e., height/thickness) of the concrete specimens tested, standard test specimens must be used. The most common specimens are cubes with a side length of 150 mm or cylinders with a diameter of 150 mm and 300 mm high [66–68]. Specimen preparation and testing procedures are specified in the corresponding standards [66, Part 1, Part 2, 104].

The use of drilled cores for destructive laboratory testing is the most reliable method for testing the strength of an existing concrete structure [[105], Part 1]. Nondestructive methods such as ultrasonic pulse velocity, rebound, or penetration resistance require calibration [66, 71, 106, 72, 105, Part 2].

The sustained load strength of concrete is controlled by two counteracting mechanisms. While a continuous increase of strain under a sustained load may weaken the integrity of the concrete, a strengthening effect is exerted by the continuing hydration of the cement, which is more pronounced for younger concrete than for older concrete. The sustained load strength of concrete loaded at an age of 28 d is ca. 80% of its short-time strength, which is less influenced by creep (Fig. 6) [63, 107].

The fatigue strength of concrete decreases with an increasing number of stress cycles and an increasing stress range. The relations between the maximum stress and the average number of cycles leading to failure for various ratios of minimum to maximum stress are given in Figure 7. Concrete does not show a fatigue limit up to 10^7 load repetitions [108]. Analytical procedures for the prediction of the fatigue strength of concrete are presented in [63, 109].

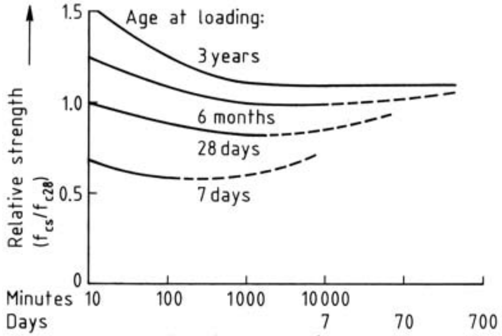

Figure 6. Relative sustained load strength of concrete f_{cs}/f_{c28} for different durations of loading and ages at the time of loading [107]

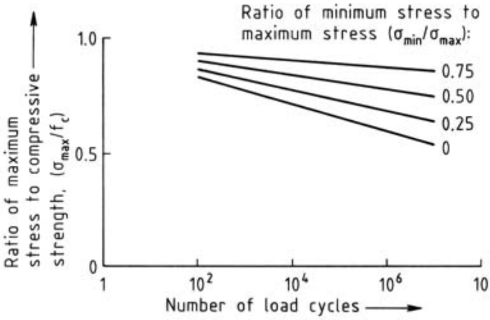

Figure 7. Fatigue strength of concrete for different stress levels

5.2.2. Tensile Strength

The tensile strength of normal concrete is approximately one-tenth the compressive strength. Detailed analyses by CEB [63] predict that the tensile strength should not increase in proportion to the compressive strength. In general, the tensile strength of concrete is determined by testing beams subjected to flexure [66 Part 5] or cylinders that are subjected to diametrically opposed axial line loads, giving the so-called tensile splitting strength [66 Part 6, 110-114]. The direct tensile strength can be determined by axial tension according to [115]. Different test methods yield different results because of differences in stress state, stress distribution, and probability of failure.

5.2.3. Fracture Mechanics

The application of linear elastic fracture mechanics to concrete is limited because of the heterogeneity of the material and because of the development of a process zone, i.e., a region of microcracks in front of a major crack.

Accordingly, specimens with minimum dimensions at least 20 times the maximum aggregate size should be used when the conventional fracture mechanics characteristics of a concrete are determined.

The fracture toughness K_{IC} of cement paste, mortar, and concrete are as follows:

hydrated cement paste. $K_{IC} = 5 - 15$ N/mm$^{3/2}$
mortar. $K_{IC} = 10 - 20$ N/mm$^{3/2}$
concrete. $K_{IC} = 15 - 50$ N/mm$^{3/2}$

K_{IC} increases with increasing degree of hydration and decreasing w/c ratio. Because aggregates act as crack arresters and cause multiple crack growth, K_{IC} increases with increasing content and size of aggregates.

Fracture mechanics concepts can be applied successfully in concrete technology and design, e.g., for the description of fracture processes, for estimating notch sensitivity, and for the design of large unreinforced concrete members [116].

A further parameter is the fracture energy G_F, which corresponds to the total energy required to separate a concrete section loaded in tension. Since G_F is less dependent on size than K_{IC}, it can be used to analyze smaller concrete members [117]. According to [63] the fracture energy G_F of a given concrete can be estimated from its compressive strength and the maximum aggregate size:

$$G_F = F_{F0}(f_{cm}/f_{cm0})^{0.7}$$

where f_{cm} is the the mean cylinder compressive strength in N/mm^2 and f_{cm0} = const. = 10 N/mm^{2}. G_F increases from 0.25 to 0.38 as the maximum aggregate size increases from 8 to 32 mm.

5.3. Deformation Characteristics

The deformations of concrete under load can be separated into elastic and time-dependent deformations. In structural analysis, time-dependent strains are of considerable importance in estimating the serviceability of constrained members or prestressed structures in which a loss of prestress may occur. All time-dependent deformations are markedly influenced by the concrete composition and by the prevailing climatic conditions. Thermal expansion is discussed in Section 6.6.

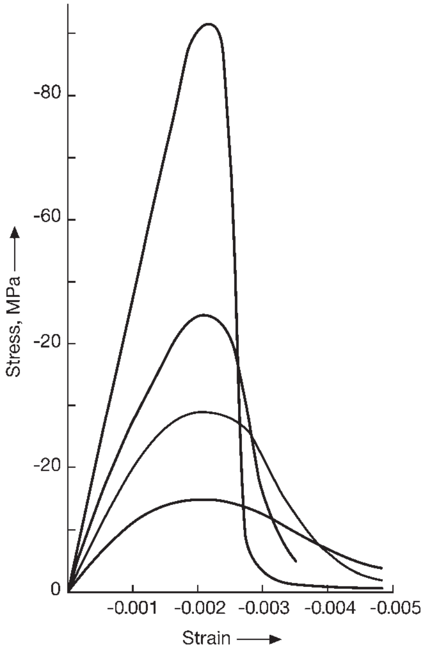

Figure 8. Stress–strain relationship for concretes of different strengths

5.3.1. Relationship of Stress to Strain

Stress–strain diagrams of various concretes with different strengths are presented for compression in Figure 8. The diagrams were recorded at a constant strain rate. Under compression, these diagrams are nonlinear even at low stress levels. With increasing stress, the nonlinearity increases. The strain at maximum compressive stress is almost independent of the strength of the concrete and amounts to ca. 2×10^{-3}. For higher strength concretes the increasing brittleness of the material is reflected in a steep descending branch of the stress–strain curve. Analytical models for the description of stress strain relationships as functions of concrete strength are given in [63]. The stress–strain relationships are also influenced by the strain rate, as shown in Figure 9. A reduction in strain rate causes a slight reduction in strength and a pronounced increase in the ductility of the concrete.

The stress–strain relationship for concrete loaded in tension is almost linear up to failure, which is normally brittle. Failure strains range from ca. 0.1×10^{-3} for a concrete loaded in axial

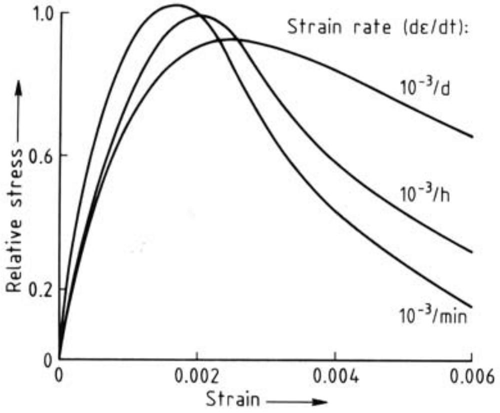

Figure 9. Influence of strain rate on the stress–strain relationship of concrete

tension to 0.3×10^{-3} for concrete subjected to flexure [15, 96].

5.3.2. Modulus of Elasticity and Poisson's Ratio

The curves in Figure 8 show that there is no constant modulus of elasticity for concrete in any part of the stress–strain curve. It is, therefore, customary to define an initial tangent modulus given by the slope of the stress–strain relationship at the origin, a tangent modulus at a given stress, or a secant modulus over a certain range of the diagram at ca. $0 < \sigma \leq 0.5 f_c$. The lower and upper limits of this range vary in different standards and recommendations [66, 118, 119]. The modulus of elasticity E_c for normal concrete is in the range 20 000–40 000 MPa. A higher compressive strength of the concrete leads to a higher modulus of elasticity. This correlation [63] is expressed empirically as follows:

$$E_C = \alpha_E E_{c0} (f_{cm}/f_{cm0})^{1/3}$$

where E_c = modulus of elasticity in N/mm^2, α_E = factor to consider the stiffness of the aggregates; for natural aggragates $0.7 < \alpha_E < 1.2$, f_{cm} = mean cylinder compressive strength in N/mm^2, and f_{cm0} = const. = 10 N/mm^2.

The modulus of elasticity can also be deduced from the natural frequency of concrete specimens subjected to longitudinal, transverse, or torsional vibration as the dynamic modulus of elasticity [15]. These nondestructive tests yield higher values of E_c.

Poisson's ratio v of concrete is about 0.2 as long as the stress level σ does not exceed $0.8 f_c$. At higher stress levels, values of Poisson's ratio exceeding 0.5 are observed due to multiple crack formation [96].

5.3.3. Creep

Creep is defined as the time-dependent increase of load-dependent strain under constant stress. It is often expressed in terms of the creep coefficient ϕ_c, which is the ratio of creep strain ε_{cc} to initial (elastic) strain ε_{ce}. For the range of working loads, the creep coefficient of concrete ranges from ca. 1 to 4. Creep is partially reversible. The part of creep that can be recovered on unloading is referred to as *delayed elastic strain*, whereas the irreversible part is generally described as *flow*.

The water content of concrete exerts an important influence on creep deformation. *Basic creep* is defined as the creep of concrete in a state of moisture equilibrium. Basic creep becomes smaller as the water content of the concrete prior to load application decreases. *Drying creep* is defined as the difference between basic creep and the creep of concrete that is allowed to dry under load. Drying creep is thus proportional to moisture loss. Creep deformation increases because of microcracking, particularly at higher stress levels [87].

Creep of concrete increases with an increase in the amount of cement paste, of the water content of the concrete prior to loading, and of the w/c ratio. Creep increases at low relative humidity and with decreasing member size. A higher degree of hydration at the time of loading reduces creep.

There are several mathematical methods for estimating the time development of creep. In these formulas, which may incorporate viscoelastic models, terms or functions represent characteristics of the concrete, geometry of the member, and nature of the environment [63, 25, 87, 120].

5.3.4. Shrinkage and Swelling

Shrinkage and swelling are load- and temperature-independent volume changes essentially

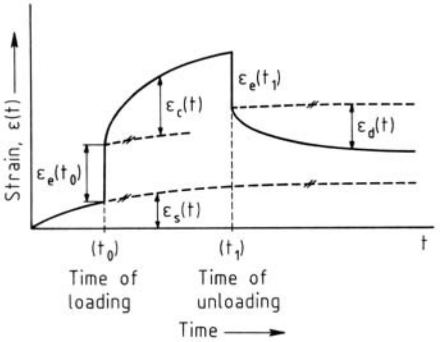

Figure 10. Total deformation of concrete loaded at t_0 and unloaded at t_1 as a function of time. ϵ_e is elastic strain, ϵ_s is shrinkage strain, ϵ_c is total creep strain, ϵ_d is delayed elastic strain

caused by changes in the moisture content of the concrete. As a first approximation, shrinkage is proportional to the moisture loss. When the concrete is rewetted, swelling occurs, although some irreversible shrinkage may remain.

The total shrinkage of hydrated cement paste may amount to one percent. Aggregates restrain shrinkage so that shrinkage of concrete is considerably less and is ca. 0.1×10^{-3} to 1×10^{-3}. Rapid drying of concrete generates shrinkage-induced tensile stresses in the surface zones that may lead to cracks [87, 120]. Analytical models for the prediction of shrinkage as a function of concrete composition, geometry and exposure of the concrete member are given for example in [25, 63].

The total deformation of concrete is shown as a function of time in Figure 10.

6. Physical Properties

Most of the physical properties of concrete are controlled by its composition, mainly by the type and amount of aggregates used and the water content of the fresh or hardened concrete.

6.1. Density

Concrete is classified according to its density:

lightweight concrete. $\varrho \leq 1850$ kg/m^3 [121]
$\varrho \leq 2000$ kg/m^3 [26]
normal-weight concrete. $\varrho \leq 2600$ kg/m^3 [26]
heavyweight concrete. $\varrho > 2600$ kg/m^3 [26, 65]

Lightweight concrete has a lower thermal conductivity than normal-weight concrete and it reduces the dead weight of a structural element. Heavyweight concrete is used mainly as a radiation-shielding material or ballast.

6.2. Porosity

The total porosity of concrete comprises gel pores and capillary pores in the hydrated cement paste, the porosity of aggregates and aggregate interfaces, and voids due to incomplete consolidation. Additionally, a protective pore system may be introduced into the matrix by air-entraining additives or air-entraining cements. The size of pores ranges from small gel pores with diameters of ca. 10^{-6}mm up to several millimeters for the voids [122]. In normal concrete with dense aggregates, the total porosity is 8–15% by volume. Air-entrained concrete contains an additional 2–6% pores. Lightweight concrete with porous aggregates, lightweight concrete with a honeycomb structure, or cellular lightweight concrete may have a total porosity of 60–90% by volume. Such concretes have low strength and are used only for thermal insulation [15].

6.3. Thermal Conductivity

The thermal conductivity of concrete increases with decreasing porosity and increasing moisture content. Crystalline aggregates give higher conductivity than amorphous aggregates. For normal concrete the thermal conductivity is 1.5–3.7 W m^{-1} K^{-1}. The thermal conductivity is shown as a function of the density of dry concrete in Figure 11 [15].

6.4. Electrical Conductivity

Dissolved ions present in the water in the pores of hardened concrete are primarily responsible for the electrical conductivity. For dry concrete, specific ohmic resistance is $10^{11}\Omega \cdot$ cm, whereas for concrete saturated with water it is ca. $10^4\Omega \cdot$ cm. Concrete contaminated with soluble salts has

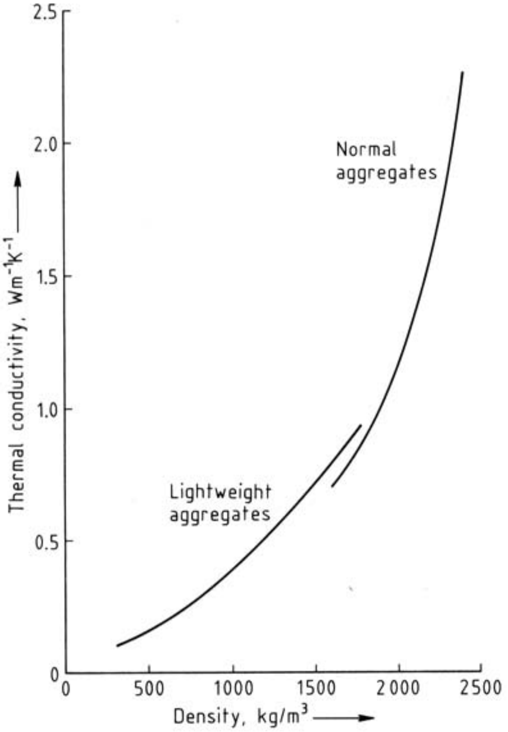

Figure 11. Thermal conductivity of concrete as a function of concrete density

even lower resistance. Because the water in the pores is an electrolyte, conductivity increases with increasing w/c ratio [15].

6.5. Permeability

An important parameter for concrete durability is its permeability, which describes the ability of gases or liquids to penetrate into and through concrete sections. The movement of gases or liquids in concrete primarily occurs along aggregate/paste interfaces and in the capillary pores of the cement paste matrix. Because the volume of capillary pores increases with an increasing w/c ratio, permeability increases correspondingly. High values of permeability can be expected when the capillaries form an interconnected continuous network caused by a low degree of hydration. For w/c ratios exceeding ca. 0.7, continuity of capillaries must be assumed even after complete hydration [15].

The saturated capillary flow of water under the influence of hydraulic pressure is usually described by an empirical relation according to DARCY [123]. Neglecting the viscosity and the density of water, a specific water permeability k_w is derived, values of which ranging from $k_\mathrm{w} = 10^{-10}$ to 10^{-14} m/s have been reported for normal concretes [124, 125].

For the flow of gases, the viscosity and compressibility of the fluid must be considered. For normal concrete mixes the coefficient of gas permeability K_g is in the range of 10^{-14} to 10^{-18} m^2/s. Since the flow of gases depends on empty capillary pores, the coefficient of gas permeability is strongly influenced by the moisture content of the concrete [126]. The gas permeability of concrete is closely related to the ingress of deleterious substances into concrete and thus may serve as an indication of its durability [125].

For barriers or retaining structures in the chemical and petrochemical industries, the penetration of hazardous fluids by capillary action must be controlled to protect the soil, ground water, and other environmental compartments from contamination. Recommendations and requirements are given in [127, 128]

Moisture movement is important in the drying of concrete. The diffusion of water molecules in the vapor phase or in condensed films depends strongly on the local moisture concentration, the diffusion coefficient and can be 10^{-8} to $10^{-11}\mathrm{m}^2/\mathrm{s}$ for concretes of normal compositions at relative humidity of 0–100% [129].

6.6. Thermal Expansion

The thermal expansion of concrete is controlled by the thermal expansion of the cement paste and the aggregates. Therefore, different aggregates lead to different coefficients of thermal expansion of the concrete. Restraint of the matrix by coarse aggregates or the formation of microcracks, however, causes a total deformation of concrete that is not equal to the sum of the individual deformations of matrix and aggregates weighted by their volume concentrations. The coefficient of thermal expansion for concrete made with quartzitic aggregates is ca. $12 \times 10^{-6}\mathrm{K}^{-1}$. For concrete made with calcareous aggregates, it is ca. $6 \times 10^{-6}\mathrm{K}^{-1}$ [15, 130].

Changing temperatures always cause a moisture movement in the matrix, which may lead to shrinkage or swelling. These deformations are added to the thermal dimensional changes.

6.7. Shielding Properties

Concrete is an economical material for shielding against high-energy X-rays, gamma rays, or neutrons because it combines structural properties with good shielding characteristics. Because of its heterogeneity, concrete contains a variety of different elements for attenuation or absorption of the different types of radiation. Although these elements exist in normal concrete, special designs with selected materials can improve the shielding properties.

Neutrons are classified according to their energy as fast, intermediate, and slow (thermal) neutrons. The attenuation of fast and intermediate neutrons by elastic scattering by light elements, such as hydrogen or boron, and inelastic scattering by heavy elements lead to slow neutrons that are finally absorbed by heavy elements. Gamma rays are emitted in the steps of neutron attenuation [15, 131].

Because the attenuation of X-rays and gamma rays is proportional to the density of the material penetrated, heavy elements are required for effective shielding.

Special aggregates for shielding concrete can be natural heavy-element aggregates like baryte, iron ores, or granulated iron. Light elements can be added by using aggregates that contain large amounts of crystal water such as serpentine or by the introduction of insoluble boron compounds [132].

In the structural design of a biological shield, one should keep in mind that the attenuation of radiation generates heat that causes stress. Furthermore, high-energy radiation causes crystal defects in the aggregates that may reduce the strength of the concrete [133].

7. Durability

Structural concrete is subjected to a variety of physical and physicochemical influences that result from environmental conditions or other types of attack. In most instances, concrete needs no particular protective measures. In reinforced or prestressed concrete structures, the concrete must prevent corrosion of the reinforcement by providing a high alkalinity to passivate the steel surface.

Concrete aggregates are inert to most types of external attack. However, the hydrated cement paste may interact with the environment because of its interconnected *pore structure*. Water, ionic solutions, or gases may penetrate into the concrete through the capillary pores or microcracks to react chemically with constituents of the cement paste, thus causing deterioration. A durable concrete, therefore, should have a dense structure with a low total porosity and consequently, a low permeability. Low w/c ratios and sufficient curing of the concrete are mandatory. By following the principles in the design of high-strength concrete, which basically involve a very dense cement paste and an improved aggregate/paste interfacial zone, the resulting material also exhibits high resistance against most corrosive agents, because the penetration of aggressive compounds into the concrete is prevented. In many applications of these advanced materials, the enhanced durability is more important than the high strength. In more general terms the material is referred to as high-performance concrete (HPC).

An important factor in durability is the *moisture content* of the concrete. Because most damage mechanisms require a certain amount of water, dry concrete exhibits a high durability. Continuous wetting of concrete may increase the depth of penetration of dissolved compounds, and repeated drying–wetting cycles can accelerate the deterioration [134].

7.1. Chemical Attack

Chemical attack on hydrated cement paste involves either partial or complete dissolution of certain hydration products or formation of new compounds, accompanied by an increase in solid volume or in expansive gels.

Water that does not contain excessive amounts of ions or industrial waste pollutants does not dissolve cement paste compounds to a significant degree. However, continuing exposure to distilled water may leach the calcium hydroxide from the paste. Natural waters containing considerable amounts of *carbonic acid* will attack the cement paste and calcareous aggregates, forming soluble calcium hydrogencarbonate. Efflorescence of $CaCO_3$ is often observed.

The compounds of hydrated cement paste are dissolved by *organic and inorganic acids* and the rate of dissolution increases as the pH of the environment decreases. Moderate attack can be seen when the pH of the surrounding solution drops below 6.5–6.8.

The formation of expansive phases in interior concrete sections can be detected by the formation of a network of surface cracks, through which white efflorescence or penetration of a gellike material can occur.

Sulfates penetrating into the matrix will react with either calcium hydroxide or calcium aluminates to form gypsum ($CaSO_4 \cdot 2\ H_2O$) or ettringite ($3\ CaO \cdot Al_2O_3 \cdot 3\ CaSO_4 \cdot 32\ H_2O$). The disruptive effect of ettringite formation is more pronounced because it involves a considerable increase in solid volume [135].

Magnesium compounds, either contained in the aggregates or penetrating from outside, can be decomposed to form an expansive gel of magnesium hydroxide.

Alkali–silica reactions occur between the alkaline materials of the cement and amorphous or poorly crystallized silica of some siliceous aggregates. When moisture is available, an expansive gel is formed that causes a continuous deterioration of the concrete. Questionable aggregates can be tested for the presence of reactive silica [40]. Their use as concrete aggregates may require special cements with low effective alkali contents [43].

The activity of natural waters and soils is evaluated in standards, where recommendations are given for the composition of concrete to be used in contact with them. Concrete that is subject to strong chemical attack may require protective coatings of organic materials on the surface [35, 26, 135–137]. A comprehensive list of chemical compounds and their effect on concrete is given in [63, 136].

7.2. Physical Attack

Frost. The mechanism of freezing of water in concrete is rather complex and not entirely clear. Thorough discussions of this subject may be found in [122]. The following description is highly simplified.

Water contained in the larger capillary pores of concrete starts to freeze at temperatures below ca. $-8\,°C$. If the concrete is critically saturated, i.e., more than ca. 90% of its pores are water-filled, the expansion of ice may have a disruptive effect if free expansion of ice or migration of the remaining liquid water into free spaces cannot take place. Thus, important parameters for controlling frost damage are the amount of freezable water in the concrete and the rate of ice formation.

The application of deicing salts to a frozen concrete surface may cause further damage. While the ice on the concrete surface will melt, a sudden drop in the temperature of the underlying concrete layer occurs. Furthermore, deicing salts can increase the degree of saturation and the number of freeze–thaw cycles. Additional damaging effects due to osmotic pressure or pressure from salt crystallization have not been clarified [122].

Preparing concrete with high resistance to freezing and deicing agents requires aggregates with a high resistance to freezing and a dense pore structure of the cement paste that is provided by low w/c ratios and sufficient curing. Furthermore, when critical saturation is likely to occur, a protective system of small, spherical, closely spaced pores must be introduced into the mortar matrix by air-entraining additives or air-entraining cements. Because these pores do not fill with water under normal conditions, they provide space for the expansion of ice or water upon freezing.

Elevated Temperature. The resistance of concrete to elevated temperatures depends on the mineral composition of the aggregates and the water content of the concrete. The mortar matrix in a concrete that is allowed to dry while hot will exhibit large shrinkage deformations, whereas the aggregates expand as the temperature increases. These opposing deformations lead to the formation of cracks, thus reducing concrete strength. Individual compounds of the cement paste start to decompose above 110 °C, and the dehydration continues up to the sintering of particles above 1000 °C [138, 139].

Concrete exposed to temperatures above 100 °C in a moist state undergoes phase transformations in the hydrated cement paste. In the absence of finely divided siliceous material, these phase transformations increase the total porosity of the paste and cause a significant reduction in the concrete strength. If fine siliceous aggregates or siliceous additives are present, new compounds are formed that can compensate for the loss of strength [138].

Radiation. Concrete subjected to high-energy radiation may lose strength. While there is no damaging effect of radiation on the hydrated cement paste, lattice defects can be formed in some types of crystalline rocks used as aggregates. Heterogeneous rock material with crystalline compounds such as granites undergoes a substantial loss in strength [133].

Abrasion and Wear. The surface regions of concrete structures can be subjected to abrasion and wear due to traffic loads, sliding, or scraping of hard objects, or repeated impact. Damage is often encountered on pavements, walls of silos or bunkers, and in pipes and ducts for water that carries solids (erosion). Water flowing at a high velocity can cause cavitation. Concrete with a high resistance to wear requires a low w/c ratio and careful curing. Vacuum processing of the fresh concrete and the use of hard aggregates or additives can substantially improve the resistance to wear.

7.3. Corrosion of the Reinforcement

The surface zones of reinforced concrete structures can be damaged by corrosion of the embedded reinforcement. The formation of voluminous iron hydroxides generates tensile stresses that cause spalling of the concrete cover. The most common causes of corrosion of the reinforcement are carbonation of the concrete or intrusion of corrosive ions such as chlorides.

Carbon dioxide in the atmosphere penetrates the surface zones of concrete and reacts with the alkaline hydration products of the cement. In this diffusion-controlled reaction, insoluble calcium carbonates are formed and the pH of the pore solution of the matrix drops from more than 12 to ca. 8.7. In this environment, an embedded steel reinforcement is no longer protected by passivation because the passive layers become unstable, and anodic dissolution of the iron occurs when oxygen and moisture are available [140].

The passive layer of steel in concrete can also be destroyed by chloride ions. The major sources of chloride contamination of concrete are deicing agents, seawater, and the thermal decomposition of polymers such as PVC by fire.

Although some chloride can be immobilized chemically or physically by the hydration products of the cement, additional chloride ion greater than a threshold concentration will destroy the passive layers of the steel reinforcement locally, and corrosion occurs [64, 124]. Structures exposed to seawater may, therefore, require an increased concrete cover of the reinforcement [35].

Carbonation and intrusion of active ions are controlled by diffusion. A dense pore structure of the cement paste matrix, especially in the surface zones, reduces the penetration rate and thus improves durability. Under very severe conditions, additional protective measures such as surface coating of the concrete or the steel reinforcement may be required.

8. Special Concretes

The basic principles of concrete technology for normal concrete are generally valid for other types of concrete, which may differ from normal concrete with respect to composition or properties tailored for special applications. Preparation, handling, and testing of such concretes are often specified in separate standards or guidelines. The most important types of concrete that differ from normal concrete are lightweight and heavyweight concrete, mass concrete, fiber-reinforced concrete, and polymer concrete.

8.1. Lightweight Concrete

Lightweight concrete has a lower bulk density than normal concrete, which can be achieved in several ways. Structural lightweight concrete with a dense structure is prepared with lightweight aggregates, such as tuff, expanded shales, or calcined waste products. Structural lightweight concrete may be reinforced or prestressed like normal concrete.

Lightweight concrete with a honeycomb structure is prepared with only coarse aggregates, which are enveloped by a thin shell of fine mortar, thus providing a large volume of interstitial voids. Such concretes can be used for masonry units or drainage purposes. Cellular lightweight concrete and aerated autoclaved concrete are prepared by introducing foam-forming additives into a mortar mix. Because of their low compressive strength, these cellular lightweight concretes are used only for making masonry units or for thermal insulation.

The basic relations between the w/c ratio and concrete strength are valid for structural lightweight concrete, although with limitations because the strength of the matrix may be higher than the strength of the aggregates. Furthermore, the definition of a w/c ratio is uncertain because the porous aggregates can absorb various amounts of the water added to the mix. Preparing lightweight concrete, therefore, always requires trial mixes. In general, compressive strength increases with increasing bulk density. For densities of 1.0–2.0 kg/dm^3, the compressive strength is 10–60 MPa. Compared with normal concrete, lightweight concrete has a lower compressive strength, lower modulus of elasticity, lower thermal conductivity, and lower thermal expansion, but higher creep and shrinkage deformations [15].

8.2. Heavyweight Concrete

The major applications of heavyweight concrete are as shielding against nuclear radiation, as ballast, and as anchor bodies. Heavyweight aggregates like baryte, ores with densities of 3.6–4.6 kg/dm^3, slags, or iron can be used to achieve bulk densities of the concrete exceeding 2.8 kg/dm^3. The mix design for heavyweight concrete follows the principles for normal concrete except that additional care must be taken to ensure the specified concrete density. Segregation must be avoided in handling heavyweight concrete. Therefore, comparatively dry mixes are preferred [3].

8.3. Massive Concrete

The term massive concrete refers not to a particular composition but rather to a concrete structure of such size that the heat of hydration of the cement must be considered. In interior parts of large concrete cross-sections, the heat of hydration may generate temperatures $> 80\,^{\circ}\mathrm{C}$, causing thermal stresses that can lead to crack formation in the concrete during early hydration. The temperature increase in the concrete member can be kept low by using cements with a low heat of hydration, addition of finely divided pozzolanas, and reduction of the cement content of the mix. The size of the aggregates may be as great as 125–150 mm. The curing of massive concrete may require thermal insulation of the surfaces to avoid steep temperature gradients over the cross-section. Otherwise cracking of the concrete is likely to occur [141, 142].

8.4. Fiber-Reinforced Concrete

The mortar matrix of concrete can be reinforced by short fibers randomly oriented and homogeneously distributed. The diameter of these fibers may vary from several micrometers to ca. 1 mm and the length from a few millimeters to 50 or 60 mm. High-strength steel fibers are used in steel fiber reinforced concrete placed as shotcrete or poured as normal concrete. High fiber concentrations lead to poor workability, which can be overcome with special placing procedures [95]. Alkali-resistant glass fibers were formerly sometimes used in thin shells or cladding elements. New types of organic, ceramic, and carbon fibers are being tested as substitutes for asbestos.

Fiber-reinforced concrete has good ductility in both compression and tension, and fiber reinforcement is an effective tool for crack width control of concrete [143]. Problems in manufacturing fiber-reinforced concrete are the limited workability of the fresh concrete and the diminished effectiveness of the fibers because of insufficient bonding between fiber and matrix.

8.5. Polymer Concrete

In polymer concrete, organic resins form an essential part of the binding material. Polymer concrete has high strength in tension and compression, and exhibits a superior resistance to chemical attack, freezing, and thawing as compared to normal concrete. Disadvantages may result from the high cost of the resins and reduced thermal stability compared to that of normal concrete. The polymers may be added to the fresh mix as the only binding material, e.g., epoxy concrete: polymer concrete (PC); they can be combined with water and cement, as in polymer cement concrete (PCC); or an already hardened concrete can be impregnated with monomers for subsequent polymerization as in polymer-impregnated concrete (PIC) [62].

Typical applications for polymer-modified cementitious materials are protective surface layers in aggressive environments or the repair and strengthening of damaged or deteriorated reinforced concrete structures.

9. Mortar

Mortar is distinguished from concrete by the maximum size of its aggregates. In general, mortar contains only sand with a maximum grain size of 2–4 mm. Other binding materials such as hydraulic lime can be used in addition to cement.

In concrete construction, cement mortars are used for connecting precast elements, as injection mortars in ducts of posttensioned structures with bonded tendons, and for the repair of old concrete surfaces with areas of deterioration.

Because of the small maximum size of aggregates, mortars contain higher w/c ratios than are normally encountered in concrete technology. Therefore, they exhibit lower compressive strength and volume stability. These disadvantages can be offset by the use of water-reducing and expansion-producing additives [15, 74, 96].

The composition and strength requirements for masonry mortars are specified in national standards and international documents. Lightweight aggregate mortars with reduced thermal conductivity have been developed to improve the thermal insulation properties of a masonry structure. Polymer-modified cement-based mortars with fine sand as the aggregate make possible bed joints only ca. 3 mm thick (thin-layer mortar). Centrally mixed mortars may contain retarding additives to allow placement of the mortar up to 48 h after mixing.

A variety of polymer-modified mortars designed for the repair of concrete structures with deteriorated surface zones are available. Basic requirements of mortar for such applications are the ability to form strong bonds with old concrete and a low shrinkage strain. Furthermore, they must resist the prevailing environmental attack and prevent the penetration of aggressive compounds.

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