CONCRETE

Properties and Manufacture

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PREFACE

THE book describes the properties of concrete, its manufacture and use in building and civil engineering construction. A scientific approach to the properties of materials and concrete has been united with a practical approach to methods of construction.

The book is intended to be useful to the student and graduate engineer as well as a reference book for the site engineer. To this end the theoretical and practical considerations have been combined in a degree found necessary in the Author's practical experience.

The subject of concrete is vast and the literature on it is extensive, but a selective list of references for further study of individual aspects of the subject is provided.

Information is included from many sources but the Author has endeavoured to give credit to these references. Many of the diagrams, graphs and illustrations are based on published information, the source of which has in each case been acknowledged. The plates to Chapter 7 are from photographs kindly made available by the Cement and Concrete Association.

In the preparation of this work the Author has had the advantage of the generous help of his colleagues, but in particular wishes to acknowledge with thanks the assistance of Mr. R. G. D. Smith-Gander. In addition he expresses gratitude to his wife for her efforts in the preparation of the script for printing.

T. N. W. A.

CHAPTER 1

THE PROPERTIES OF CONCRETE

Introduction

Concrete is a constructional material which consists essentially of a binding agent and a mineral filler. The binding agent is an hydraulic cement which develops its strength when mixed with water and, by hydration, changes from a loose powder to a hard, brittle, stone-like material.

A number of cements are in use, the most common being ordinary Portland. Other cements in common use are blast-furnace slag, high alumina and super-sulphated cements. The manufacture and properties of these are described in Chapter 2.

When cement reacts with water part of the water is chemically combined, but the remainder dries out, causing the set cement to shrink. To overcome the disadvantages of this shrinkage and to reduce the cost — for cement is relatively expensive — an inert filler is used. This usually consists of large, medium and small pieces of rock combined with sand. In properly mixed concrete the filler is coated with a layer of cement paste, and the reaction of the cement with the water combines the whole mass into concrete.

The filler, or aggregate, as it is termed, forms about 75% by volume of the whole. Various materials may be used as aggregate, the most common being naturally occurring sand and gravel. Manufactured aggregates are also used, particularly those of low density; certain other aggregates are used for special purposes, such as the shielding for an atomic reactor. The various aggregates, their properties and methods of preparation, are described in Chapter 2.

Concrete is used for a wide variety of purposes — as a foundation and structural material, as a walling material, and as a lightweight material for insulation. It is used for the construction of roads, airfields, buildings, water-retaining structures, docks, harbours and sea defences. It follows, therefore, that all the various properties of concrete are of interest to the engineer, their relative importance depending upon the use to which it is put.

As a structural material, strength is important; in construction, however, simplicity and control of manufacture are necessary. For docks, harbours and sea defences, resistance to seawater is required as well as strength. In road construction, freedom from cracking and resistance to abrasion and frost are important. The various properties of concrete can be altered by varying the proportions of the cement, water and aggregate, and by choosing an appropriate aggregate. This proportioning is known as mix design, and is described in Chapter 3.

Before the proportions of the various constituents can be decided, it is essential to know something of the general properties of concrete, and it is the purpose of the remainder of this chapter to describe these. The first section describes the properties of the plastic concrete after mixing, and the second section deals with the properties of the set concrete. Various other properties are discussed later in the book, e.g. resistance to deterioration is described in Chapter 6.

Before considering the general properties of concrete, its limitations should be realized. It may have a high compressive strength up to 10,000 p.s.i. but has only a low tensile strength of about one-tenth of the compressive strength, and thus needs to be reinforced with steel to form a structural member. Concrete also changes with age, its strength gradually increases and it dries out. As it dries it shrinks, and hence it is continually subject to slight changes in length with time. It also expands and contracts with changes in temperature. To avoid excessive cracking which might result from drying, shrinkage or temperature movement, steel-mesh must be provided in association with expansion joints. Concrete is slightly permeable to moisture and damp and cannot be used in situations where complete impermeability is required.

The main disadvantage of concrete is that the use of poor materials and inferior workmanship, together with inattention to detail in manufacture, result in a construction material of little value or use.

Good concrete is made from cement, aggregates and water; poor concrete is made from exactly the same materials.

Properties of plastic or wet concrete

Plastic concrete is a freshly mixed material which can be cast into various shapes. On being allowed to stand it will set and take the shape of the mould and remain rigid.

The relative amounts of cement, aggregates and water mixed together control the properties in the wet state as well as in the hardened state; for example, the more water and cement that is added, the wetter and more fluid will be the concrete.

The important properties in the plastic state are workability, harshness or cohesiveness of the mix, resistance to segregation, and bleeding.

Workability

Workability is a characteristic that is familiar to engineers but is difficult to define.

By workability is usually meant the ease with which concrete can be handled from the mixer to its final fully-compacted position. This includes the facility with which it can be charged into and discharged from the conveying equipment, the ease with which it can be placed in the formwork, and the amount of vibration necessary for full compaction. None of these properties can be measured by any practical method and in fact workability never is measured, although the compacting factor and Vee Bee apparatus are used to measure certain empirical properties which are usually termed workability. The compacting factor apparatus gives a measure of the internal work required to compact the concrete. The Vee Bee test was also devised to measure workability but again only in the restricted sense of the internal work of compaction. The equipment used to measure the compacting factor and Vee Bee degrees are shown in Plate 1.

Knowledge of the workability is most necessary in the production of a " well-designed " concrete mix. It is the use of this knowledge that forms the art of mix design, because there are too many variables which affect workability for it to be

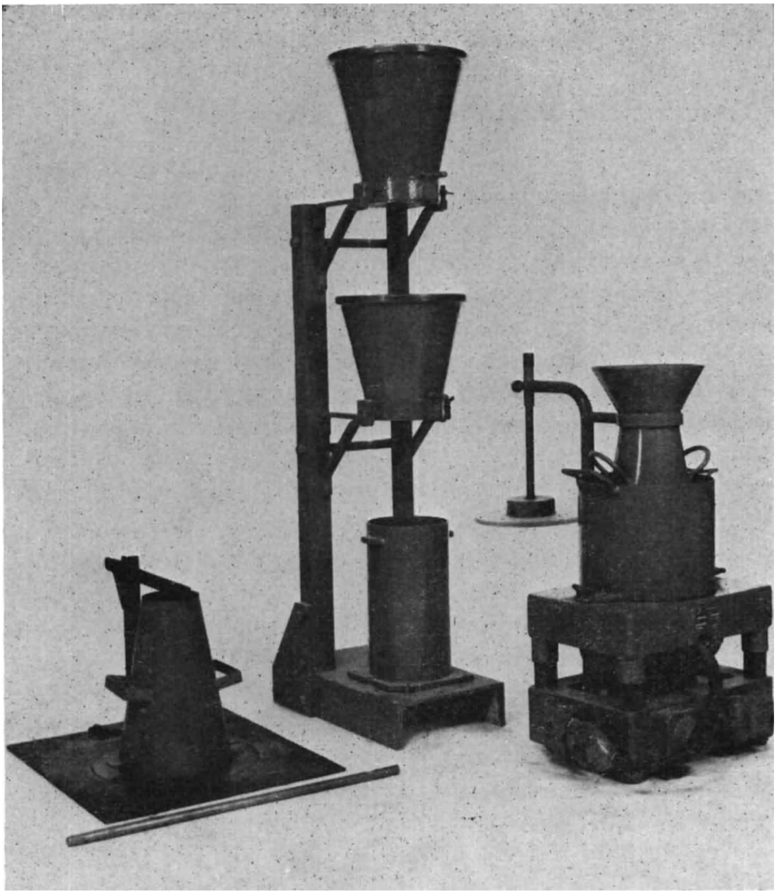


Plate I. Slump cone, compacting factor and vee bee apparatus.

possible to link them mathematically. The following factors affect the workability of concrete:

the overall grading of the aggregate and the shape angularity and surface texture of the coarse and fine aggregates;

the quantity of water per cubic yard of concrete;

the ratio of coarse to fine aggregate and their bulk densities;

the maximum size of the aggregate;
the capacity of the aggregates to absorb water.

A change in one property of an aggregate affects the other properties, so that a change of grading will affect the bulk density, the ratio of coarse to fine aggregate and the water absorption.

To appreciate how a concrete can be obtained with the necessary workability combined with other required properties, the effects of these various factors must be considered.

Different types of aggregate produce different degrees of workability. The most workable concrete is produced by using smooth rounded aggregate, particularly water-worn gravels, such as those of say the Trent Valley. The workability is reduced when flaky or elongated particles or crushed rock aggregates are used.

The particle shape affects the density of packing. This may be shown by carrying out a bulk density test on aggregates which differ only by their being rounded or angular. There is a direct relation between angularity and workability: an increase in angularity reduces workability. Increased flakiness and elongation also reduces workability, but the effect of angularity is greater than that of either of these. The measurement of angularity of single-sized aggregates, and the use of this figure in the design of mixes is described in Chapter 3.

The absorptive capacity of an aggregate also has an effect on workability, in that a non-saturated aggregate with high absorption will tend to reduce the available water in a mix, but this factor is only of secondary importance in most site work.

The surface texture of the aggregate is also known to have an effect on both the workability and the strength of the concrete, but the difficulties of measuring it and applying the results are such that this factor cannot be taken into account.

The effect of the grading is not constant but depends upon the cement and water content. The grading is of little importance in rich mixes but becomes more important when lean mixes of high workability are required. It is of less importance with rounded aggregates and is more important for crushed rock aggregates. Examples of the variation of workability with grading are given in Figs. 3.3 to 3.11.

For any one value of the water/cement ratio there is one proportion of sand to coarse aggregate that produces the greatest workability, but this can often be determined only by experiment. For continuous gradings, the proportion of sand may be 30 to 35 per cent; for gap-graded concretes, the proportion may be 28 to 30 per cent.

Segregation

This is the mechanical re-sorting of the concrete into its constituent parts. The large aggregate is separated from the cement mortar and becomes devoid of fine material. Segregation is caused by bad handling and placing which breaks up the cohesion of the mass of concrete. Chutes, conveyor belts and other methods of discharging concrete into a coned heap cause segregation. The coarse stone rolls down the heap and segregates at the bottom.

Segregation can also be produced by over-vibration; this causes the large aggregate to sink to the bottom and displace the fine mortar upwards, but such segregation usually only takes place with very wet mixes, really unsuitable for vibration.

Bleeding

Bleeding is the separation from the wet concrete of water or water and cement, and may be associated with wet segregation. The solid particles of coarse and fine aggregate settle, with a consequent rise of the water or a water/cement mixture. This produces a weak surface which in the case of a road slab will disintegrate. Bleeding is usually due to too much water and a lack of fine material, and can be remedied by proportioning the mix to include more sand and if necessary more cement. Bleeding may also take place by the escape of cement slurry from between the joints of the formwork. This results in unsightly honeycombing and can be remedied only by better construction of the formwork.

Properties of hardened concrete

The properties of concrete in the plastic state are important only in the construction stage, whereas the properties of concrete in the hardened state are important for the remainder of its life. In practice, however, it is impossible to consider both sets of properties separately, as they affect each other. They are so intertwined that they always have to be considered together, and in attempting to attain one property a compromise has to be made in the other properties. For example, high-strength concrete with low shrinkage can be achieved only by the use of a low ratio of water to cement and a high proportion of large aggregate. Such a mix will probably be harsh and unworkable in the plastic state. If it is to be placed in thin sections it needs to be workable and somewhat cohesive, and a large aggregate cannot be used. The workability will have to be increased, the mix made richer in cement, and the total water content increased, all of which will tend to increase the shrinkage.

The main properties of hardened concrete are strength, permeability, shrinkage, elasticity and creep. They all change with time and depend upon, or are affected by, the moisture content of the concrete.

In building construction, strength, elasticity and creep are important; in water-retaining structures, reduced shrinkage and high impermeability are as important as strength; in a road slab, strength and resistance to deterioration are equally important. Thus it is impossible to say that one property is more important than another. However, as the strength of concrete increases, the other properties of concrete improve, so strength is often considered as the most important property of concrete, and to some extent there is justification for this view.

Strength of concrete

The strength of concrete is its resistance to rupture, and may be measured in a number of ways. Thus we have the strength in compression, in tension, in shear and in flexure. All these define strength by reference to a method of testing; some methods determine basic properties of the material whilst others do not. Concrete is a brittle material with a compressive strength about ten times its tensile strength. When it fails under a compressive load the failure is essentially a mixture of crushing and shear failure. The mechanics of failure are not yet fully understood, but an approximation to the failure load can be made by assuming that the concrete, in resisting failure, generates both cohesion and internal friction. It can be shown that with such an assumption the basic shear strength is given by the Coulomb equation

$$s = c + \sigma \tan \phi$$

where

s = shear strength
c = cohesion
σ = inter-granular stress
ϕ = angle of internal friction

The shear strength may be determined by subjecting concrete to three-dimensional loading in a triaxial compression test; the concrete is loaded in compression in two directions at right-angles, whilst being loaded to failure in the third direction. The results of such a test show that the resistance to failure increases as the lateral loading increases by about three or four times the lateral loading, so that concrete which might fail at 3000 p.s.i. without lateral loading would fail at a stress of 6000–7000 p.s.i. with a lateral loading of 1000 p.s.i. See Fig. 1.1. In other words a concrete cylinder immersed in a liquid at a pressure of 1000 p.s.i. would fail at a compressive stress of 6000–7000 p.s.i. whereas, if tested in air, it would fail at 3000 p.s.i. It follows from this that where concrete is laterally restrained it will fail at a higher stress than when unrestrained.

The triaxial test measures a basic property of the material; it is difficult to carry out, however, and it is easier to measure the strength of concrete by a tensile, flexural or compression test, the most usual of which is the compression test.

Tensile Strength. In the simplified methods of design described in the Code of Practice CP 114 it is assumed that concrete does not resist tension. Since cracks are caused by shrinkage, concrete cannot be relied upon to resist tension during flexure, but at the same time concrete does possess a tensile strength. Its tensile strength is approximately 10 per cent of the compressive strength, but may vary from about 8 per cent to 20 per cent depending upon its age, the type and quality of the cement, and the aggregates.

Tension tests used to be carried out on briquettes, but the

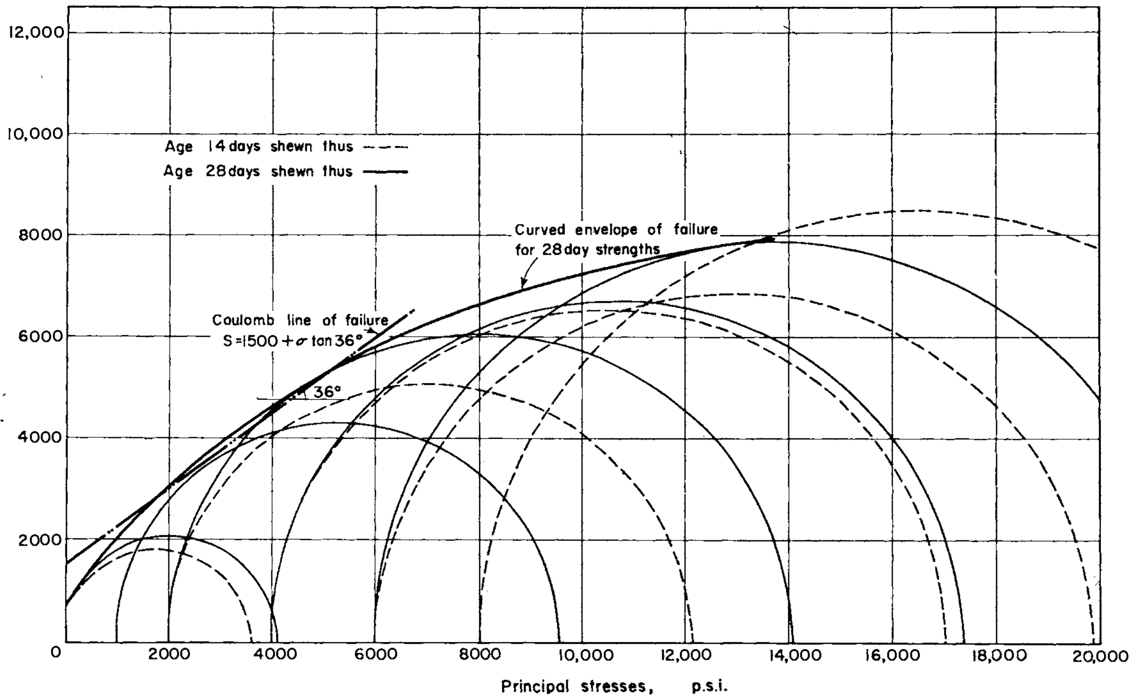


Fig. 1.1. Mohr diagram of concrete strength in triaxial test.
High pressure triaxial tests on concrete. Mix 1:2·1 : 3·9 by wt. ¾″
Gravel aggregate. O.P. cement. w/c ratio. 0·5. 6″ × 3″ diam. cylinders.

results depended too much upon the operator's own personal ability to be of much value. Other forms of test have been carried out, but the simplest is the tensile test on a concrete cylinder. This is performed by splitting the cylinder longitudinally by loading it in compression along its length. This produces a tensile failure vertically across the diameter of the cylinder.

Flexural Strength. The strength of concrete for pavements and roads is often specified as a flexural strength. The flexural strength is known as the modulus of rupture, and is determined from tests on beams:

$$\text{modulus of rupture} = \frac{PL}{bd^2}$$

where

P = load to cause failure
L = span between supports
b = width of beam
d = depth of beam

The beams, 28 in. long and 6 × 6 in. cross-section, or 16 in. long and 4 × 4 in. cross-section, are tested in bending under third-point loading and the stress determined.

Concrete of pavement quality may have a compressive strength of 4000 p.s.i. in which case the modulus of rupture will be about 600 p.s.i. see Fig. 1.2.

Compression Strength. The compression strength is the maximum load per unit area sustained by a concrete specimen before failure in compression. In this country the usual test is the crushing of a 6 in. cube in a compression machine, loaded at the rate of 2000 p.s.i. per minute.

The test is simple to carry out and the results, although difficult to interpret in terms of actual strength, are associated with a large amount of building and engineering experience.

Many of the important properties of concrete improve with increase in strength; density is more or less increased, porosity and permeability are reduced, and resistance to deterioration increased, so that strength may be used as a criterion of quality. It is this fact combined with the use of the compression strength in structural design that has placed the compression strength

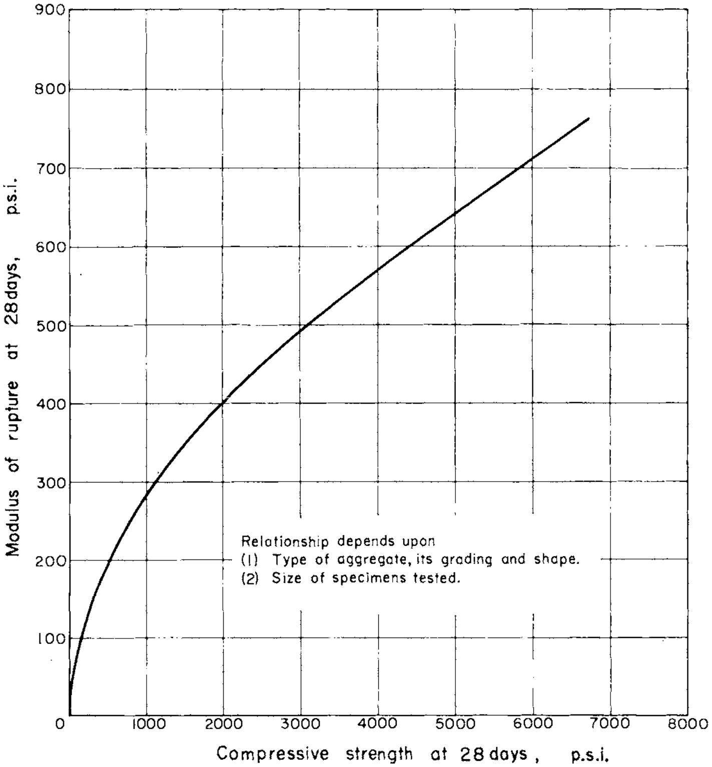


Fig. 1.2. Approximate relationship of modulus rupture and compressive strength.

in the unique position of being used as a criterion of concrete quality, whereas in fact, the quality of concrete is a measure of its uniformity of strength and workability (see Chapter 5 on quality control).

Most structural concrete is proportioned to have a strength of 3000–4500 p.s.i. at 28 days. With a factor of safety of 3, this gives permissible design stresses of 1000 to 1500 p.s.i. Prestressed concrete is usually required to have a strength of 7000–8000 p.s.i. at 28 days. In pre-tensioned prestressed concrete there is a further requirement, namely the strength at the time of release of the wires, which is usually 5000–6000 p.s.i. at 3 days after casting.

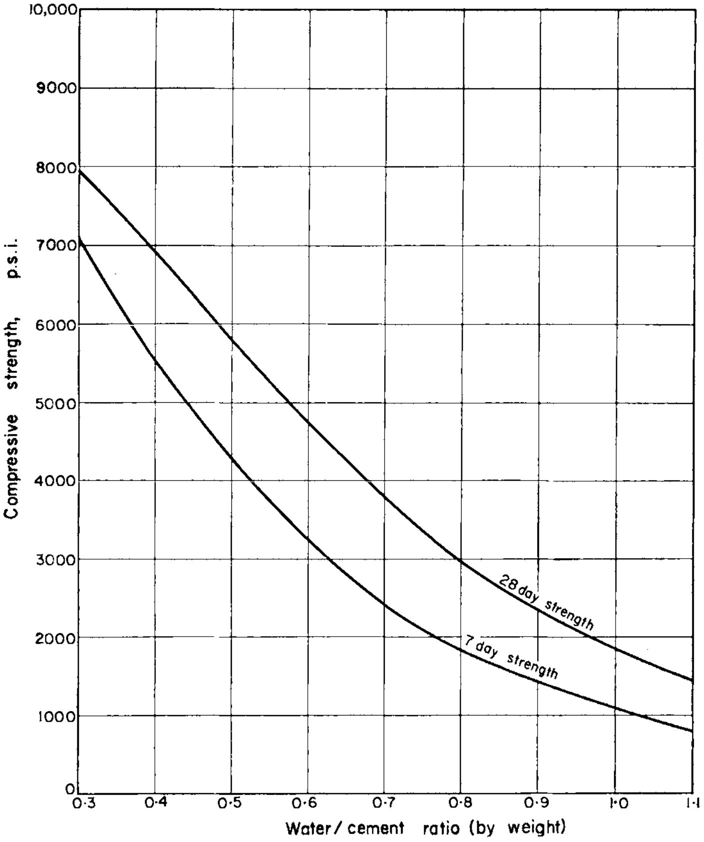


Fig. 1.3. Relationship of compressive strength and water/cement ratio for ordinary Portland cement.

The compression strength of mass concrete may be only 1000–2000 p.s.i. and of dry-lean concrete 500–1000 p.s.i.

The strength of concrete increases with time and temperature. A given strength may be achieved by keeping the concrete for a long time at a low temperature or a shorter time at a higher temperature. For normal temperatures of curing up to say 60°C, there is a relationship between the strength of concrete and the product of time × temperature. This product is termed the maturity. At temperatures other than normal ambient temperatures the behaviour is different. Saul has shown that at low temperatures once concrete has reached a certain initial strength at a temperature above freezing, then it continues to gain strength even down to −10°C. Plowman has related the strength of concrete at a given maturity to the strength of concrete at 28 days when cured at 64°F (standard conditions of curing B.S. 1881) and has taken 11°F as the temperature below which concrete does not continue to increase in strength once it has hardened. The relationship devised by Plowman is useful for calculating the strength of Portland cement concrete at various ages once the strength at a given maturity is known. The equation and graph for carrying out such a calculation is given in Fig. 1.4.

At high temperatures, there is not the same direct relationship, but there is still a relationship between the strength resulting from any one maturity and that of concrete at 28 days cured at 64°F. This has led the Author to develop a method of testing concrete at early ages after boiling to predict the strength at 28 days.

The effect of steam curing of concrete is discussed in Chapter 4.

The direct relationship of strength to maturity varies with the composition of the concrete and the type and quality of the cement. Typical variations of strength with time for different cements are given in Fig. 2.2.

Influence of Various Factors on Strength. Water: The influence of various factors on the strength of concrete has to be taken into account in the successful proportioning of the components of a mix to achieve the desired properties. The first factor is the influence of water. The strength is largely determined by the ratio of water to cement; the higher the water/cement ratio, the lower the strength. As the amount of water increases above that necessary for complete hydration of the cement (water/cement ratio of about 0·22 to 0·25) it merely produces a more porous structure and results in a decrease in strength. Concrete with a water/cement ratio of 0·25 cannot be made, because it cannot be fully compacted. The relation between strength and water/cement ratio first determined by Abrams is in fact more complicated than that shown in Fig. 1.3. There is not just a single relation but a number of relations. For example, as the

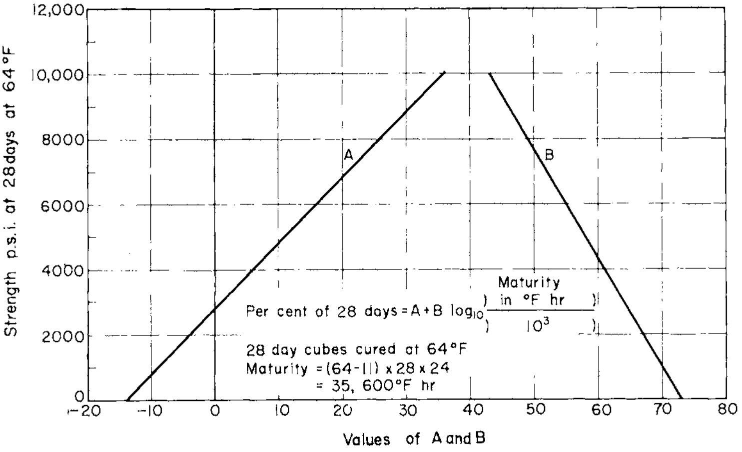


Fig. 1.4. Plowman's relationship of maturity and strength.

mix becomes wet and very workable, the strength falls off from that which would be predicted from Fig. 1.3. Similarly, as the mix becomes too dry it becomes impossible to compact fully, and again the strength is less than would be expected. If, however, the mix proportions are changed so that the concrete is neither too wet nor too dry, then within these limits the water/cement ratio curve holds good. It can be shown that the amount of air in the concrete affects the strength, and that strength is proportional to the ratio of cement to water plus air, see Fig. 2.14.

In fresh concrete, the aggregates contain water; if the aggregates are dry when placed in the mixer, they absorb water and leave less available for mixing with the cement; if the aggregates are saturated and contain water in the interstices, this will make the mix wetter. Between these two conditions there exists one in which the aggregates neither detract from nor add to the water added for mixing with the cement. This is when the aggregates are saturated inside but dry on the surface, i.e. saturated, surface dry, a condition simple to specify but difficult to measure accurately. As far as strength is concerned, the *effective* water/cement ratio is the ratio of the amount of water, added to a mix when the aggregates are saturated surface dry, to the amount of cement.

The effect of absorption of water by the aggregates is important when different aggregates are used and when the aggregate/cement ratio is changed, and in the laboratory when trial mixes are being made. Most of the difficulties concerning the effective water/cement ratio in a trial mix can be resolved by carrying out trial mixing using the proposed aggregates in a condition closely approximating to their condition on the site.

The strength is affected not only by the water/cement ratio, but also by the total quantity of water used per unit volume, so that if the water/cement ratio is maintained constant but the mix proportions varied so that less water is required per cubic yard of mix, then that mix will be stronger. The increase may be of the order of 250 to 500 p.s.i. in favourable cases.

Aggregates: The size and shape of the aggregates, and the aggregate/cement ratio all affect strength. A mix containing large aggregate up to 1½ in. size will have a higher strength than a mix containing smaller aggregate, and a concrete containing crushed rock will have a higher strength than a similar concrete made with a rounded aggregate. These facts can be explained by visualizing the failure of concrete as being due to a shearing action through the mortar. It follows that shearing through the aggregate will take place if this forms the weakest path, but the shear path will be round the aggregate if the aggregate surface is smooth and the resistance generated round the aggregate is less than that through it. The shear force and hence the strength will also be larger if the aggregate forms a larger proportion of the whole, or if larger aggregate is used. The larger the ratio of aggregate to cement, the higher is the strength for the same water/cement ratio and workability.

Mixing, Placing, Compacting and Curing: The strength of concrete is also affected by the efficiency of mixing, placing, compacting and curing. Poor mixing results in a bad distribution of the coarse and fine aggregates through the mix, so that some parts are lean and some parts rich in cement mortar. The lean parts are not fully compacted, whilst the rich parts may be over-compacted, resulting in some wet segregation. Poor placing also results in an unequal distribution of the various parts of the mix. For example, if concrete is dropped through a mesh of reinforcing bars, the bars will act as a filter and the coarse aggregate will be separated from the fine. Similarly, if concrete is dropped freely from more than 8 ft, or is allowed to form cones at the bottom of the formwork, lean patches devoid of mortar will be formed, which no amount of compaction will turn into concrete.

Proper compaction is essential for the development of the full strength. Well-compacted concrete may contain ½ to 1 per cent of air voids; normally compacted concrete probably contains 1½ to 2 per cent; the air content reduces the strength (see Fig. 1.5), every 1 per cent of air voids reducing the strength by about 5 per cent. Unvibrated concrete may contain 5 per cent of air voids, and in such an uncompacted state may have a strength only two-thirds of that possible. Concrete which is too wet to be vibrated, because vibration would cause wet segregation, will still contain some air voids trapped round the aggregate particles so that besides having a low strength due to a high water/cement ratio, it has an even lower strength because of incomplete compaction.

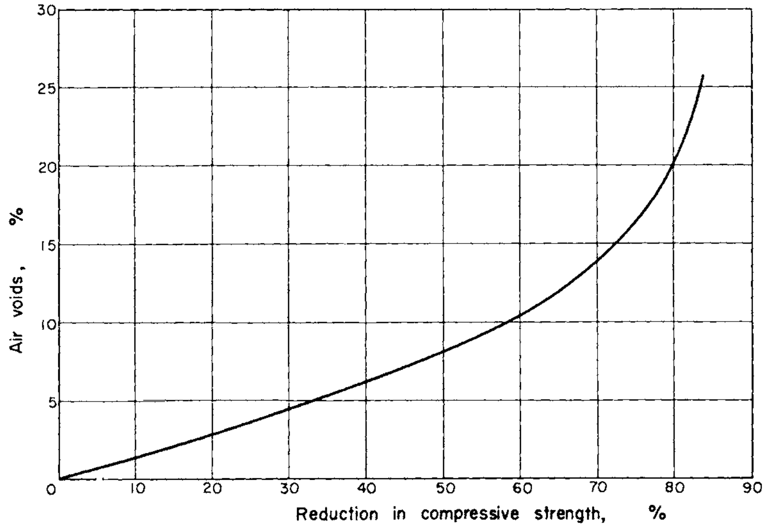


Fig. 1.5. Effect of air voids on compressive strength.

Dry mixes of low workability, if adequately compacted by vibration, have higher strengths than more workable mixes with the same water/cement ratio. This may be due to the fact that the normal relation between strength and water/cement ratio is based on a concrete which has 1½ to 2 per cent air voids present. With a drier mix, it is possible by prolonged vibration to reduce the air voids to below 1 per cent with a consequent increase in the strength.

Improper curing will also result in a lower strength, and it is therefore essential that curing be carried out properly. Proper curing depends upon the presence of sufficient moisture and heat to ensure that the cement is adequately hydrated. It follows, therefore, that the curing time in winter will be longer than in summer, and a minimum of 7 days in winter and 3 in summer is often necessary.

The Compression Strength Test. It has already been mentioned that the 6 in. cube is used to determine the compression strength of concrete. This size of cube is used on site work where the large aggregate does not exceed 1½ in. For concrete containing 2 or 3 in. aggregate, 8 and 10 in. cubes are sometimes used, but where the cube size is less than 4 times the size of the large aggregate it is usual to remove the large aggregate before making cube specimens.

For laboratory work, when the aggregate does not exceed ¾ in., 4 in. cubes are sometimes used; the cube strength increases with a reduction in the cube size, however, so that 4 in. cubes give a compression strength some 5 to 10 per cent greater than 6 in. cubes. This strength is proportionally reduced for cubes larger than 6 in. (see Fig. 1.6). On the Continent the usual size of cube is about 8 in.

The compression strength may also be determined from concrete cylinders. The usual size is 6 in. diameter by 12in. long. The cylinders are loaded in the compression machine in much the same manner as for cube crushing, but whereas cubes are crushed between faces cast in the mould, cylinders must be capped at the ends, and this is usually done with high alumina cement. Cylinders of concrete may be cut from either plain or reinforced concrete using a diamond drill, and the compression strength determined after the ends have been capped. The length of the cylinder affects the results, and wherever possible the length should be between 2 and 3 times

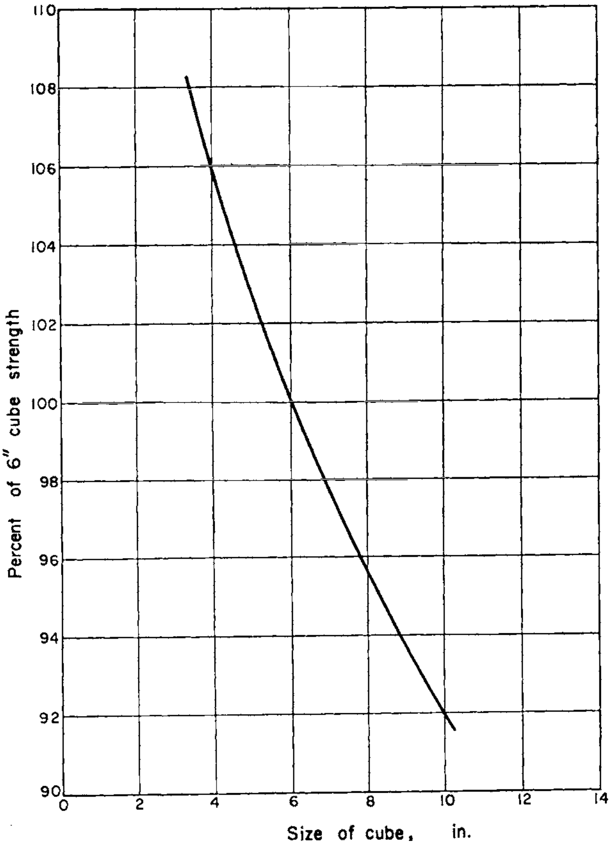
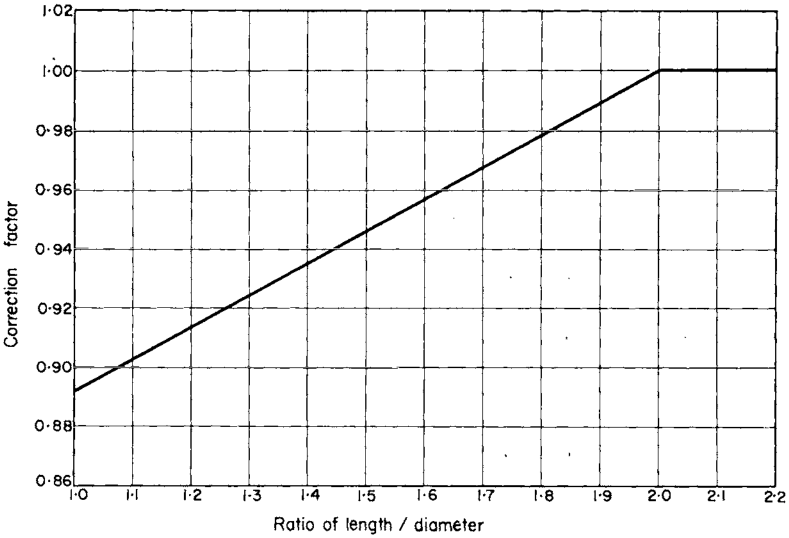


Fig. 1.6. Strength of cubes of various sizes as per cent of 6 in. cubes.

the diameter. If the length of the cylinder is less than this, the measured strength increases as the length is reduced; this can be corrected by using Fig. 1.7. Since the compression strength of 6 in. cubes at 28 days is the usual criterion of strength, then a further correction must be made if tests are carried out at other ages. In addition, the strength as measured from a cylinder is less than that from a cube, and it is necessary to correct for this (see Fig. 1.8).

Although at first sight the compression test appears to be a simple one, it is in fact, difficult to assess the state of stress which



(Applies to L/D between 1·0 and 2·0 only)

Fig. 1.7. Correction factor for compressive strength of cylinders with various ratios of length to diameter.

leads to failure. The stress distribution in a cylinder with the height equal to twice the diameter is less complex, in that the middle half of the specimen is subject only to compressive loading; in the cube test, however, the load at failure is affected by factors such as the friction between the concrete and the platens of the testing machine, and the size of both the aggregate and the cube. The characteristics of the testing machine also affect the results, a hydraulic-ram type of machine giving up to 10 per cent higher cube strength than a machine in which the load is applied through a proving ring. Friction in the ball and socket joint of the loading platens may also affect the load by 5 per cent.

The rate of loading has some effect, and the usual rate of loading is 2000 p.s.i. per minute. At 60 p.s.i. per minute the strength is reduced by 12 per cent, and at 60,000 p.s.i. per minute the strength is increased by the same amount. Since the other factors already mentioned have a greater effect on the strength, however, slight variations in the rate of loading are not important.

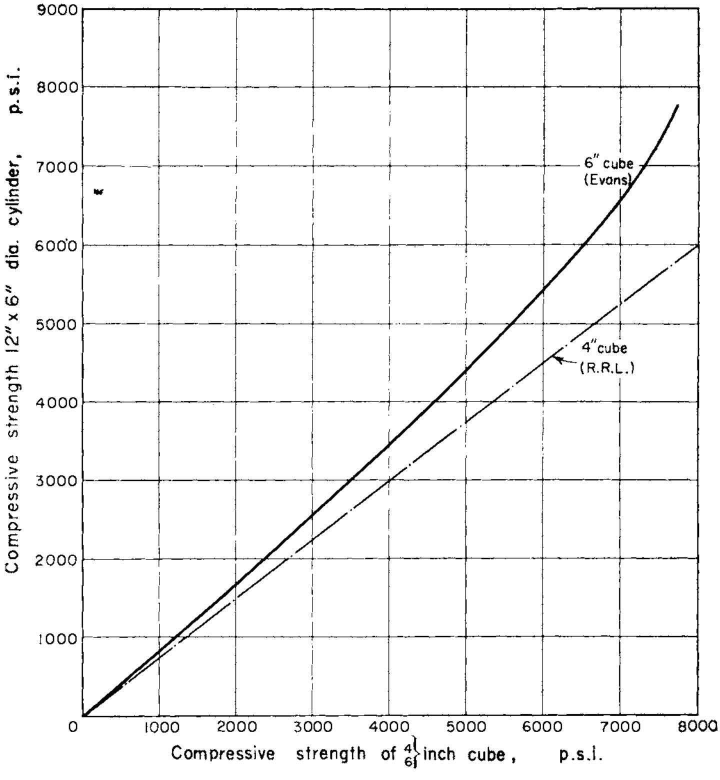


Fig. 1.8. Relationship of compressive strength of cube and cylinder.

The minimum variation in the strengths of identical cubes made under excellent laboratory conditions is about 300 p.s.i. for concrete with a nominal strength of 3000 p.s.i.

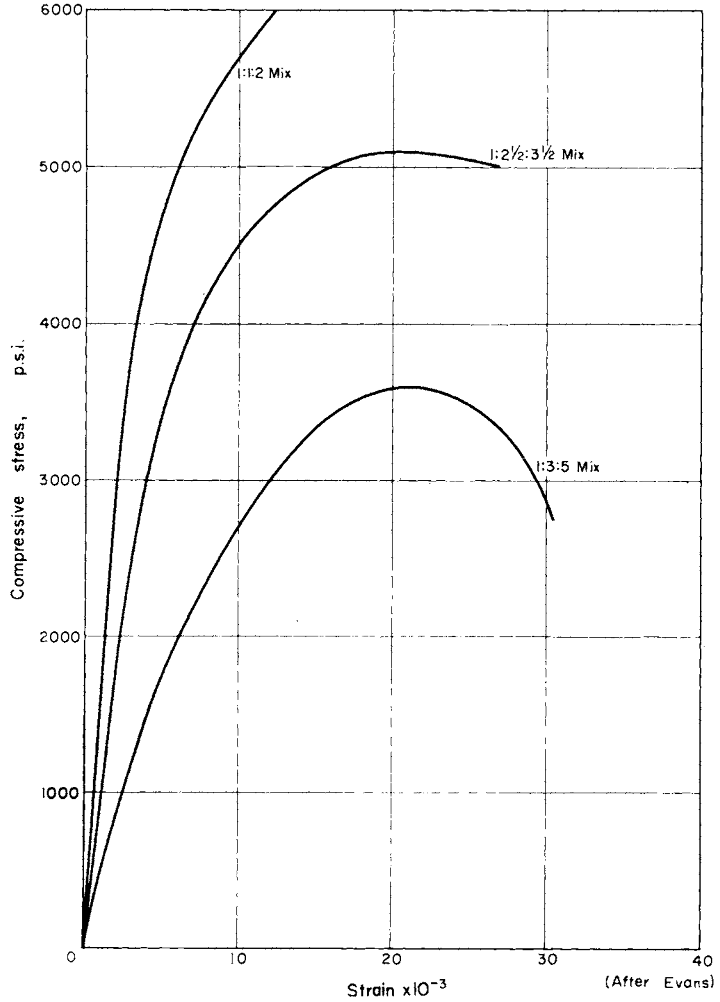
Elastic Properties of Concrete

No material is completely rigid, and like other materials concrete distorts under the influence of applied forces. If, when the applied force is removed, the material completely recovers its original shape, then it is said to be perfectly elastic. Concrete is only partially elastic, since it suffers from creep during loading. Elasticity is measured by the modulus of elasticity (Young's Modulus) which is a measure of the resistance to deformation.

Modulus of Elasticity. The modulus of elasticity is defined as the ratio of the change of stress to the change of elastic strain:

$$E = \frac{\text{unit stress}}{\text{unit strain}} = \frac{P/A}{e/L}$$

The stress-strain diagram may be plotted from a tension or



(After Evans)

Fig. 1.9. Stress/strain curves for different mixes.

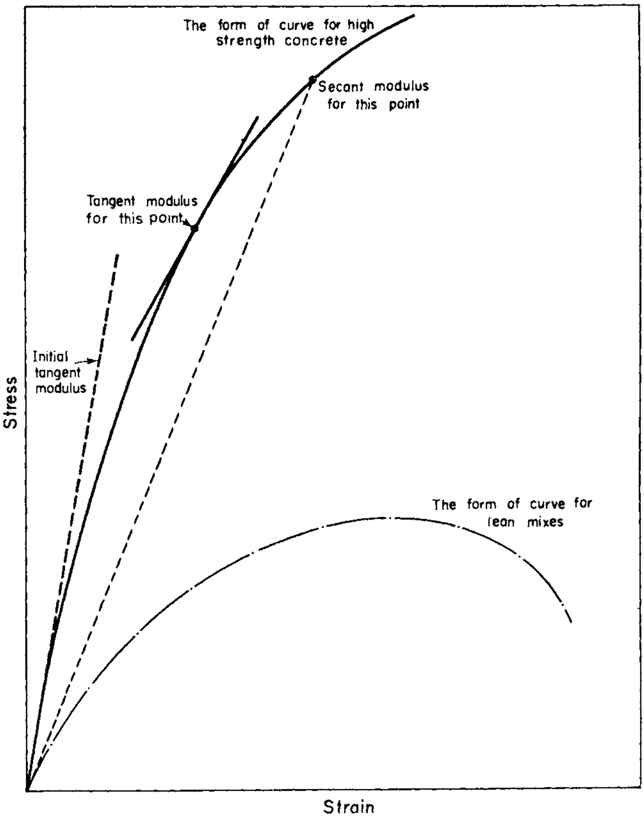


Fig. 1.10. The different modulus of elasticity.

a compression test. It is a curved line, indicating that concrete is imperfectly elastic; the strain increases with the length of time for which the load acts, and repeated loading and unloading also increases the strain for a given stress. In addition the stress-strain curve varies with the compressive strength (see Fig. 1.9).

It is nevertheless convenient in structural analysis to treat concrete as though it were in fact an elastic material, the modulus of elasticity then varies according to how it is calculated. It can be calculated in three ways: (see Fig. 1.10) it may be considered as the slope of a tangent drawn to the stress-strain curve through the origin, in which case it is known as the initial tangent modulus; secondly it can be determined as the slope of a tangent at any point on the stress-strain curve, and expressed as a tangent modulus; or it can be calculated as the secant modulus, which is the slope of a line drawn from the origin to any point on the stress-strain curve.

The initial tangent modulus is of value only for low stresses, and the tangent modulus must be determined graphically from the stress-strain curve; the secant modulus is therefore more generally used, because it can be calculated from the actual deformation at any one time. The modulus is usually determined from compression tests on concrete specimens, because the tensile test carried out on briquettes is inaccurate.

Concrete has a tendency to creep even under very small loads, and the slower the rate of loading the greater is the curvature of the stress-strain diagram and the lower the modulus. Most loads on concrete are of long duration so that in measuring the modulus it is reasonable to apply the load slowly and to permit the creep to be included in the observed strain. Creep appears to be related to shrinkage, however, and it is often difficult to ensure that the strain measurements include only elastic strain and creep, and not shrinkage. Since shrinkage depends upon the rate of drying and the size of the specimen, an exact determination of the total strain under such circumstances is impossible and the result can only be an approximation. On the other hand, in prestressed concrete work it is essential to measure the total movement including that due to shrinkage.

The determination of Young's Modulus by static loading is subject to errors due to the impossibility of attaining uniform loading during the test; strains on one side of a cylindrical specimen may be twice those on the other side. These difficulties can be overcome by measuring the modulus of elasticity by dynamic methods, i.e. by the application of a sonic impulse wave. Such waves produce almost negligible strain in the specimen and the value of the modulus determined by this method corresponds to the tangent modulus at zero stress; in consequence it is greater than the secant modulus.

The elastic modulus may also be measured by determining the deflexion of a plain concrete beam in bending. The measured value of the modulus is then the same as that determined from a static compression test.

For loads up to 50 per cent of the ultimate, the modulus determined from a tension test is about 10 per cent greater than that determined from a compression test. The modulus of elasticity in shear varies from 0·4 to 0·6 of the modulus in compression.

Poisson's Ratio. When compressed longitudinally, materials contract longitudinally and expand laterally, and vice versa; the ratio of lateral strain to longitudinal strain is known as Poisson's ratio.

For isotropic elastic materials the theoretical value of Poisson's ratio should be 0·25. For concrete, values ranging from 0·10 to 0·30 have been measured, but there is no consistent variation with the strength, richness or aggregate grading. Some tests show that Poisson's ratio is larger for low stresses than for high ones, and a commonly assumed figure is about 0·15 for a concrete with a compressive strength of 3000 p.s.i., but see Fig. 1.11.

Shrinkage of Concrete

Concrete changes in volume with change in its water content; since most concrete tends to dry out after casting, this change usually results in shrinkage, but under certain conditions an increase in volume occurs.

Shrinkage may take place whilst the concrete is still plastic due to conditions of rapid drying before setting, but more usually the shrinkage takes place due to slow changes in water content during the life of the concrete after it has set.

Plastic Shrinkage. Plastic shrinkage is the shrinkage which occurs before the concrete is set or has attained any significant strength. The principal cause of such shrinkage is the rapid evaporation of water from the concrete surface, and in consequence it is most likely to occur in slab and pavement construction when subject to hot sun or drying winds.

Water absorption from the concrete by a dry sub-soil or sub-base may also cause plastic shrinkage as, for example, in

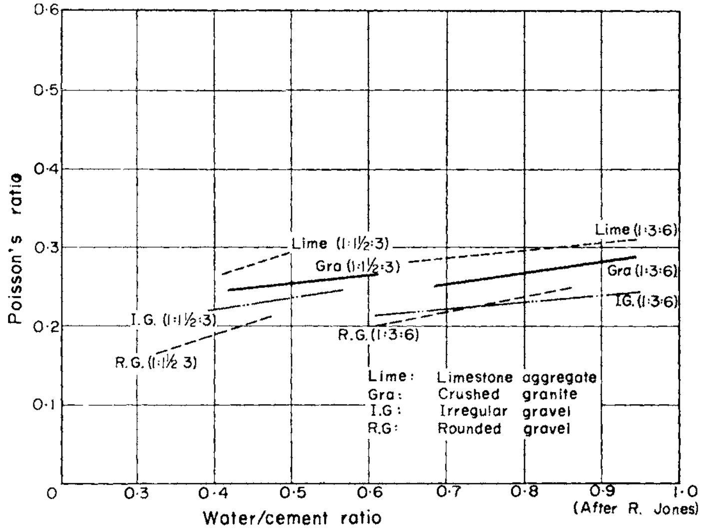


Fig. 1.11. Variation in Poisson's ratio due to water/cement ratio, type of aggregates and aggregate/cement ratio.

concrete floors constructed on top of dry hardcore. Here, however, the ill effects of such shrinkage, namely the formation of wide deep cracks, is usually overcome by subsequent trowelling of the concrete.

Plastic shrinkage usually results in straight, wedge-shaped cracks or cracks with a crow's foot pattern. They may extend through the depth of the concrete and usually develop immediately on the disappearance of the wet sheen on the concrete surface.

The corrective measures necessary to prevent plastic shrinkage are all concerned with the prevention of evaporation from the concrete surface. They include the application of a membrane curing compound to the concrete surface immediately after finishing, covering it with wet hessian, kraft paper or polythene sheeting, or spraying with water. In certain climates sun-shades or wind-breaks may be necessary.

Plastic shrinkage cracks can be removed from the concrete by re-vibrating or re-trowelling the surface 3 to 4 hours after casting.

Shrinkage of Set Concrete. If fresh concrete is allowed to set and then dry it will shrink, due to the changes which take place in the cement paste during hydration and drying. Concrete cured under water does not shrink — on the contrary, it expands slightly. Again, if concrete is dried out it shrinks, but expands again upon subsequent wetting so as to regain part of its original colume (see Fig. 1.12). These volume changes are in addition to the initial volume change during compaction or the final volume changes due to seasonal or other variations in temperature.

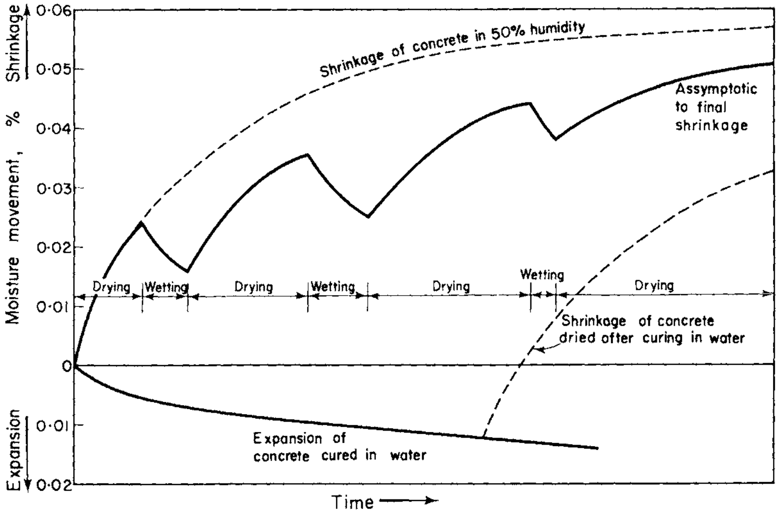


Fig. 1.12. Diagram of effect of wetting and drying on shrinkage.

The shrinkage of concrete, or rather its volume change due to the effect of moisture, is caused by the chemical combination of the cement with water and the changes in moisture content of the concrete mass. The hydration of the cement produces a gel which binds the particles of aggregates together. As hydration occurs part of the water is absorbed by the gel and this causes some contraction of the total volume of cement plus water.

Where the concrete can dry out, water flows from the gel through the minute pores and capillary channels, and there is a reduction in the volume of the cement gel and a total decrease (or shrinkage) in the absolute volume of the solids. Most of this is reversible, so that on subsequent thorough saturation the concrete regains much of the shrinkage.

Since shrinkage is a three-dimensional movement due to the contraction of the cement gel, then aggregate, reinforcement and adjacent surfaces to which concrete is completely or partially bonded all act as restraints; thus concrete containing large aggregate shrinks less than that containing small aggregate, lean mixes shrink less than rich mixes, and reinforced concrete shrinks less than plain concrete.

Intrinsic Shrinkage. The volume change which occurs in concrete sealed inside a large dam — where it can neither absorb nor give off water — is known as intrinsic or autogenous shrinkage. The concrete inside the dam has a certain water content, part of which is absorbed during hydration of the cement particles. The rate of hydration and growth of the gel decreases with time but as hydration takes place water is absorbed from the mass. This causes a reduction in the volume of the concrete which is not offset by the increase in volume of the cement gel. The result is shrinkage, due to the formation of hydration products having a smaller volume than the original cement and water mixture. In general this shrinkage is only about 0·01 per cent, i.e. about one-fifth of the amount which occurs due to the drying of the concrete, and it is usually of much less importance.

If, instead of the moisture content of the concrete remaining constant, water is absorbed to replace that used during hydration, then there will be no shrinkage due to absorption of the water from the cement gel during the cement hydration, for the water used in hydration will be replaced from outside the concrete. The cement gel then increases in volume as more water is drawn into the concrete, and the net result is a volume increase. The conditions for this to take place are that the concrete must be continuously cured in water, and its mass must not be so large that the water is unable to permeate the concrete fast enough to replace the water used in cement hydration.

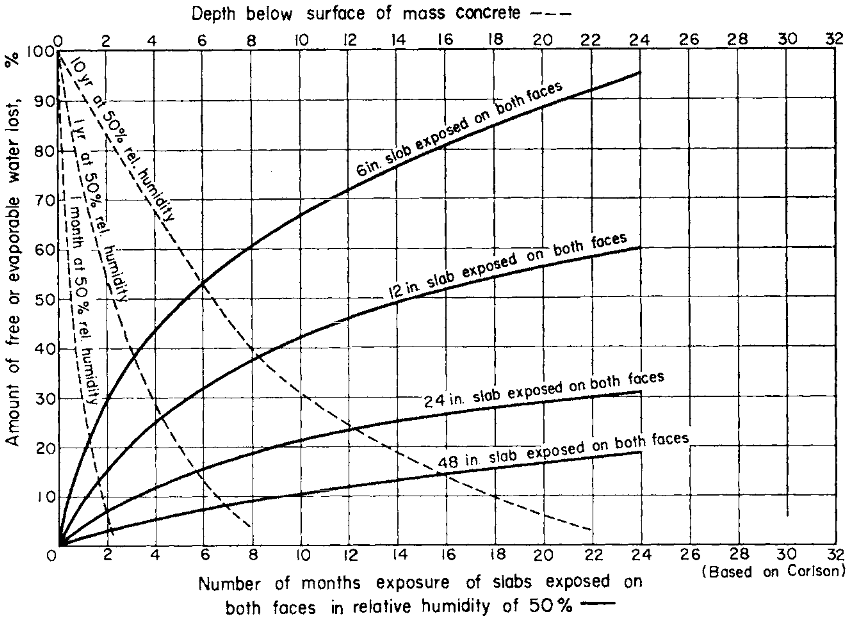
Drying Shrinkage. When concrete is hardened and cured under water and then allowed to dry, shrinkage occurs. First the water saturating the voids in the concrete dries out. This continues until the total moisture content is reduced by about half. Further drying results in water being drawn out of the mass of small capillaries which permeate the cement gel.

This process continues on an ever-decreasing scale for a long time. The effect of drawing water out of the gel is to cause it to shrink, the amount of shrinkage depending upon the reduction in water content. If the concrete is completely dried the shrinkage is greatest and is equivalent to a movement due to a drop in temperature of 100°F. Subsequent cycles of wetting and drying result in expansion and contraction of the concrete. After being dried the concrete never recovers its original volume, however, even if again completely saturated, because part of the original shrinkage is irreversible.

It is seldom that concrete is thoroughly dried; more often it suffers partial drying and partial wetting, in which case it goes through a cyclic volume change, the trend of which is towards that caused by complete drying (see Fig. 1.12).

Drying of Concrete. The rate at which concrete dries depends upon its permeability, so that all the factors that affect permeability affect the rate of drying; for example, leaner mixes have a higher permeability and dry quicker than rich mixes. Drying depends upon the moisture movement through the concrete, and this like the transfer of heat depends upon the square of the path length through which the moisture has to move, so that thin concrete walls dry out more rapidly than large masses. The rate of drying also depends upon the total moisture content at any stage. The flow of water to the dry surface takes place through the minute pores in the cement gel and in the capillaries that permeate the concrete. As the moisture content decreases, the suction pressure holding back the remaining moisture increases, and the rate of moisture movement towards the dry surface is reduced. It can be calculated, as has been done by Carlson (1937), that if a 6 in. slab takes 4 months to dry by 50 per cent then it will take 16 months for a 12 in. slab to dry out similarly (see Fig. 1.13).

Now concrete dries out in depth only by about 3 in. in 1 month (2 ft in 10 years) when exposed to dry air, so that it



(Based on Carlson)

Fig. 1.13. Rates of drying of concrete.

is doubtful whether the interior of a concrete mass ever dries out in the life of the concrete, for under constant drying conditions the moisture gradient through the concrete, which was steep at the start of the drying process, finally becomes very flat and a moisture equilibrium with the surrounding atmosphere is attained.

Various Factors which affect Shrinkage. The shrinkage of concrete depends on the cement, and different cements can produce widely differing amounts of shrinkage. The amount depends upon the chemical composition and because of this one cement may shrink half as much again as another. It is not possible, however, to predict the shrinkage characteristics from comparisons of the chemical analysis although it is known, for example, that the higher the C_3A (tri-calcium aluminate) content, the greater will be the expansion under water, the higher the C_2S (di-calcium silicate) content the greater the drying shrinkage, whilst C_3S (tri-calcium silicate), which contributes most to early strength, results in a low shrinkage. Where shrinkage is important, a suitable cement with low shrinkage can be selected only from the results of actual tests, by measuring the drying shrinkage of small bars of concrete made with the different cements. (B.S.1881 describes a suitable test). Rapid hardening Portland cement shrinks more than other Portland cements, whilst sulphate-resisting cement shrinks more than ordinary Portland cement.

The finer the cement is ground the greater will be its drying shrinkage whilst at the same time the expansion on prolonged curing under water will also be greater. This does not mean, however, that of two cements the finer ground will shrink more, because of the over-riding effect of chemical composition. The effect of fineness is only a secondary effect, less important than the cement and water contents of the concrete. Fineness has an indirect influence on shrinkage cracking, because the effect of fineness is to increase the rate of hydration of the cement and hence the growth of strength is more rapid. In consequence the subsequent drying shrinkage causes higher stresses, because the concrete is less able to creep and so adjust itself without cracking to the deformations due to shrinkage.

Aggregate: The aggregate has a two-fold effect on shrinkage: on the one hand it forms a kind of semi-rigid skeleton which shrinks less than the surrounding cement paste, whilst it also disperses the paste and so reduces the shrinkage per unit volume. Rich concretes shrink more than lean concrete. To achieve minimum shrinkage, therefore, concrete should contain the maximum possible amount of large aggregate consistent with other desirable properties such as workability.

The type of aggregate is important because its moisture movement will affect the total shrinkage; aggregates such as sandstone, basalt, and some granites, which may swell or shrink appreciably with change in moisture content, produce a concrete with more shrinkage than concrete containing flint, gravel, dolomite or limestone of low absorption. Indeed some dolerites may have such a high moisture movement as to result in disruption of the concrete. The mineral character of the aggregate also affects the shrinkage; hard, dense aggregates with a high modulus of elasticity result in less shrinkage.

Besides the type of aggregate, the grading is important. The grading used should result in a mix with a high density using the maximum size of aggregate.

Water/Cement Ratio: Shrinkage varies directly with the water/cement ratio, the higher the water/cement ratio the greater being the shrinkage. For concretes with equal water/cement ratios, that containing more water per cubic yard shrinks more (see Fig. 1.14).

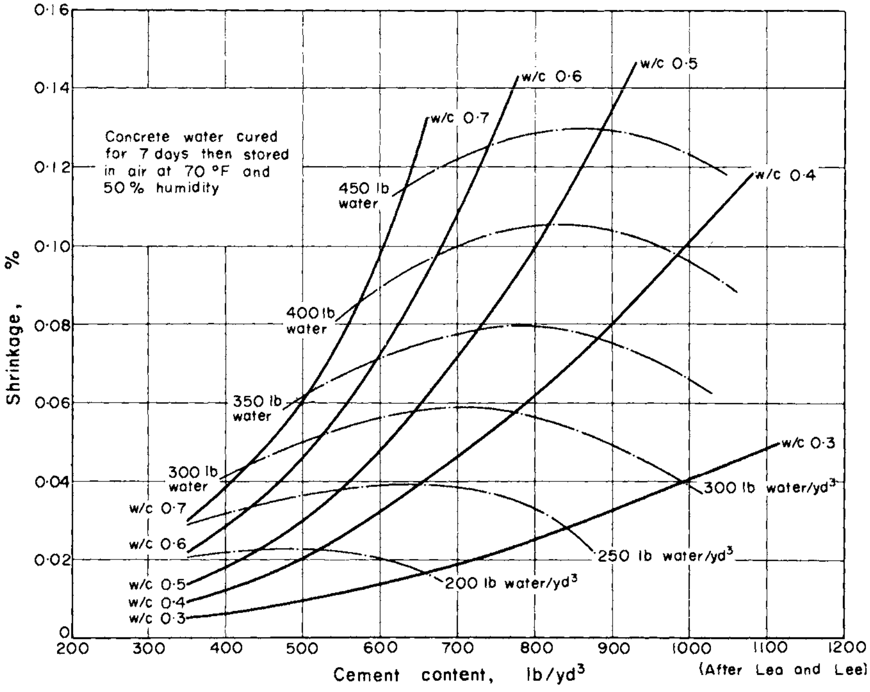


Fig. 1.14. Shrinkage — the effect of water and cement content and water/cement ratio.

In general, concretes with low water/cement ratios are usually rich mixes (i.e. with low aggregate/cement ratios) but the amount of water they contain per cubic yard of concrete is high, because the cement content is high. In such cases the lower shrinkage resulting from a low water/cement ratio is overbalanced by the greater shrinkage due to the rich mix and the high total water content, so that rich mixes with low water/cement ratios may shrink more than a lean mix with a higher water/cement ratio.

Other Factors: Reinforcement reduces the shrinkage of concrete; the heavier the reinforcement the less is the amount of shrinkage. At the same time the position and amount of steel can control the occurrence of cracks due to shrinkage; light reinforcement is used to prevent cracking which would otherwise occur.

The size and shape of the specimen also affect the shrinkage and shrinkage cracks are often located at changes of section (see Plate 2). The amount of shrinkage is reduced as the specific surface decreases. The rate of shrinkage also increases as the ratio of volume to surface area decreases, because it is easier for a specimen with a large surface area to dry out. Curing is important in helping to reduce shrinkage. Inadequate curing or early exposure to a hot sun or drying winds will increase the shrinkage. Normal steam curing has little effect, but high-pressure steam curing reduces shrinkage.

It is difficult to predict the effect of admixtures; those which reduce the amount of mixing water required, improve the workability, and at the same time do not result in a loss of density, can usually be recommended. The behaviour of some admixtures varies with different cements, however, and the determination of the effect on drying shrinkage by means of test blocks is to be recommended where no previous experience exists with the particular admixture. The use of inert mineral powders increases the shrinkage, and there is some indication that the replacement of the cement with pozzolanic material (for example fly ash with a fineness equal to or greater than that of the cement) also leads to an increase in shrinkage.

Creep

For concrete, the relationship between stress and strain is not constant, as it is for an elastic material, but the strain increases with the length of time the concrete is under load. This non-elastic deformation or creep occurs more quickly at first but at a decreasing rate during the loading period. If concrete is loaded quickly, as in a compression test, strain takes place,

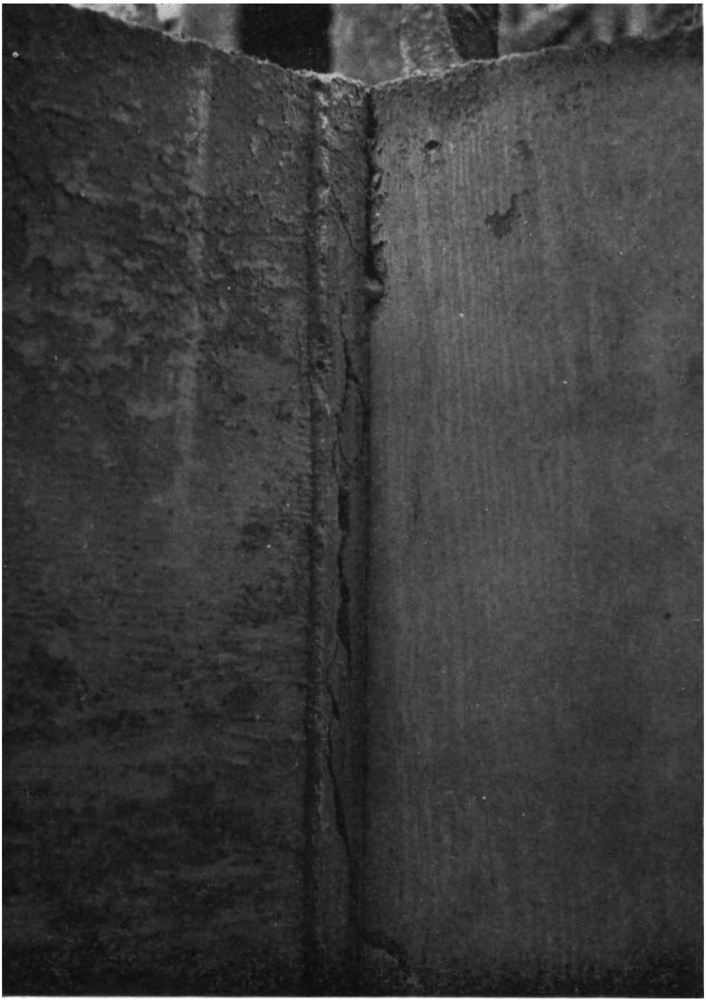


Plate 2. Drying shrinkage crack located at change of section.

which as long as the load does not cause fracture or cracking, practically disappears when the load is removed so that the concrete returns very nearly to its original size. If, however, the load is maintained for some time and then removed the concrete does not return to its original size. It returns almost to its original size over a period of time, but even after this period it will still be deformed. This permanent deformation due to loading is called permanent creep. The deformation which disappeared gradually with time is known as recovery creep, or delayed elasticity, whilst the deformation which is recovered immediately the load is removed is the elastic deformation. With increasing time of loading, permanent and recovery creep play a more important part in the deformation of concrete, so that the behaviour of stressed concrete depends upon the previous history of strains during its life.

The permanent creep consists of two parts: that due to the load only, and that due to load and time. That due to load only, increases with, and is proportional to, the stress, but is independent of the time for which the load is applied. It is known as specific creep, and is quoted as creep per unit stress; it is a strain which is proportional to stress, but which only takes place when sufficient time is allowed. The proportionality of specific creep applies only up to 0·33 to 0·5 of the ultimate strength of the concrete.

The second part of the permanent creep is due both to the stress and the time for which it acts. For small loads it forms but a small part of the permanent creep, even when the stress acts for a long period of time. As the stress above 0·33 to 0·5 of the ultimate strength the deformation becomes less and less proportional to stress and more and more dependent upon the time for which the stress acts.

Even under no load some creep normally occurs. This is because concrete shrinks due to drying.The shrinkage induces internal stresses and the internal stresses cause creep, the effect of which is to redistribute the internal stresses in the concrete.

Creep and drying shrinkage are related phenomena. Under the action of sustained stress caused either by shrinkage, or by loading of the concrete, the cement gel is subjected to forces which cause a volume change. When both drying shrinkage and loading occur together, as in prestressed concrete structures, it is impossible to separate their effects. Creep, in a loaded structure subject to drying, is very much greater than in a similarly loaded structure in a damp atmosphere, and it is greater the more rapidly the concrete is dried out. Creep at

50 per cent relative humidity is 1·5 times creep at 70 per cent relative humidity. Since the rate of drying affects creep, it follows that the larger the mass of concrete the less will be the creep. The creep of mass concrete may be only a quarter of that of a small laboratory specimen.

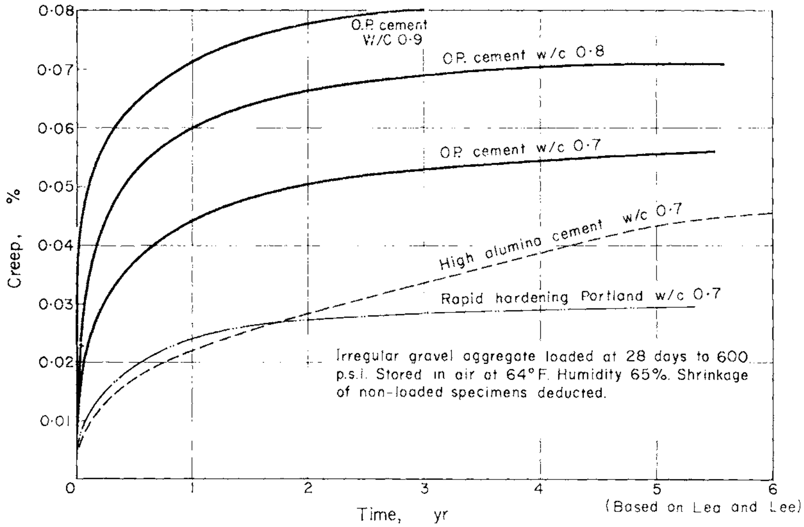
Some explanations of the occurrence of creep are based on the phenomena of shrinkage. Loading of the concrete produces stresses in the gel, resulting in a change in the moisture content consequent upon the generation of pore-water pressure, and changes in the moisture content of the cement gel are accompanied by volume changes and hence creep.

Another possible cause of creep may lie in the same changes occurring in the set cement as cause the initial irreversible shrinkage. On this theory creep and irreversible shrinkage are indistinguishable.

Influence of Various Factors on Creep.

Stress and Rate of Loading: Creep starts as soon as the load is applied. The rate of loading has some effect on the creep but it is of minor importance.

Composition of the Concrete: Creep is affected by the type

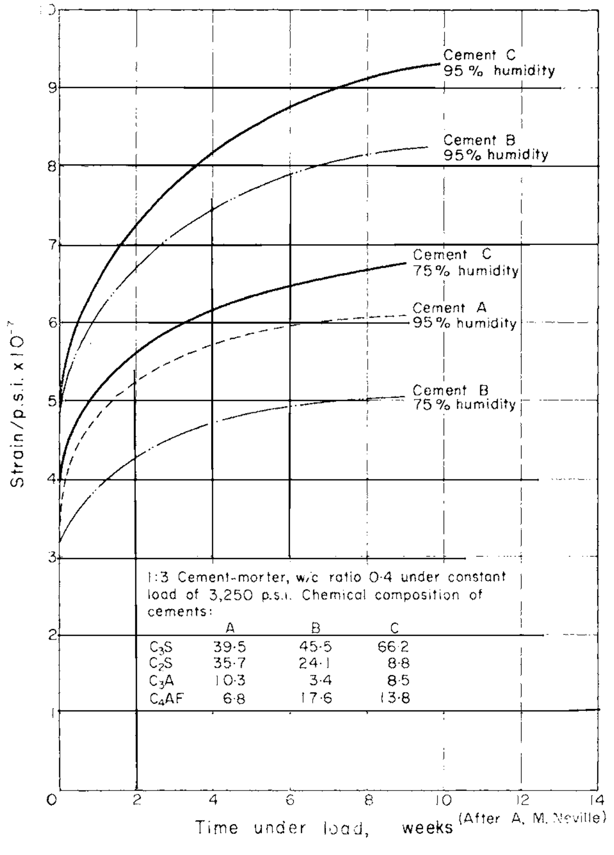


Irregular gravel aggregate loaded at 28 days to 600 p.s.i. Stored in air at 64°F. Humidity 65%. Shrinkage of non-loaded specimens deducted.

(Based on Lea and Lee)

Fig. 1.15. Creep — the effect of cement and water content.

of cement, the cement content (see Fig. 1.15), the mix proportions and the size and type of aggregate. The type of cement — its chemical composition and fineness — affect both the rate and total creep at any one time (see Fig. 1.16). Fineness is probably not as important as chemical composition. Rapid hardening Portland cement concrete may have a rate and total creep twice that of ordinary Portland cement concrete. Low heat cement also creeps more than ordinary Portland, and the creep is greater for coarse cement (which is the reverse of the case for ordinary Portland cement). High alumina cement has



1:3 Cement-mortar, w/c ratio 0·4 under constant load of 3,250 p.s.i. Chemical composition of cements:

	A	B	C
C_3S	39·5	45·5	66·2
C_2S	35·7	24·1	8·8
C_3A	10·3	3·4	8·5
C_4AF	6·8	17·6	13·8

1.16. Effect of cement and relative humidity on creep strain.

a total creep somewhere between the two, but unlike Portland cement the rate of creep does not decrease for a number of years.

Creep is affected by the type of aggregate in much the same manner as is shrinkage — sandstones and basalts may produce large amounts of creep; lesser amounts result from using flint gravel or low-absorption limestone. Creep is reduced by using a large aggregate and ensuring a small voids ratio in much the same manner as for shrinkage.

The effect of the water/cement ratio is that the creep increases with increasing water/cement ratio. Creep is less for high aggregate/cement ratios, and it increases with increasing richness of the mix, but the effect is masked largely by the overriding effect of the water/cement ratio which results in creep being greatest with lean or weak mixes when the water/cement ratio is high in order to achieve a workable concrete.

The curing history of the concrete also affects the creep; there is less creep when the cement is more completely hydrated, and therefore water-cured concrete should show less creep than concrete cured in air, but concrete which has been dried so that the initial irreversible drying shrinkage has taken place shows less creep than concrete kept fully immersed in water. Since creep is reduced as the cement is more fully hydrated, it is less the later the age at which the concrete is loaded.

The effect of admixtures generally is to increase the creep; where it is important, however, the effect of any particular admixture should be determined by test.

Considering all the various factors which affect creep such as the amount, rate and time of loading, the chemical and physical properties of the cement and aggregates, together with the mix properties and curing conditions of the concrete, it is not surprising that difficulty has been experienced in expressing creep by a mathematical equation. A number of formulae have been proposed, but one of the simplest to use, which assumes that the creep follows a hyperbolic equation, is

$$e_c = \frac{m_c t s}{n_c + t}$$

where e_c = creep strain in millionths
t = time under load in days
s = stress in p.s.i.
m_c = ultimate creep in millionths per p.s.i.
n_c = time in days when $e_c = m_c/2$

m_c is known as the creep coefficient and is a useful index for comparing different concretes.

Values of m_c depend upon the various factors given above, but for concrete with a water/cement ratio of 0·59, cured for 28 days and then loaded and stored at 50 per cent humidity, the following values have been reported:

Aggregate	m_c
Sandstone	1·67
Basalt	1·38
Gravel	0·99 to 1·07
Quartz	1·01
Limestone	0·5 to 0·72

Thermal Expansion

Variations in temperature cause concrete to expand when the temperature rises and contract when the temperature falls. Coefficients of thermal expansion of 5·5 and 6·0 × 10^{-6} per °F are commonly used, although values varying from 3·4 to 9·2 × 10^{-6} have been recorded, depending upon the type of aggregate and the method of storage of the concrete. Table 1 summarizes the effect of variation of aggregate on a 6:1 concrete.

The coefficient of expansion depends largely on the type of aggregate; concretes made with silicious aggregates have the highest coefficients, while those made with limestone have the lowest values; concretes containing igneous rocks have a coefficient between the two.

The coefficients of expansion of dry and saturated concretes are the same, but are lower than those of partially dried concrete, so that concrete cured in air has a higher thermal expansion than concrete kept in water. The curing history has little effect on the coefficient of expansion, and age appears to have only a minor effect. Different types of cement have little effect upon the coefficient except where the concrete has been stored in water, when concrete made with high alumina cement

TABLE 1.1

COEFFICIENT OF THERMAL EXPANSION OF ORDINARY PORTLAND CEMENT CONCRETES WITH VARIOUS AGGREGATES

Aggregate	Coefficient of Expansion (per°F)	
	Air Storage	Water Storage
Blastfurnace slag	$5{\cdot}9 \times 10^{-6}$	$5{\cdot}1 \times 10^{-6}$
Dolerite	5·3	4·7
Foamed slag	6·7	5·1
Gravel	7·3	6·8
Granite	5·3	4·8
Limestone	4·1	3·4
Quartzite	7·1	6·8

(Bonnell & Harper)

has a lower expansion than concrete made with Portland cement. The results of tests made on a 6:1 gravel concrete are shown in Table 2.

TABLE 1.2

COEFFICIENT OF THERMAL EXPANSION OF CONCRETES WITH DIFFERENT CEMENTS. (GRAVEL AGGREGATE)

Cement	Coefficient of Expansion (per °F)	
	Air Storage	Water Storage
Ordinary Portland	$7{\cdot}3 \times 10^{-6}$	$6{\cdot}8 \times 10^{-6}$
Portland blastfurnace	7·9	6·9
High alumina	7·5	5·9

(Bonnell & Harper)

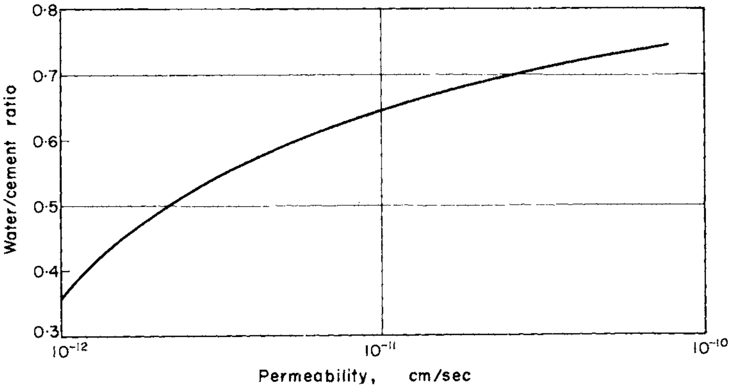
Permeability

Concrete is a slightly porous material, in which watertightness and impermeability are often as important as strength. The permeability and absorptive capacity affect the life and value of concrete which is subject to disintegrating agencies, and in hydraulic structures, low permeability is necessary to ensure watertightness.

Permeability must be distinguished from absorption; permeability is that property which permits the passage of water through the concrete when subject to pressure whilst absorption is the ability of concrete to transmit water by capillary attraction when the water is not under pressure.

When concrete is mixed, extra water is added over and above that required for hydration of the cement in order to give the concrete sufficient workability. In addition, air is entrapped during mixing, a small amount of which cannot be removed even by prolonged vibration.

The cement paste is an impermeable material, but it is riddled by a mass of capillaries, often interconnected, so that the concrete is inherently permeable. Its permeability is, however, of a relatively low order (10^{-12} cm/sec), similar to that of puddle clay (see Fig. 1.17). The capillaries which exist



Actual results depend upon water content per yd.³ Aggregate/cement ratio. Aggregate type, size and grading.

Fig. 1.17. Approximate relationship of permeability and water/cement ratio.

are formed during compaction, which causes the water to rise and so form channels. Some water is trapped below the aggregate particles, while some fills the pore spaces between the cement particles.

Hydration of the cement produces a gel which tends to fill the water voids and to decrease the permeability, although the voids are never completely eliminated. Incomplete curing or allowing the concrete to dry out during hydration increases the porosity, so that complete and thorough curing is necessary to ensure low permeability.

Factors Affecting Permeability. Those factors which affect the strength of concrete usually affect the permeability; for example, factors such as the quantity and composition of the cement, aggregate and water, together with any admixtures.

Thorough mixing, complete compaction and proper curing are all required to ensure watertightness. As regards the constituent materials, highly porous aggregates lead to concrete of high permeability whilst dense aggregates with low porosity result in a more impermeable concrete. Aggregates should be of first-class quality of their kind, and dense material should be used if available (for example, fine-grained basalts and hard limestone instead of coarse-grained sandstones). Proper grading of the aggregates is necessary to ensure adequate workability, and it is important to ensure that there is sufficient fine material present to fill the voids and produce maximum density. The effect of water/cement ratio is to reduce the permeability. The permeability increases as the voids ratio increases, but if the water/cement ratio is too low for complete compaction then the effect of the low water/cement ratio in reducing permeability will be more than offset by incomplete compaction.

The water content per cubic yard of concrete also affects the permeability, which increases with an increase in water. The water content is affected by both the richness and the water/cement ratio, and for minimum permeability it is essential to adjust the richness and water/cement ratio so that the water content is a minimum consistent with adequate workability.

Watertightness and Crack Control

The watertightness of concrete is dependent not only upon its impermeability but also upon its shrinkage. Although highly impermeable concrete can be made with a low water/cement ratio and a mix rich in cement, this produces excessive shrinkage and results in a number of shrinkage cracks. In consequence the leakage of water is greater than would occur in a structure constructed with leaner concrete of higher permeability.

The most serious matter in preventing the penetration of water is the cracking of the concrete. Neither an integral waterproofer nor a workability aid will affect this. Apart from those due to structural movement, cracks are due to drying shrinkage. The permeability decreases but the shrinkage increases as the richness of the concrete increases. To reduce shrinkage, concrete should be made more lean, and this increases the permeability. The optimum ratio of aggregate to cement for minimum cracking with minimum richness appears to be 6:1, but this, of course, depends upon the type of aggregate used.

The shrinkage of concrete which occurs in drying cannot be prevented, but it can be reduced by efficient curing. Since shrinkage cannot be prevented, neither can the tendency for the concrete to crack. If concrete is of uniform structural strength and thickness, shrinkage cracks usually appear at regular intervals, for example, every 3 or 4 ft in 18 in. beams, and every 12 ft in a concrete wall 4 ft thick. It is preferable to predetermine the position where cracks will occur and then to prevent ingress of water by the provision at the position of the cracks of water-stops in the form of, say, p.v.c. water bar. The position of a crack can be predetermined in the design stage by a reduction of the thickness of the section (since cracks occur at the thinnest sections), or it can be done in the construction stage by the formation of construction joints (since cracks occur where the shear strength of the concrete is lowest). The amount of cracking and the shrinkage can be reduced to a minimum if the concrete is placed in alternate bays and is efficiently cured; these bays should be allowed as long a time as possible for shrinkage to take place before the filling-in bays are concreted, so that much of the initial shrinkage will have taken place before concreting is complete.

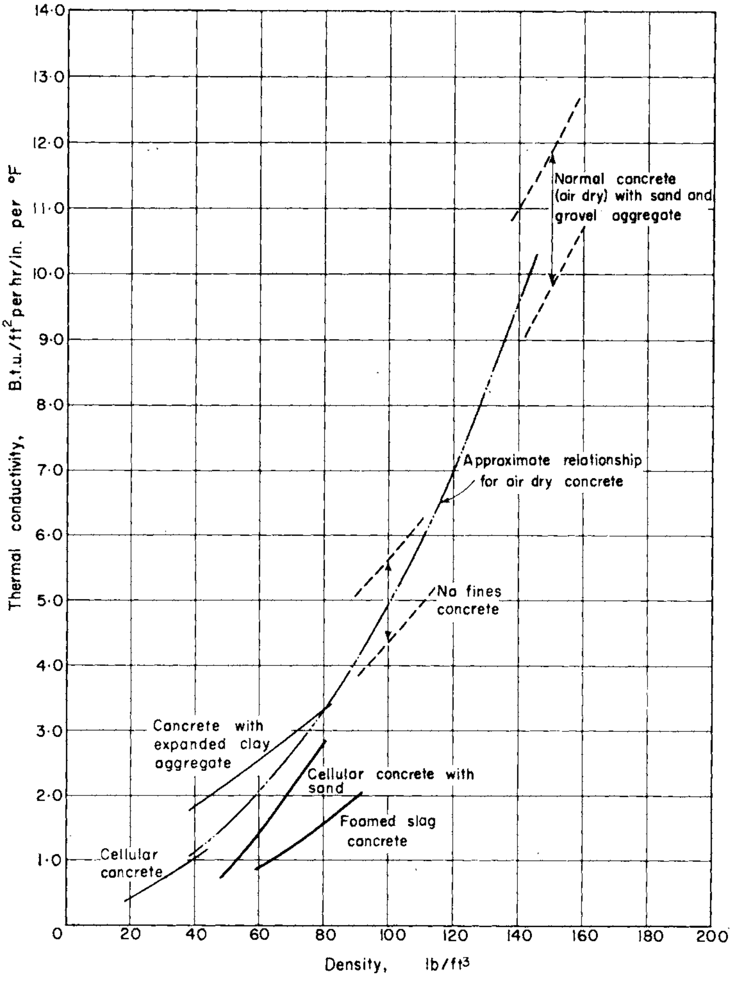


Fig. 1.18. Variation of thermal conductivity with density.

Thermal Conductivity

Thermal conductivity is a measure of the rate of heat transfer. It is important in three situations: when considering the dissipation of heat from a massive concrete structure, when considering the heat-retaining properties of concrete walls, and also in the allied problem of moisture condensation or sweating.

The rate of dissipation of heat is a function of both the conductivity and the density, whilst the transmission of heat and the condensation problem depend upon the internal and external temperatures, the relative humidity, the mass or thickness of the concrete and its conductivity. Typical values for thermal conductivity are given in Fig. 1.18.

From this it is apparent that to reduce the conductivity the concrete must be maintained dry and its density reduced, i.e. a large proportion of air must be incorporated either in the form of air bubbles or as lightweight aggregate. This leads to the use of a lightweight concrete, the properties of which are considered in Chapter 8.

The thermal conductivity varies with the aggregate, and there is a rule of thumb that the coefficient of conductivity is about twice that of the aggregate used.

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CHAPTER 2

CONCRETE MATERIALS

Cement

Cement is a bonding agent, in this book defined as a powdered material that chemically reacts with water; it hardens on drying and is used with a suitable aggregate to form concrete.

The cement most commonly used is ordinary Portland cement but there are a number of others, of which some have only limited or special use. The main groups of cements are:

Portland cement formed from burning a mixture of clay and lime.

High alumina cement manufactured from a mixture of lime and bauxite.

Slag cements in which granulated blastfurnace slag forms one of the main ingredients.

Natural or pozzolanic cements formed from naturally occurring materials, usually of volcanic origin, which will react with lime to form cementitious materials. These cements are of no importance in this country, and are not discussed further.

Special cements: these are usually manufactured from one or more of the above groups and have a special but usually limited use, e.g. expanding cements.

Portland cement

Manufacture

Portland cement is made by intimately mixing together clay and lime, and then burning the mixture at a high enough temperature to form a clinker. The clinker is then ground, together with a small amount of gypsum, into a powder.

Ground shales or slate may be used instead of clay and chalk; or marl, which is a mixture of clay and chalk, may be used instead of limestone. Where such calcareous materials are unobtainable other materials may be used, for example coral in Trinidad and oyster shells in the Gulf of Mexico. Alkali wastes are also utilized, particularly those from the manufacture of caustic soda, sulphuric acid and ammonium sulphate.

Cement works are located where the two basic raw materials are easily obtained. For example, on the north Kent coast are located cement works which use chalk from the North Downs and alluvial mud from the Thames and Medway. In the Midlands, cement works use lias limestone and shale or oolitic limestone and clay.

The mixing and grinding of the raw materials can be done with the materials dry (dry process) or by adding water to produce a thick slurry (wet process). The wet process was the one originally used for the mixing of the soft chalk and river mud because the chalks used (those of north Kent) contained bands of flints easily removed by separating out in wash-mills. The dry process is cheaper, but the wet process is preferable because of the more accurate control of the raw materials. Figure 2.1 shows the various stages of manufacture.

Dry Process. The dry process consists of reducing the raw materials, clay and lime, to dry pellets by passing them separately through a batch of crushers, drying in rotary driers as necessary and then storing in large silos. The chemical composition of the material in each silo is determined at frequent intervals and the quantity taken from each silo is proportioned to give the required composition when fed to a pulverizing ball or tube mill. The pulverized raw feed may be further blended, if necessary, in a blending silo before being fed into the kiln. In a blending silo the powdered material is aerated and flows like a liquid; it is displaced upwards by the heavier non-aerated material on top, a mixing action takes place and a uniform product is obtained.

Wet Process. The basic difference between the wet and dry processes is that in the wet process the raw materials are first mixed with water. Soft chalk and alluvial mud are fed into a wash-mill in the required proportions, and mixed and agitated with water to form a slurry.

The fine material passes out of the wash mill through screens into a second wash mill or centrifugal screening mill, where it is further reduced in size. Harder materials than chalk and clay, such as limestone and shale, are crushed before being

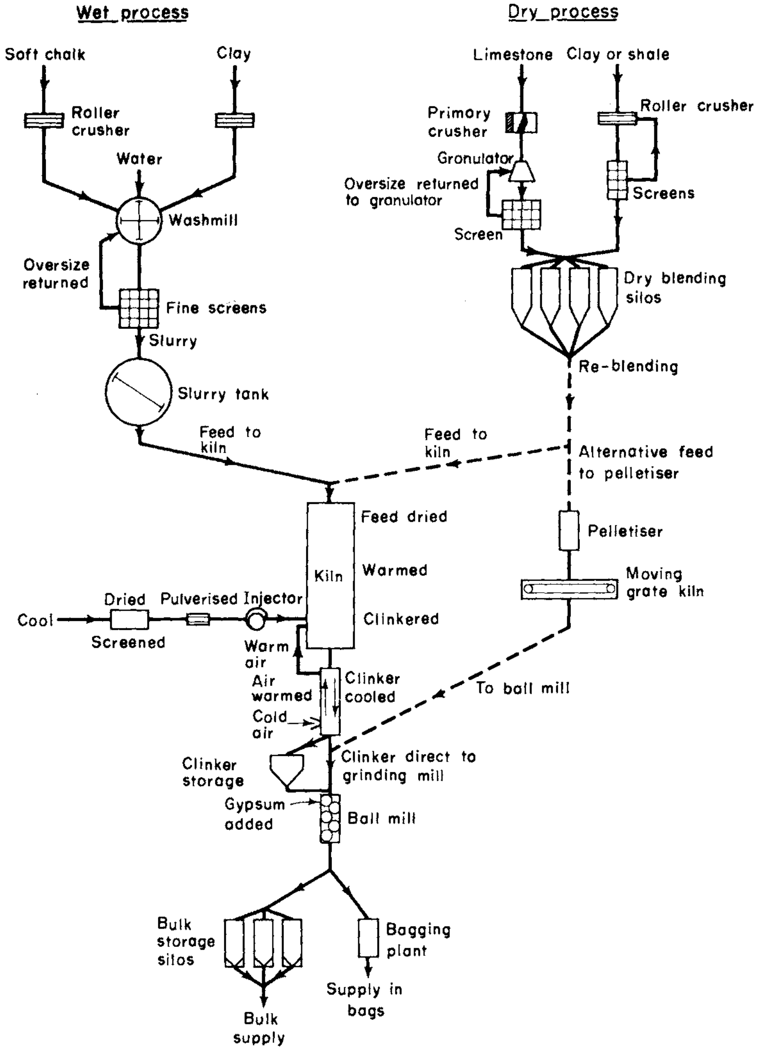


Fig. 2.1 Manufacture of Portland cement.

mixed with water, and are then fed with water into a tube mill and reduced to a slurry of the required fineness. The slurry is thickened to the required consistence by passing through a hydro-separator where the processes of sedimentation and flotation are used to produce a thick creamy liquid. The chemical proportions of the slurried materials are controlled to give a constant lime content and, where necessary, slurries from two or more slurry pits are blended to produce a uniform material. From the blending tank the slurry passes into a storage tank where it is kept agitated by mechanical stirrers and compressed air. From the storage tank it is fed to a filter, where the water is further reduced, and from here it is passed into the kiln where it is first dried and then burned.

The kiln, which is a long, refractory-lined rotating steel cylinder, is operated continuously. The raw materials are fed in at the upper end and the burned clinker removed at the lower end. As the material passes down the kiln it is dried, heated and then burned to a clinker using pulverized coal. The temperature is controlled to ensure that the clinker does not melt. After passing through the burning zone the clinker, which is a hard granular material, drops into a series of coolers, and is quenched by a blast of air. This air, warmed by the clinker, is re-circulated and used for burning the pulverized coal. After cooling, the clinker is either stored until required or passed straight to a ball or tube mill for grinding to a powder.

The ease with which the clinker can be ground is influenced by its chemical composition, the rate at which it was burned and cooled, its age, and the method used for storage. Under-burned clinker is easy to grind because of its high content of free lime, whilst over-burned clinker is hard and difficult. Quick quenching produces a tough glassy clinker which again is hard to grind, whereas slow quenching makes for easy grinding. Ageing of the clinker, especially if it can absorb moisture, makes it tough and difficult to grind, and the moisture causes sticking on the mill balls and screens.

As the clinker passes to the grinding mill a small quantity of gypsum is added to it to control the setting of the finished cement. Other materials such as calcium chloride, which is used to produce super-rapid hardening Portland cement, may also be added and ground in.

The fresh cement powder, hot from grinding, is usually stored for a period to cool, for there is a rooted objection to using hot cement. There may be nothing detrimental in it, but it is good practice to allow it to cool before use, for then any small amounts of free uncombined lime will hydrate and carbonate by reaction with moisture and carbon dioxide in the air.

The method of manufacture described above covers most of the plants in operation in this country. Some plants incorporate various modifications which have been made to improve the efficiency, these being usually designed to reduce the amount of water required in the wet process, to improve the control in the dry process, or to reduce the amount of fuel required for burning the clinker. For example, in the ACL (Alks-Chalmers: Lellep) process a slowly travelling grate and rotary kiln are used. The grate is fed with pelleted raw material through which pass hot waste gases which dry and pre-heat the material. This process allows a much shorter kiln to be used and also uses less fuel, and so leads to a higher fuel efficiency and a higher output.

Chemistry of Portland Cement

The chemical composition of ordinary Portland cement is as follows:

	Range	Average
Lime (CaO)	59 to 67%	64%
Silica (SiO_2)	17 to 25%	21%
Alumina (Al_2)	3 to 9%	7%
Iron oxide (Fe_2Os)	0·5 to 6%	3%
Magnesia ($Mg O$)	0·1 to 4%	2%
Sodium potash	0·5 to 1·3%	
Sulphur trioxide (SO_3)	1 to 3%	2%

These materials are combined in various chemical compounds (Bogue, 1955) the four most important of which are:

Tri-calcium silicate	(C_3S)	$3CaO.SiO_2$
Di-calcium silicate	(C_2S)	$2Ca.SiO_2$
Tri-calcium aluminate	(C_3A)	$3CaO.Al_2O_3$
Tetra-calcium alumino-ferrite	(C_4AF)	$4CaO.Al_2O_3.Fe_2O_3$

The tri-calcium silicate (C_3S) and the di-calcium silicate (C_2S), which together form 70 to 80 per cent of the whole, control the strength characteristics of the cement.

A high percentage of C_3S and a correspondingly low amount of C_2S will give a high early strength and will generate considerable heat in the process. The reverse combination results in a slower development of strength and the generation of less heat. The tri-calcium aluminate (C_3A) content is important. It is the least desirable compound; it hydrates rapidly and produces considerable heat during the process, but a cement with a low percentage of C_3A will develop a high ultimate strength, will generate less heat of hydration, will show greater volumetric stability, will have less tendency to cracking and will be more resistant to acid and sulphate attack, than a cement with a high C_3A content.

The quantity of lime has to be carefully controlled during manufacture. A large lime content gives a slow-setting product with a high early strength, but an excess may cause unsoundness. The amount of free lime in freshly ground cement is usually about 3 per cent, of which just under 1 per cent may be unhydrated. The amount of unhydrated lime is kept to a minimum as its delayed hydration in set concrete may cause disruption.

A large silica and alumina content produces a high-strength cement. A high silica content gives slow setting, whilst high alumina produces a quick-setting cement. A cement with large amounts of alumina (approximately 40 per cent) is described as a high alumina cement (q.v. infra).

Iron oxide combines with the lime and the silica and is beneficial for those cements high in silica, for it causes a decrease in the C_3A. It also acts as a fusing agent, but if too much iron oxide is present the resultant clinker is difficult to grind. It is iron which gives the grey colour to ordinary Portland cement.

Magnesia is limited in most British cement to about 1 per cent, as if present in large quantities it causes unsoundness. The alkalis, soda and potash, are of doubtful value and are kept to a minimum. They may produce efflorescence in the set concrete; if more than 0·6 per cent is present, which is usual for British Portland cements, they will react with certain aggregates (see p. 246).

The sulphur trioxide present is derived principally from the gypsum added to the clinker before grinding, although some sulphur may be derived from the coal used in burning. Sulphur compounds are undesirable, as they tend to cause unsoundness of the cement.

Cement Hydration

When mixed with sufficient water, cement becomes plastic. Gradually with time it loses its plasticity and becomes friable and cannot be made to cohere if disturbed; at the same time it has no strength and can be broken between the fingers. Initial set has taken place. If left longer, the mixed cement paste hardens until it can be broken only with difficulty and it has a hard stony texture. The time required for initial set measured by the Vicat needle test (B.S.1881) appears to be governed by the time necessary for the formation of either tri-calcium aluminate (C_3A) or tri-calcium silicate (C_3S). Sometimes a false set may take place in which the cement paste sets in a few minutes, but on being re-mixed it again becomes plastic and does not suffer any loss of strength. High temperatures in the grinding mills can produce this false set by causing the gypsum—added to control the set — to lose some of its water, which gives a rigidity to the cement paste sufficient for it to appear to be set.

Soundness

Soundness of a cement indicates freedom from volume change or the cracking of the cement paste. It is determined by an empirical test (Le Chatelier test) in which cement paste is boiled in water and any swelling or cracking is noted. Experience has shown that cements which pass this test will not be unsound in concrete work.

Unsoundness of the cement must not be confused with unsoundness of the concrete, however, which may be due to a chemical reaction between certain aggregates and cement (see alkali reaction of aggregates).

Seeding of Cement

It has been found that ground cement paste may be used as an admixture to increase the strength of cement. Cement paste is made from cement and water and is allowed to set, and the crystal growth promoted by heat treatment. The resulting hardened paste is ground into a powder and then added to concrete at the rate of 2 per cent by weight of cement. This results in an increase in strength at 28 days of up to 10 per cent. This increase is in addition to any obtained by the addition of, say, calcium chloride.

It appears that the increase in strength is due to the seeding of the fresh cement paste with minute crystals which form nuclei for a rapid crystal growth in the saturated cement/water solution.

Setting and Hardening

The most important property of concrete is the setting and hardening of the cement paste after being mixed with water. The processes are complex and not completely determined. Many theories have been proposed, and these include the development of a gel film round the cement paste, the formation of crystalline hydration products, and the mutual coagulation of components in the cement paste.

The two main theories are the crystalline theory and the gel theory, the older being the crystalline theory of Le Chatelier which dates back to 1882. According to this theory the setting and hardening is due to the locking together of an intergrowth of crystals (hence the crystalline theory). The alternative theory is the gel theory proposed by Michaelis in 1893. He suggested that a colloidal non-reversible gel is formed in the saturated solution which surrounds the cement particles. The coagulation of this gel causes the setting of the cement.

These theories have now been largely integrated into a combined theory (Lea, 1956), according to which, when cement and water are mixed into a paste there is formed a super-saturated solution from which a gel-like mass of crystals precipitate. Many of the cement grains are either unhydrated or only partially hydrated and are surrounded by hydration products through which water has to diffuse to reach the unhydrated core, a process which becomes slower with time.

Whilst still in a plastic condition the cement paste shrinks slightly as water is taken up in hydrating the cement, but once the cement paste becomes rigid there is a small expansion due to the gel depositing around the cement grains and causing them to swell and so exert an expansive pressure. The initial set, which is observed in normal cement pastes some 2 to 4 hours after mixing, occurs when gel-like crystals growing from individual cement grains meet and form a more rigid lattice able to stand a certain pressure.

The cement gel formed is in an unstable state and has a tendency to shrink and give off water so as to be reduced to a stable state. If the cement paste is kept submerged and cured continuously under water this tendency to shrink is offset by continued hydration of the cement particles and there is no measureable change in the total volume of the cement paste. If, however, the cement paste is allowed to dry out, then considerable shrinkage occurs, known as drying shrinkage. Part of this is irreversible but the remainder is reversible so that the cement paste will swell again on being wetted, and shrink on being dried.

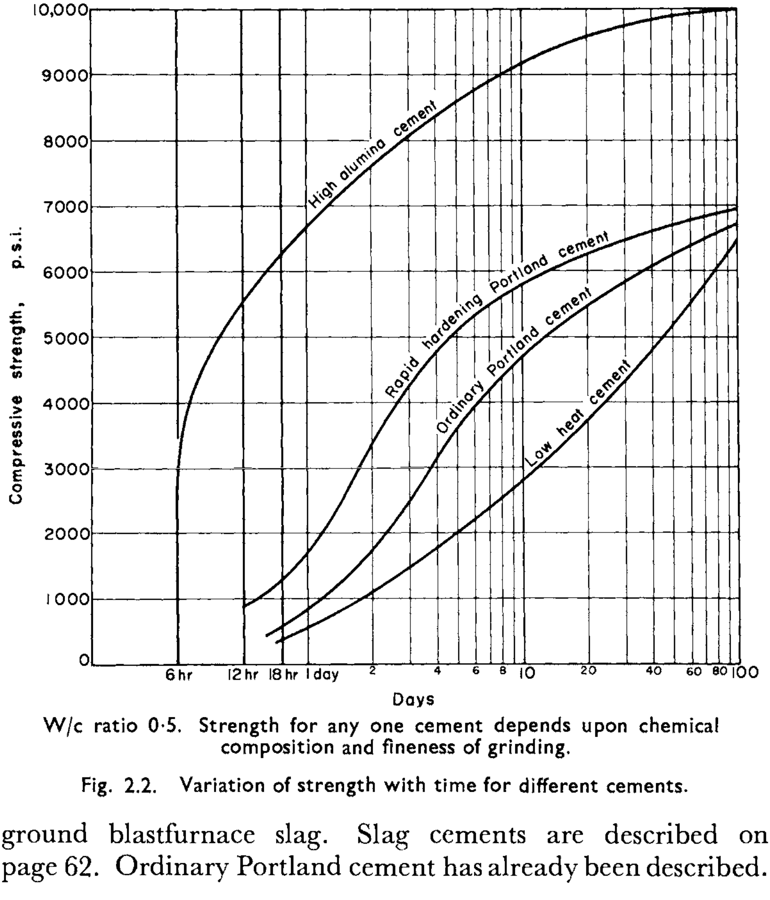
Final set, as specified in, say B.S.12, appears to have no chemical significance in the process of the formation of gel-like crystals or in the contemporaneous growth of larger crystals. The formation of a stable gel, or the growth of large crystalline masses, is reckoned in terms of months as opposed to a "final set" of not more than 10 hours for ordinary Portland cement.

Healing or Re-setting of Cement

After mixing with water, many of the grains of cement still remain unhydrated even after long periods of curing. If a set cement paste is cracked and broken then unhydrated cement grains are exposed, so that if the pieces are fixed together and then cured in water the exposed grains hydrate and the pieces bind together again. It is probable that after fine hair cracks have been caused by (say) shrinkage and the concrete is again cured under water, the hydration of the exposed unhydrated cement cores helps to close the cracks.

Types of Portland cement

In this country there are four main types of Portland cement: ordinary, rapid hardening, sulphate resisting and low heat. In addition there is Portland blastfurnace slag cement, consisting of 60 per cent ordinary Portland cement mixed with



W/c ratio 0·5. Strength for any one cement depends upon chemical composition and fineness of grinding.

Fig. 2.2. Variation of strength with time for different cements.

ground blastfurnace slag. Slag cements are described on page 62. Ordinary Portland cement has already been described.

Rapid Hardening Portland Cement

The difference between rapid hardening and ordinary Portland cement is that rapid hardening cement gains strength more quickly (see Fig. 2.2). At 1 day and 3 days it should have the strength to be expected from ordinary Portland at 3 and 7 days respectively. Rapid hardening cement may be produced by finer grinding of the clinker, more intimate mixing of the raw materials, or better burning of the mixed materials. If the raw material exists in nature in an intimately mixed state — as is the case when the basic material is a marl, whose composition needs adjustment merely by the addition of extra clay, or, as is usual, more chalk — then a rapid hardening cement is produced. Many ordinary Portland cements have properties similar to those of a rapid hardening cement, and there is no rigid demarcation between the two cements. Extra rapid hardening cement is also marketed; this is a rapid hardening Portland cement, to which 2 per cent calcium chloride has been added to increase the rate of gain of strength in cold weather.

Sulphate Resisting Portland Cement

Concrete made with ordinary Portland cement may be adversely attacked by soil water containing sulphates. The sulphate resistance of Portland cement is increased if the tri-calcium aluminate (C_3A) content is decreased, and this is done by substituting iron oxide for some of the clay (alumina) during manufacture.

Apart from this change in chemical composition the properties of sulphate resisting Portland cement correspond closely to those of ordinary Portland cement. The rate of gain of strength and the setting properties are about the same; to achieve this, sulphate resisting cement is usually ground a little finer than ordinary cement to offset an otherwise slower rate of hardening due to the changed chemical composition. This extra fineness may lead, in a rich mix, to a slight increase in the amount of drying shrinkage.

Low Heat Portland Cement

When cement is mixed with water its hydration generates heat in the same way as in most other chemical reactions. This heat may be an advantage or a disadvantage, according to whether it tends to keep the concrete warm in cold weather, or to raise the temperature too high, as in the construction of large concrete dams where due to the mass of concrete the heat of hydration is not easily dissipated.

High temperatures cause thermal stresses, which may result ultimately in the concrete cracking. These may be avoided by using a cement with a low rate of heat evolution and a low total heat of hydration. A low tri-calcium aluminate (C_3A) content results in a decrease in the total heat of hydration, without affecting the rate of gain of strength. If the tri-calcium silicate (C_3S) is reduced and at the same time the di-calcium silicate C_2S is increased proportionally, there is a large decrease in the rate of heat evolution, with a corresponding decrease in the rate of gain of strength; the final strength at say 12 months is not affected, however. To achieve a low heat cement, therefore, the chemical composition of the raw material fed to the kiln is adjusted to give a low C_3A and C_3S content with the appropriate adjustment in C_2S.

Low heat cement is available only to special order, when it is arranged for a works to turn over to producing such cement for a period of a few weeks. Since it is usually required in large quantities for mass work, this method of supply works well enough in practice.

Low heat Portland cement should not be confused with a super-sulphate cement which has low heat evolution and as such is suitable for mass concrete work.

High alumina cement

High alumina cement is composed of alumina, lime, iron oxide and a small amount of silica. It is characterized by a rapid development of strength due to the high alumina content 30–45 per cent and the rapid evolution of heat on setting and hardening. It is highly resistant to sulphate attack.

It differs from ordinary Portland cement in that larger amounts of alumina are combined with the lime. This has two effects. During manufacture, the mixture of alumina, lime and iron oxide fuses into a molten mass which is more costly to grind than the sintered clinker of Portland cement. Secondly, the chemical composition results in a very rapid growth of strength so that the cement attains the majority of its strength within 24 hours. The British Lightning, the French Ciment Fondu, under which name it is made and sold in this country, and the American Lumnite, are all examples of high alumina cement.

Manufacture

High alumina cement is made by mixing together the required proportions of limestone and bauxite and then heating the mixture to a high enough temperature, about 2600°F, until chemical combination takes place. It is possible to sinter the material to form a clinker as in the manufacture of Portland cement, but the temperature difference between clinkering and fusion is so small that in most processes fusion takes place and the material is drawn off as a liquid. The liquid is cast into pigs which, after cooling, are crushed and ground to a powder.

Whilst limestone or chalk is common enough, bauxite, which is an aggregate of aluminous minerals, occurs only in a few areas in the world in deposits which are commercially workable. France, Italy and Greece are among the world's largest

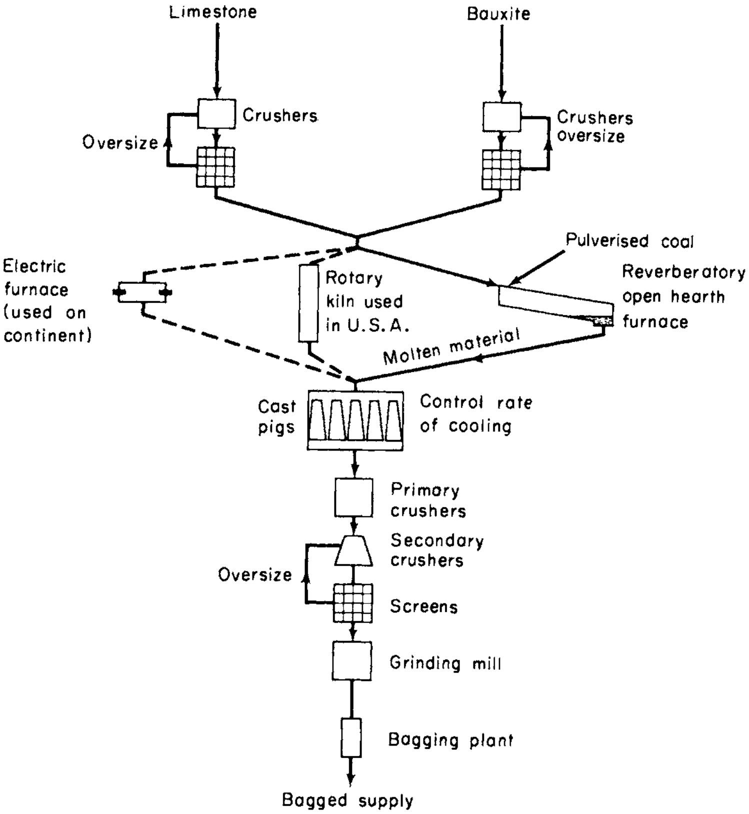


Fig. 2.3. Manufacture of high alumina cement.

producers. All the bauxite for high alumina cement is imported into this country. Commercial bauxite which is composed of various aluminium hydrates also contains silica, iron oxide, titanium oxide and clay as impurities.

There are a number of different processes used to manufacture high alumina cement. Figure 2.3 is a line diagram which shows the various stages of manufacture. A rotary kiln furnace similar to that used for Portland cement is used in the U.S.A.; this differs from that used for producing ordinary Portland cement in that the discharge end is tapered to form a dam and hence permit a pool of molten material to be formed in which complete fusion can take place. The mixture of bauxite, coke and limestone is fed into the furnace much in the same manner as with normal blastfurnace operation. On the Continent, particularly where cheap hydro-electric power is available, electric furnaces have been used, but in this country and in France the reverberatory open hearth furnace is the most common. Pulverized coal is used as fuel and the feeding of raw materials is arranged so that the furnace gases passing through them drive off moisture and carbon dioxide. The fused materials are tapped off continuously and cast into pigs. The rate of cooling influences the setting time and rate of hardening of the finished cement and, in addition, the ease with which the crushed clinker can be ground.

After primary crushing and grinding the powdered material is passed between magnets to remove any metallic iron and is then passed to a tube or ball mill for final fine grinding. Because of its hardness the clinker is coarse ground in comparison with ordinary Portland cement. No additives are included during or after grinding, the setting being controlled by the rate of cooling of the fused product.

Not only is the cost of the raw material higher for high alumina cement than for ordinary Portland, but so also are the manufacturing costs. In addition to the extra fuel required to fuse the materials, the cast pigs are hard to crush and grind so that grinding costs are high.

Chemistry of High Alumina Cement

The constituents of high alumina cement are:

Alumina	30–45%
Lime	35–45%
Silica	4–9%
Iron oxide	0–20%
Titania	2%
Magnesia	2%
Sulphate	1%

The alkali content is less than in Portland cement and has to be restricted, or else trouble will occur due to the cement setting too quickly.

Specifications (e.g. B.S.915) require a minimum alumina content of 32 per cent, and limit the ratio of alumina to lime to 0·85–1·3.

The total heat evolved during hydration is of the same order as Portland cement, but most of it is evolved within the first 24 hours.

The chief compounds in high alumina cement are various calcium aluminates (CA, C_3A_5, C_5A_3, etc.). These combine with water to form hydrated mono-calcium aluminate and hydrated alumina. The present knowledge of high alumina cement chemistry does not permit of a ready calculation of the various compounds formed in the hydrated cement.

Hydration of High Alumina Cement

On hydration of the cement grains a gelatinous mass commences to form round the grains after an hour or so; this grows rapidly with the formation of crystals so that after 24 hours the original grains of cement largely disappear, to be replaced by a gel and crystal structure.

High alumina cement combines with more water than does Portland cement; whereas the water/cement ratio for hydration of Portland cement is about 0·22, for high alumina it is about 0·35 and due to incomplete hydration may be 0·50. There is a reduction in combined volume of solid and water but this contraction — which is nearly complete after 24 hours — is masked by the swelling of the cement which begins at the time of final set.

The setting time of high alumina is similar to that of ordinary Portland cement. It is affected by salts which can change the pH value, an increase in pH corresponding to an increase in setting time. Salts such as calcium and sodium hydroxide, sodium carbonate and sulphate, and sulphuric acid accelerate the set, whilst sodium and potassium chloride, hydrochloric acid, and organic materials such as glycerine and sugar, retard the set; in fact, sugar may even prevent the setting and hardening entirely.

Soundness

High alumina cement does not suffer from unsoundness in the same way as does ordinary Portland cement, for it contains no free lime and little sulphur trioxide which are the sources of unsoundness in Portland cements. Hydrated high alumina cement can, however, be affected by a combination of high temperature and high humidity which causes an inversion of the hydrated calcium aluminates. At normal temperatures the compounds $CaO.Al_2O_3.10H_2O$ and $2CaO.Al_2O_3.8H_2O$ are produced. These compounds are meta stable and may change to $3CaO.Al_2O_3.6H_2O$. If the concrete is kept dry this change does not take place, and if the temperature is low the change takes place only very slowly at great age. However, when high temperatures are combined with high humidity the change is rapid and results in a great loss of strength, see Figure 3.20.

High temperatures with high humidity are achieved if concrete made with high alumina cement is cast in large masses, or if high alumina cement is used under tropical conditions, involving high humidity.

Mixtures of High Alumina and Portland Cements

The addition of ordinary Portland cement to high alumina cement reduces the strength of the latter and also accelerates the setting time. Calcium hydroxide accelerates the set of high alumina cement and this salt is formed when Portland cement is mixed with water. Gypsum (calcium sulphate) when present in large quantities also accelerates the set, but in small quantities tends to retard it. It follows, therefore, that the addition of small quantities of ordinary Portland cement will hasten the initial set of high alumina cement. Similarly the addition of a small quantity of high alumina to ordinary Portland cement will accelerate the set of Portland cement. When sufficient Portland cement is added to high alumina cement the concentration of the gypsum and calcium hydroxide become sufficient to cause what is known as a flash set of the mixture.

Slag cements

Cements made with slag may be divided into two main groups:

(a) mixtures of blastfurnace slag and Portland cement clinker ground together;

(b) mixtures of blastfurnace slag and lime ground together.

The first group is the only one of importance, and even of this group only one type of Portland blastfurnace cement has been used in any quantity in this country. Increasing interest is being shown, however, in two other types, namely supersulphated cement and slag cement made by the Trief process. The second group of slag lime cements are used now only in small quantities on the Continent. They usually contain from 10 to 20 per cent slaked lime or 20 to 30 per cent of hydraulic lime and are inferior binding agents, although the addition of small amounts of gypsum can increase the strength of some of them appreciably.

Blastfurnace Slag and Portland Cement Mixtures

Distinction can be made between three types of slag cement: Portland slag cement, slag Portland cement, and slag sulphate cement; in each of these the first named compound predominates.

Table 2.1 gives the composition of Portland blastfurnace cements in various countries.

In this country the term Portland blastfurnace cement covers all mixtures of Portland cement and slag, containing not more than 65 per cent of granulated blastfurnace slag.

Blastfurnace slag is the molten flux from a blastfurnace obtained as a by-product in the manufacture of pig iron. The slag is produced from the silicate, argillaceous and calcareous constituents of the iron ore together with the ashes from coke fuel. The main components are thus the same as those of Portland cement but the proportions are different. The proportions depend upon the type of ore, the composition of the limestone used as a flux, and upon the process of manufacture. For example, the slag from a hot-blown open hearth steelworks gives better strengths than that from a steelworks using the Thomas process when the same ore is processed.

TABLE 2.1

Country	Name	Portland cement clinker (%)	Granulated blastfurnace slag (%)
Great Britain	Portland blastfurnace cement	35 minimum	65 maximum
U.S.A.	Portland blastfurnace slag cement	75–35	25–65
Germany	Eisenportland cement Hochofenzement	70 minimum 15–69	30 maximum 35–31
France	Ciment metallurgique de fer Ciment metallurgique de haut fourneau	70–80 25–35	30–20 75–65

Slag is obtained from the blastfurnace in a molten state, and is carefully treated by rapid chilling. Slowly cooled slag, such as air-quenched slag, is largely crystalline and has no hydraulic properties. Rapid chilling produces a super-cooled glass and prevents crystallization; it also has the advantage of granulating the slag, breaking it up into small particles suitable for subsequent grinding to a powder. Rapid chilling may be achieved by allowing the slag to run into a tank of water, but this produces a material with a high water content and since it has to be dried before it can be ground, this is a disadvantage. If the slag is quenched by a jet of water, however, suitable granulation can be achieved with little residual water. The chemical composition affects the ease with which the slag can be granulated; for example, those with a high alumina content granulate easily. In its granulated form blastfurnace slag is fairly stable and is unlikely to deteriorate, except that when it contains large amounts of manganese oxide it is subject to long term unsoundness.

Granulated slag has little cementing value until it is ground to a powder and mixed with an activator. The activator is usually either Portland cement or gyspum although lime, anhydrite, sodium carbonat or caustic soda have all been suggested. Portland cement is an activator because it releases free lime to react with the slag cement.

Portland Blastfurnace Cement

Portland blastfurnace cement contains not more than 65 per cent of granulated slag and is specified in B.S.146. Portland cement is usually manufactured from the slag itself, which is used instead of clay or shale, but since it already contains up to 50 per cent lime, a smaller amount of lime is necessary. The slag and lime are burnt in a rotary kiln in the manner described for Portland cement. After burning, the cement clinker is mixed with up to 65 per cent of dried granulated slag and ground to powder in the usual type of ball mill.

Portland blastfurnace cement is similar in its general properties to ordinary Portland cement, although concrete made with it gains strength at a slower rate than with ordinary Portland cement and evolves less heat on hydration. The heat of hydration is not as low as low heat cement, but it is more suited for mass concrete work than ordinary Portland cement. The rate of gain of strength, however, is within the limits of B.S.12 for ordinary Portland cement. Owing to the slower rate of hardening and low heat of hydration, concrete made with slag cement requires careful curing, especially protection against too rapid drying and the effects of cold weather.

Hardened Portland blastfurnace cement contains less free lime than ordinary Portland cement and its hydration products are more stable. It is usually ground much finer than ordinary Portland cement and this tends to increase the workability. Its specific gravity is about 3·0. It is of lighter colour than ordinary Portland cement.

Slag Sulphate Cement

Granulated slag cement may be activated with gypsum or anhydrite, and such cements are known either as slag sulphate cements or more usually, as super-sulphate cements, probably because they were first imported into this country from Belgium where they are known as "ciment metallurgique sursulphate".

The combined action of sulphate and slag is not easily understood and has not been as well investigated as that of Portland cement. Slag sulphate cements are finely ground but they evolve less heat of hydration than Portland cement, and in fact they could be classified as low heat cements and used where such cement is needed as in massive concrete work.

They require a minimum water content to develop their cementing properties fully, but with increase in water there is a gradual increase in cementing efficiency, the peak being at a ratio of water to cement of 0·6 to 0·7.

The super sulphate cements used in this country are made by grinding a mixed mass of granulated blastfurnace slag, calcium sulphate (hard burnt gypsum or anhydrite) and Portland cement clinker. The proportions are usually 85 per cent granulated slag, 10 per cent anhydrite and 5 per cent Portland cement. The specific gravity of the cement is about 2·9. The initial set varies from ½ to 2 hours and the final set from 1½ to 4½ hours. The cement is of whitish colour, and produces a light-coloured concrete.

Only slight quantities of heat are evolved during hydration, although the shrinkage is slightly greater than for ordinary Portland cements. Proper curing is essential with possibly, in addition, the painting of the exposed surfaces of the concrete with lime, to prevent the formation of a soft skin.

Trief Cement

Trief cement is a slag sulphate cement produced by wet grinding. To produce slag sulphate cements the granulated slag has to be ground to a fine powder, and there are two methods of doing this.

(a) Dry Grinding: The granulated slag, which normally contains about 10 per cent of moisture, has to be thoroughly dried and then ground in the usual type of ball mill.

(b) Wet Grinding: M. Trief, a Belgian, a number of years ago patented a process for wet grinding slag cement. The slag is ground in a ball mill with about 30 per cent water and the slurry is fed into storage vats with sufficient water to produce a mixture which can be agitated to prevent sedimentation. The slurry may be pumped direct from the vats to the batch mixer, and there mixed with 30 per cent of Portland cement and the necessary aggregates to produce concrete.

Instead of using Portland cement, the setting may be promoted by adding anhydrite as with slag sulphate cements, though work has yet to be carried out in this country on an extensive scale to determine fully the effect of adding anhydrite.

When using Trief cement care is necessary in the fine aggregates, because a slightly organic sand can inhibit the setting of the cement, whilst in addition difficulty may be experienced if the water content of the sand is too high. It may then be necessary to add extra Portland cement to give the required water/cement ratio.

Special cements

Expanding Cements

Concrete shrinks on drying, and this may result in cracking and even lead to structural unsoundness in water retaining structures. To counteract the shrinkage and nullify its disadvantages the use of expanding cements has been suggested. To eliminate shrinkage the amount of expansion must equal the normal shrinkage at any one time. This means that the expansion should take place during the period when the concrete is drying, but this is impossible. If concrete made from expansive cement is dried it undergoes a shrinkage of the same order as normal concrete under the same conditions, and like normal concrete it expands slightly on wetting.

Thus although it cannot be used to counteract shrinkage, expanding cements have been used in underpinning work (Lossier, 1948) where there is difficulty in arranging for new concrete to carry its share of the foundation load.

The expansion of expanding cements is due to the formation of calcium sulpho-aluminate in the presence of high lime concentration. This has to be under controlled conditions, as the increase in volume would be detrimental to the concrete strength if the concrete were left to expand freely; in fact, uncontrolled expansion might even result in the disruption of the concrete.

Magnesium-sulpho-, and calcium-sulpho-aluminates may both be used as expanding agents, but the necessity for controlled expansion results in only calcium-sulpho-aluminate being used in practice. This chemical is produced by the reaction of calcium sulphate, alumina and lime, and was first produced commercially in a sulpho-aluminate clinker with the following composition (Lafuma, 1952):

$Al_{2}3O$	19·0%
CaO	41·3%
Fe_2O_3	5·7%
TiO_2	0·8%
SO_3	22·1%
Soluble SiO_2	7·0%
Insoluble matter	2·8%
Loss on ignition	0·9%

This clinker was used for the manufacture of expanding cements in a mixture of ordinary Portland cement, which supplies the lime.

The examination of this clinker showed that it was composed of calcium sulphate, calcium aluminate and di-calcium silicate, so that the same expansion might be obtained by a mixture of high alumina cement and gypsum.

Concrete containing a mixture of sulpho-aluminate and ordinary Portland cement kept wet will expand, but there must be at least 8 per cent sulpho-aluminate present. On drying, expansion will cease, but on re-wetting there is the possibility of further expansion. To ensure that the expansion can be controlled a stabilizing agent is added to the cement mixtures. This is usually blastfurnace slag which reacts slowly with the calcium sulphate and absorbs it by reaction.

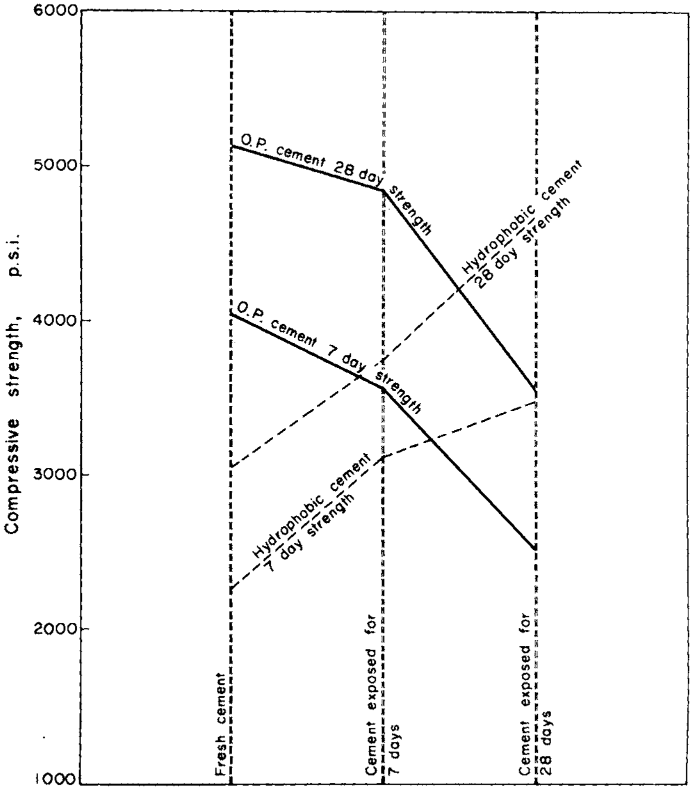
The amount and duration of the expansion can be controlled by varying both the proportions of sulpho-aluminate, blast-furnace slag and ordinary Portland cement, and also in grinding of the sulpho-aluminate and the slag. By grinding the sulpho-aluminate coarsely the expansion can be delayed so as to avoid premature expansion which would reduce the initial strength of the concrete. Fine grinding, on the other hand, causes rapid hydration and expansion, although the total expansion will be less. The rate of gain of strength of the Portland cement also affects the expansion, the higher the strength the slower the swelling and the greater the delay.

Calcium sulpho-aluminate may be produced by manufacturing a sulpho-aluminate clinker and then grinding to the required fineness, or by mixing high alumina cement and gypsum. The latter is a cheaper method but limits the control of the expansion which can be achieved through controlled grinding of the sulpho-aluminate clinker. The manufacture of a sulpho-aluminate clinker in France is as follows. The raw materials are prepared by wet-grinding gypsum, bauxite and chalk in the proportions of 50 per cent gypsum and 25 per cent each of chalk and bauxite. This mixture is then burned to form a clinker in a rotary kiln, using pulverized coal. When cool, the clinker is crushed and then ground to the required fineness.

Hydrophobic Cements

Hydrophobic or waterproofed cements do not deteriorate if stored under damp humid conditions, as would ordinary Portland cement. This is shown in Fig. 2.4. Hydrophobic cements have interground with them various organic materials, usually oils, fatty acids or metallic stearates, which cause the cements to be water repellent.

Manufacture of the cement is the same as for ordinary Portland cement, except that the clinker is sprayed with a waterproofing material before grinding. The proportion of organic material used is usually not more than 0·25 per cent by weight of clinker. The resulting cement powder repels water, but this property breaks down over a long period of exposure. Concrete made with waterproofed cement also shows water



Results of tests on a concrete with w/c 0·50 A/C 6·0 : 1

Fig. 2.4. Effect of weathering exposure on O.P. and hydrophobic Portland cement.

repelling properties in that the water absorption is less, but again this reduces with time.

Hydrophobic cements are necessarily air-entraining cements in that the materials used to waterproof the cement have air-entraining properties; for example, an air content of 6·5 per cent may be obtained during normal mixing of a concrete with a water/cement ratio of 0·5. In consequence the compression strength of concrete containing hydrophobic cements is much lower than that of one containing ordinary Portland cement. Exposure tests which cause the gradual breakdown of the hydrophobic material result in a net gain of strength, in that the decrease in strength due to air-set is more than offset by the increase in the strength due to the entrainment of less air consequent upon the breakdown of the waterproofing material.

It is not possible to intergrind calcium chloride with hydrophobic cement to act as an accelerator and overcome the effect of the hydrophobic additive, because calcium chloride is intensely hygroscopic and its effect is to nullify the hydrophobic material.

It is sometimes claimed that hydrophobic cements have an improved resistance to sulphate attack. In general, any increased resistance is that due to air entraining, which results in a reduced permeability; it is not possible to increase the resistance of a cement to sulphate attack merely by spraying the clinker with an organic compound.

Aggregates

About 75 per cent of the bulk of concrete is composed of aggregate whose main attribute is its inertness, but it does not have merely a passive role in concrete, acting only as a filler. It has an active role, and its characteristics often control the behaviour of the concrete. Suitable concrete aggregates may differ widely in their properties, the differences being as great as those between the various cements. They can be grouped in various ways; for example we can classify them according to their origin into igneous, sedimentary, or metamorphic; or according to their density into normal, heavy or lightweight aggregate; or again, according to the way in which they are produced, into natural sands and gravels, crushed rocks, or manufactured aggregates. To some extent these classifications overlap; thus sedimentary rocks include natural sands and gravels, and both these and crushed rocks form most of the normal weight aggregates. Manufactured aggregates include all the lightweight ones which are available in this country. Aggregates are therefore described below under the following headings:

1. Petrological classification
    - Igneous rocks
    - Sedimentary rocks
    - Metamorphic rocks

2. Sands and gravels
3. Manufactured and lightweight aggregates
4. Heavy aggregates; these are described on page 305.

Petrological Classification

The raw material from which natural aggregates are produced is rock. There are a large number of different types, but all are composed of grains or mineral crystals. The properties of a rock depend upon the composition, grain size and rock texture, and these in turn depend on the mode of origin. There are three main rock groups, igneous, sedimentary and metamorphic, each with a different mode of origin; igneous rocks were formed from molten masses extruded from the interior of the earth, sedimentary rocks from the breakdown of other rocks, and metamorphic rocks from the alteration and recomposition of sedimentary rocks so as to form new rocks.

Igneous Rocks

The properties of igneous rocks depend almost entirely upon the way in which the molten masses were extruded. Large deep-seated masses cooled slowly and developed a coarse crystalline structure; smaller masses intruded into the stratification in existing rocks cooled more quickly, developed a finer crystalline structure and caused only slight alteration to the surrounding rock. Sills and dikes are sheets of igneous rock formed between the bedding planes or in crevices of existing rock. Because they were thin they cooled quickly and have a very fine crystalline texture. Volcanic material erupted on to the surface of the earth, cooled extremely quickly, and formed super-cooled or glassy structures, often chemically unstable. Volcanic material which was expelled full of gas has a vesicular texture like pumice and is light in weight. Many volcanic rocks react adversely with a high alkali content in ordinary Portland cement.

Granites are roughly equigranular rocks with mineral grains large enough to be detected by eye. The main minerals are felspars and quartz. The colour ranges from white to grey or from pink to red, and the specific gravity from 2·61 to 2·75. The porosity is low, an average absorption being 0·15 per cent of dry weight. The crushing strength in the solid, is about 15,000 to 20,000 p.s.i. Granite has a poor resistance to fire as it cracks and crumbles under heat, probably due to the large coefficient of expansion of the quartz crystals. It breaks down by prolonged weathering into a mixture of clay and sand, the clay being a particular form known as kaolinite.

In its non-weathered form, granite may be available in large blocks with three planes of cleavage more or less at right angles which, on crushing, tend to form cubical aggregate, the ideal form of crushed rock.

Rocks associated with granite commercially, are gneiss granodiorite, granulite, pegmatite, quartz diorite and syenite.

Like the granites, *gabbros*, including diorite, are formed of minerals more or less equal in size and large enough to be seen by the eye, but they are chiefly iron magnesian minerals and felsparl. Gabbros are dark grey, greenish, reddish or black rocks. The specific gravity is about 2·8 or 2·9, and an average solid density is 178 lb/cubic ft. Gabbros are equal to granites in their strength and durability.

Diorites are similar to gabbros, the distinction between them being based on the relative proportions of the minerals present.

The *dolerites* are a transitional group of rocks between gabbros and basalts. The coarser grained dolerites grade into gabbros and the finer grained into basalts. They are equigranular rocks, ranging in colour from grey or dark green to black. Their chemical composition is the same as gabbros, and the specific gravity varies from 2·9 to 3·3. They are commonly found in dikes and sills in northern England and Scotland. They are usually tough rocks well suited as aggregate, especially in mass construction. Some dolerites, however, suffer from a high moisture movement of the order of 0·04 per cent, which can produce concrete with a high shrinkage; some contain chlorophaeite which is readily oxidized and so can cause flaking and spalling. Where there is no previous record of satisfactory service, dolerites for thin concrete sections should be avoided.

Basalt is a dark rock composed of mineral grains so minute that they cannot be seen by the naked eye, or if perceptible are too small to be identifiable. They range in colour from dark grey, green or purple to black and are composed of the same minerals as rocks which would have solidified under different physical conditions into gabbros or dolerites.

The specific gravity is 2·9 to 3·1. Basalt, being a fine-grained hard rock, is a good aggregate, when in a fresh — as opposed to a weathered — condition.

Porphyry is a commercial trade group which includes micro-granite, quartz – porphyrite, and rhyolite. It includes intrusive rocks whether or not they contain phenocrysts, it includes rhyolites even though they are not porphyritic. Felsite is typical of this group. It is composed of mineral grains too small to be seen by the naked eye. These have the same composition as those which under different conditions would have resulted in granite. The specific gravity varies from 2·4 to 2·65 and is generally lower than that of granite. The colour is light and may include most colours except greys, greens or black.

Sedimentary Rocks

The industrial areas of this country are close to areas of sedimentary rocks so that these supply a major portion of all concrete aggregates.

The derivation of sedimentary rocks is somewhat as follows. Igneous rocks formed from the cooling and solidifying of liquid masses may, in time, become exposed to the effects of weathering at the earth's surface. Alternating heat and cold breaks down the rock, water flowing over it dissolves some materials and so loosens or forms cavities in the surface, freezing and thawing attack and break up the rock so that it is formed into a loose mass, and percolating water removes some minerals and causes the decomposition of others.

All these weathering agencies play a greater or lesser part in the break up of solid rocks to form sediments. Rock fragments are sorted, transported, and re-sorted by streams, rivers and the sea so that eventually they lose their identity of origin. They may be transported many miles until finally they are re-deposited. Other materials laid down on top cause them to be consolidated into a single mass, or they may be cemented with chemicals deposited in the interstices so that they form a new and different rock — a sedimentary rock, derived from the destruction of previously existing rocks. For concrete aggregates the two main sedimentary rocks are sandstones and the calcareous rocks, limestone and dolomite.

Sandstone is part of the commercial Gritstone group which includes breccias, conglomerates, grits and agglomerates, but the main type of the group is undoubtedly sandstone. It is composed of grains of quartz held together by a cement. The grain size varies from 2 to 0·6 mm, but they grade imperceptibly from conglomerates (consisting of cemented gravel or boulders) to siltstones. No hard and fast division can be made between these materials.

Sand grains are often pure quartz, but they may also contain mica and other minerals. The cementing material of a sandstone may be quartz, iron-oxide, clay or calcium carbonate. The colour varies, and white, grey, yellow, red and brown are common; this depends upon the cement, silica cement resulting in white and grey sandstones, and iron oxide producing yellow, red and brown sandstones.

Most sandstones are porous and somewhat permeable, the porosity varying from 5 to 30 per cent. The density in the solid is from 125 to 175 lb/cubic ft. and the crushing strength from 1500 to 15,000 p.s.i. The high porosity results in a large moisture movement on wetting and drying, and produces concrete which is more susceptible to shrinkage. Sandstones with a weak clay or iron oxide cement break down easily and are unsuitable aggregates.

Thick-bedded sandstones which are uniform in texture and free from stratification are very suitable aggregates, but thin-bedded material produces unsuitable flaky aggregates which, if used, result in harsh mixes, difficult to compact.

The chief calcareous rocks are *limestone* and *dolomite*. They are composed of calcium carbonate (limestone), and the double calcium-magnesium carbonate (dolomite). They range in colour from white to grey and black. In texture they may be fine or coarsely grained, and firm and compact or loose and porous. The specific gravity may vary from 2·0 to 2·7 and the strength from 2500 to 40,000 p.s.i. The porosity may range from almost zero for bituminous limestones to 25 per cent for loosely cemented oolitic limestone. The finer-grained compact limestones form excellent aggregates. In general the more the limestone approaches dark grey or black the harder and more suitable it becomes. Dolomites are usually somewhat harder than limestones, and their specific gravity may reach 2·9.

Metamorphic Rocks

When sedimentary and igneous rocks are affected by the intense pressures and stresses which occur when earth movements take place, or by the great heat and the chemically active gases and liquids from masses of hot igneous rocks, they are changed. Their structure and mineral composition is altered so that they become new rocks, i.e. they are metamorphosed. Metamorphism is the antithesis of weathering; both processes cause changes in existing rocks; but weathering breaks down a rock whilst metamorphism builds up a new one.

Metamorphism accomplished by high temperatures and pressures produces dense and massive rocks having chemical and physical stability, such as marble, or slabby or flaky rocks such as shale.

Schist is the group which includes slates. These rocks with folded and oriented structure break down into flat flaky pieces which are undesirable as concrete aggregates. Even those which break into a more cubical structure show weakness. Under the stresses of continued freezing and thawing or wetting and drying they break up along the planes of weakness, so that in general rocks which have been strongly metamorphized by pressure are unsuitable.

On the other hand, firm compact rocks such as quartzite are suitable and it is only the massive rocks from the following groups which are used.

Gneiss, which is characterized by a roughly developed imperfect foliation, is included in the granite trade group. It includes a wide variety of rocks, the characteristic of which is a roughly parallel arrangement of the minerals. Those which are useful as aggregates are solid and massive rocks whose general properties resemble those of massive igneous rocks.

Quartzite is a firm compact rock, generally a metamorphosed sandstone with well cemented grains. Like sandstone it may range from almost pure quartz to a mica-schist with a foliated structure. In fact quartzite, mica-schist and gneiss form a continuous series of rocks. The firm compact rocks are suitable for concrete, but those containing a high proportion of mica are not; mica causes planes of weakness whilst at the same time it weathers badly and increases the porosity of concrete.

Natural Sands and Gravels

Natural sands and gravels are the most commonly used materials. They are derived from the weathering of rocks, so that they are composed of the more resistant minerals. They may be classified by reference to the method by which they were deposited as follows: stream-bed, terrace, marine, wind-blown and glacial deposits.

Stream-bed deposits are materials obtained from the beds of existing streams and rivers. Like all deposits which have been transported and deposited by running water they have a heterogeneous composition, the complexity of which increases progressively with the distance from the source, as more rock formations are traversed. The final properties of a stream-bed deposit depend upon the amount of degradation and weathering, and the sorting effect of the stream.

Terrace deposits are older deposits of material previously laid down as stream-bed deposits. When the flood plain of an old river is uplifted by earth movement then the river cuts into its own flood plain, first deepening its bed and then gradually forming a new plain not as wide as the previous one. Part of the old flood plain is left as a terrace. This kind of deposit is especially well developed in the Thames Valley where terrace deposits are the sources of sand and gravel. Flood-plain deposits are the finer materials such as fine sand, silt and clay deposited outside the normal stream bed of a river, during periods of flood. They vary in extent and type of material, and if they contain suitable aggregates then thorough washing is necessary to remove the silt and clay.

Marine deposits, in particular beach gravels, form important sources in some places, but beach sands are usually too much of a single size to be important. Most beach gravels are post-glacial deposits formed in place by the action of waves and currents, as a result of which only durable rounded materials are deposited. Where efflorescence is detrimental, vigorous washing is necessary to clean off the salt contamination.

Wind-blown sands are often extensive in area but are usually of little value for concrete. They are often single sized and may even be composed largely of shell fragments. When they are not composed of friable material they may be used together with a single-size coarse aggregate to form a gap-graded material.

Glacial deposits are usually heterogeneous and erratic deposits formed during the Ice Age and deposited by the receding ice sheets. They occur over the British Isles north of a line joining Bristol and the mouth of the Thames, and are well developed in East Anglia. Although many deposits are of no value, being mixtures of clay, sands and gravels intermingled with boulders and rock flour, some deposits contain sufficient sand and gravel to be worth exploiting. Extensive processing is usually necessary, and a high wastage can be expected.

Sand. Sand for concreting is material having a grain size varying from $\frac{3}{16}$ in. to No. 100 mesh sieve. At the upper limit it grades imperceptibly into fine gravel and at the lower limit to silt. The term refers only to the grading, but quartz is the most common mineral. Many other minerals may be present depending on the rocks from which the sand was derived, but often the remaining minerals do not add up to more than a few per cent of the total. Feldspar is the most abundant material after quartz, whilst occasionally other minerals may be present in large quantities, for example carbonates formed from sea shells or coral; such sands are usually described as shell-sand or coral sand. Sands that have undergone long transportation in water before deposition are largely of quartz, the less resistant minerals having been eliminated. The shape of sand grains varies, wind-blown particles being highly rounded whereas water-deposited sands are angular. Rounded sands are referred to colloquially as "soft" sand — a reflection of the feel of the sand and not the hardness of the sand grains.

Sands may occasionally be coated with other materials some of which may be detrimental as, for example, organic matter derived from humus or peat. Iron oxide is a common mineral coating which has no great effect on the resulting concrete.

Sea sands are usually coated with calcium and magnesium chloride which cause efflorescence. Sands are often found associated with gravels, and may sometimes contain silt. If there is more than 10 per cent of silt then the sand will usually need washing before use.

Gravel. Gravel used for concrete is material varying from about $1\frac{1}{2}$ in. down to $\frac{3}{16}$ in. The maximum size may vary; it may be $\frac{3}{4}$, $1\frac{1}{2}$ or occasionally $2\frac{1}{2}$ or 3 in. Gravel larger than 3 in. is seldom used.

The larger gravel consists of individual pieces of the parent rock, but the smaller material is often composed of only one material, quartz. Such quartz gravel has usually been derived from a quartzite strata, from quartz veins, or the smaller pebbles may be single crystals derived from granites.

In the south of England much of the gravel is composed of flint and chert. The origin of these is not entirely clear although they are known to occur along the bedding or joints planes in the chalk and so have been derived from these formations. The sand associated with flint and chert gravels is usually quartz and not flint fragments. Gravel formed of individual pieces of rock is generally pitted as a result of the removal of the softer or more easily altered minerals. Apart from flint, gravel is not usually composed entirely of one material; more often it consists of many different rocks, although gravels from one material may occur in river valleys, particularly in the south of England.

Elsewhere the gravel deposits are varied, often being material which was deposited during the Ice Age which has been reworked and transported by modern rivers. This is true of the glacial gravels of Yorkshire, the Trent Valley and Cambridge which contain, for example, material derived from Scottish rocks.

The winning of concrete aggregates

The vast majority of concrete aggregates used in this country are obtained by placing an order for delivery with the local suppliers, but the exploration for and exploitation of aggregates is still important, particularly for civil engineering work in more remote regions. In the Middle East, Africa, India and other Asian countries the successful undertaking of construction work is often dependent upon the location of adequate supplies of suitable aggregates. For major projects the exploration for aggregates necessitates a geologist and possibly a geophysicist to carry out geological and resistivity surveys. The exploration for aggregates in this country is usually on a more modest scale. The service of a geologist may be necessary where bedrock deposits are to be exploited and exploratory borings are to be put down to prove the extent and variation of the deposit.

For the majority of jobs, however, all that is required is a visit to the quarries or pits whose samples, prices, available materials or other considerations make it likely that the material will be suitable. Such visits are important; from what he sees the engineer will be able to determine whether the works will supply regular quantities, if there are likely to be any hold-ups due to lack of facilities, whether the aggregates will be washed or screened properly, and whether they may be contaminated before delivery due to poor stockpiling. A visit may also indicate that the supplier is in a position to offer some other service, such as pre-mixed graded aggregates, not otherwise called for by the consumer because of lack of knowledge that such a service existed.

When a consumer has found the supply best suited to his needs it is advantageous to stick to it. The concreting gang get used to the appearance of the aggregates and are able to handle them better, whilst the mixer driver is more easily able to control the mix because he has the "feel" of it, and in fact there is an increase in the concrete quality.

The winning and processing of aggregates requires the same degree of skill and "know-how" on the part of the pit or quarry manager as does the making and using of concrete. The concrete engineer should know the processes involved so that he can appreciate the difficulties and more sensibly word a specification which will ensure the delivery of properly graded material.

Concrete Aggregate Production

The extent and type of workings are first determined, and then vegetation topsoil and overburden are removed, together with any contaminated layer or stratum of weathered rock. The usual mechanical equipment such as dozers, scrapers or draglines together with tipper lorries will be required for this work. After removing the overburden, the development of the pit and processing of the material depends on its type, i.e. whether the deposit is a sand and gravel or a rock quarry.

Sand and Gravel Deposits. The working of sand and gravel deposits varies slightly, depending upon whether it is above or below the water table as is shown in Fig. 2.5. In a dry pit the material is excavated by face shovel or dragline and loaded on to a conveyor belt and conveyed to primary screens. In wet workings the material is removed by suction pumps or by a bucket excavator, and is then either pumped by pipeline or is

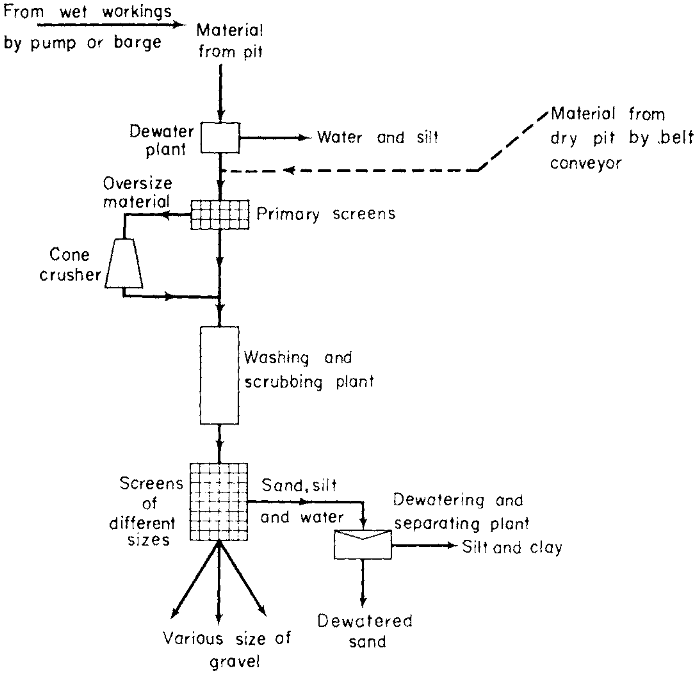


Fig. 2.5. Flow diagram for gravel and sandpit.

Plate 3. Washing aggregate on vibrating screen.

dumped in barges which carry the material to the processing plant where it is removed by suction pumps to a de-watering plant.

The material from the pit is screened to remove oversize material; it is then washed and screened into the required sizes, and finally the sand is de-watered. In some pits working dirty deposits the primary screening takes place after washing. The primary or scalping screens remove all oversize material or rejects. These are then crushed in a cone crusher which discharges on to the conveyor collecting the material from the primary screens. This conveyor carries all the material to a washing and screening plant. High-pressure jets of water remove and break down the clay, silt and fine material. The sand and silt is removed by washing through screens of suitable mesh either in a rotary barrel washer or on a vibrating screen, and the wash water carries away the sand, silt and dirt to a de-watering and separating plant. In the de-watering plant, by means of a balanced counterflow of water, the silt, rock-flour, and material finer than a No. 100 sieve, is removed from the sand and the de-watered sand is delivered to the stockpile.

Meanwhile the coarse material passes over a series of screens and is sorted into single-size coarse aggregates, usually in the grades $1\frac{1}{2}$ in. to $\frac{3}{4}$, $\frac{3}{4}$ to $\frac{3}{8}$, $\frac{3}{8}$ to $\frac{3}{16}$ in. material, and whence by re-combining single size materials in various proportions a regraded material can be produced (see Plate 5). By re-arranging screens various bulk gradings can be supplied such as $\frac{3}{4}$ to $\frac{3}{16}$ in. or $1\frac{1}{2}$ to $\frac{3}{16}$ in. The material is screened on inclined vibrating screens which have almost entirely replaced the revolving drum screen. The advantage of the inclined screen is that better screening is obtained; this is because the coarse material is removed first, whereas with the drum screen the fine material is removed first.

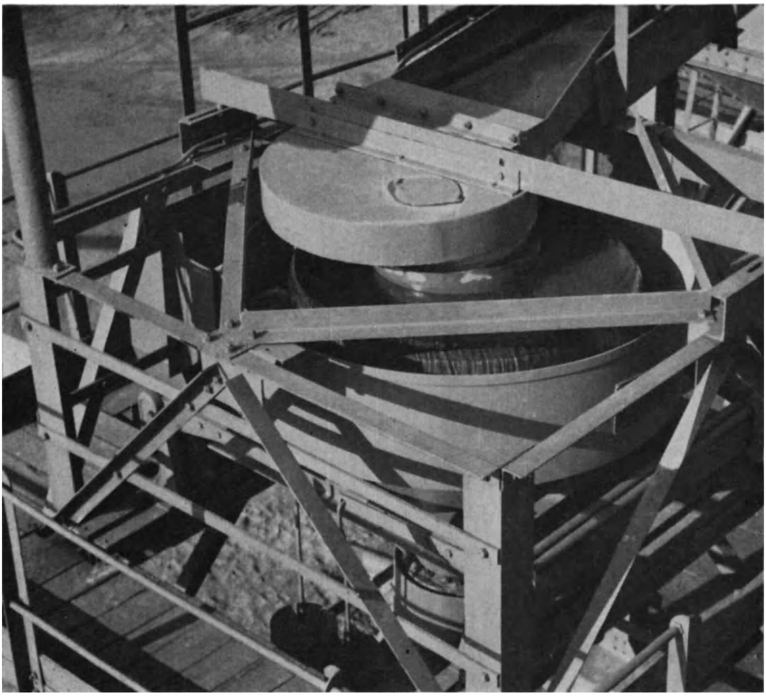


Plate 4. Sand de-watering and separating plant.

Inclined vibrating screens are efficient if fed properly. If fed

Plate 5. Regrading aggregates by re-combining single-size material.

at too high a rate or with the screen at too great an angle a large quantity of material passes over the screen which ought to pass through. If the angle of inclination is too flat, however, the screen may be blinded with material only slightly bigger than the screen size.

In most plants only one grade of sand is produced, consisting mainly of particles lying between $\frac{3}{16}$ in. and No. 100 sieve, but some large plants produce two or three grades. The grading characteristics of the fine aggregate within the limits set by the plant is a matter of natural occurrence and generally the manufacturer can only control the upper and lower limits of sizes. On larger jobs, or those in which special gradings of sand are required, the sand can be re-graded by a hydraulic separator. This works on the principle of elutriation in that an upward flow of water will carry with it certain particle sizes depending upon the mass of the particle; other separators are used in which the water flows outwards as in a centrifuge. Special sand gradings can be produced, but the process is economic only if the original sand before re-grading contained about 70 per cent of useful material.

Crushed Rock Aggregate. The production of coarse aggregate from quarried rock is a sequence of crushing, screening, rejecting and re-crushing to obtain the yield of the particle sizes required (see Fig. 2.6). The objective is to crush the rock to the required size, while at the same time producing particles nearly cubical in shape. The type of rock, its bedding, jointing and cleavage, all affect the extent to which a cubical shape can be achieved, and it is necessary to exercise careful selection to avoid unsuitable material.

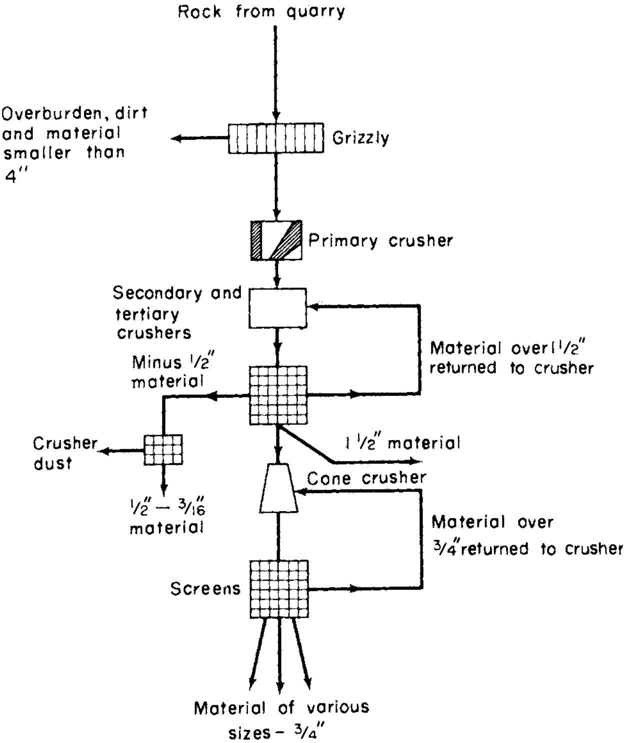


Fig. 2.6. Flow diagram for crushed rock aggregate.

Rock, from the quarry, is passed over a "grizzly" — a series of inclined bars between which drops all material smaller than about 4 in. including overburden and dirt. The hunks of rock are then crushed in primary jaw crushers and reduced to about 6 in. They are then reduced in secondary and tertiary crushers to the required sizes. After crushing the material is screened into separate sizes by vibrating inclined screens, and then carried by belt conveyors to stockpiles.

Secondary crushers may be gyratory or cone crushers, although these tend to produce thin flaky material. Impact crushers, on the other hand, produce a more cubical aggregate than is possible from the "squeeze" type of crusher such as jaw or gyratory crushers which reduce rock size by a squeezing pressure. An impact crusher splits the stone along the grain, or by impact breaks it directly across the grain, and so produces aggregate which is somewhat stronger than the parent material because most weaknesses are removed by the method of impact. Unfortunately with materials having a free silica content over 5 per cent, the hammer wear may be very high.

The conditions which favour the production of good cubical aggregate are:

(1) low reduction ratio, especially in the final stages of crushing (this is important with gyratory and roller crushers but not so important with impact breakers which produce aggregate of a good shape even at high reduction ratios);

(2) the removal, by scalping, of the chippings and fines formed in primary crushing (this also reduces wear on the crusher and prolongs the life of the crusher faces);

(3) the use of corrugated crushing surfaces, which should be discarded when worn.

The influence of aggregates on concrete

Strength. The crushing strength of average rock aggregates is higher than the strength of the concrete made with them. The maximum crushing strength of concrete is about 10,000 to 15,000 p.s.i. which is about the minimum strength of average rock aggregate, which varies from about 10,000 to 50,000 p.s.i. The bond between the cement and aggregate controls the concrete strength with all but the weakest aggregates. Weak aggregates, such as weakly-cemented sandstones, some expanded clays and lightweight materials such as vermiculite, place a limit on the attainable strength.

Although the aggregate bond controls the strength this does not mean that failure does not take place through the aggregate; where the bond is strong then the shear strength which can be mobilized around the surface of the aggregate may exceed the shear strength across the aggregate, and in such a case the failure plane lies through the aggregate. But where the bond is poor the failure will be along the surface of the aggregate particles.

Surface Texture. The bond strength between cement and aggregate is affected by the surface texture and cleanliness of the aggregate; the rough texture of crushed rock aggregate produces a higher strength than the smooth surface of worn uncrushed gravel, but this may be offset by the fine coating of dust produced during the crushing process. In addition, on those sites where control is not strict the extra water necessary to give crushed rock aggregates the same degree of workability as concrete with rounded aggregate may result in lower strengths than would otherwise be anticipated.

Although the surface texture reflects the original internal structure and composition of an aggregate, these are of little practical significance except, for example, in so far that the orientation of grain structure in certain rocks may produce flaky aggregates. Particles with very smooth surfaces do not produce a good bond with cement paste, and this tends to reduce the strength, but the effect may be offset by a reduction in the water/cement ratio following the increased workability obtainable with such rounded aggregates.

Elongated and flaky aggregates, if present in appreciable quantities, will affect the strength; thus micaceous or slaty material, besides reducing workability, also reduce the strength by producing planes of weakness. The amount of flaky aggregate which will cause a reduction in strength depends upon the richness of the concrete; it is about 10 per cent in a 6:1 but 15 per cent in a 4½:1 concrete.

Highly weathered or decomposed surfaces are undesirable because they may be easily detached from the sound core of rock, thus reducing bond, and also because weathered materials are usually highly porous and absorptive. A limited quantity of weathered aggregates can be tolerated, however, but appreciable amounts, above say 5 per cent by weight, will reduce the strength and resistance to deterioration.

Bond Characteristics and Surface Coatings. The capacity for bonding with the cement paste is one of the most important attributes of an aggregate and the surface texture is probably one of the most important single properties of an aggregate which affects the concrete strength. Unfortunately the adhesion between cement paste and aggregate is influenced by several complex and poorly understood physical-chemical phenomena, in addition to the physical and mechanical processes inherent in the penetration of the cement paste into the aggregate voids.

An aggregate should be clean and free from unwanted material, whether it be chemical impurities, rock flour or other surface coatings. Surface coatings are usually detrimental because the aggregate bond is reduced, and organic matter which is a common coating of sands may react detrimentally with the cement and delay the set. In this country there is little trouble due to reactive aggregates, but elsewhere many natural coatings contain reactive minerals, e.g. opaline silica, which react with the cement alkalis.

The usual coatings are clay, silt and organic matter. Aggregates coated with these materials can be made satisfactory by washing but even so, frequent inspection after washing is necessary to ensure that they do not still contain clay balls or organic matter.

Some aggregates may be encrustated with calcium carbonate, iron oxide and perhaps gypsum. If the calcium carbonate is firmly adhered to the aggregate it may improve and not reduce the bond strength, but iron oxide may cause staining and may, by oxidation, cause excessive volume change in the concrete.

Impurities. Sands, particularly those in Scotland, may contain organic matter, the presence of which will sometimes be indicated in the "organic" test by the reaction of caustic soda to produce a brown colour. However, iron-bearing minerals also produce similar colouring and some organic matter appears not to react, so that the caustic soda test is fallible. Suspect aggregates must be compared with aggregates of known purity by compression tests on concrete cubes.

Sea-shore sands may contain up to 5 or 6 per cent of sea salts and so result in heavy dosing of the concrete with chlorides, particularly calcium chloride. In a concrete with 30 per cent sand this is equivalent to 10 per cent of the cement content; this is five times more than the usual dosage of 2 per cent, and some difficulties may occur with too rapid hydration and premature stiffening of the mix.

Clay or silt is a common impurity found in many sands and gravel aggregates, apart from fine coatings on the aggregate particles themselves. A small amount of silt is not harmful provided it can be wetted by the water but mica, for example, is not wetted so that cement cannot adhere to it; hence it lies in the concrete without bond and this encourages disintegration. For this reason granite dust should not be used as a fine aggregate because it is detrimentally enriched with mica flakes from the crushing process, and in crushed granite rock the amount of dust should be reduced to below 5 per cent by weight.

Coal sometimes occurs in natural sands and gravels, and as little as 4 per cent is sufficient to cause failure of the concrete. Powdered coal absorbs water and oxygen and in so doing increases in volume.

Volume Change on Wetting and Drying. Excessive moisture movements in aggregates leading to large shrinkage are a cause of deterioration. Laminated aggregates containing clay and certain limestones and sandstones may suffer from excessive shrinkage, as high as 0·06 per cent. The excessive moisture movement (0·04 per cent) of some dolerites has already been mentioned, on page 72.

Porosity. The size, abundance and continuity of pores in a rock, i.e. its porosity, is one of its most important properties. The porosity of a rock affects its strength, water absorption and permeability, and these in turn control the durability of the aggregate in its resistance both to freezing and thawing and to chemical attack. Absorption tests indicate whether an aggregate has a high effective porisity, and values in excess of 2 to 3 per cent in 24 hours may indicate unsuitable aggregates,

Aggregates which absorb more than this, up to 5 or 6 per cent, may still be suitable if the pore sizes are large. Where the pore sizes are small, below 0·004 to 0·005 mm, then the water does not drain readily from the aggregate and prevents the passage of water during freezing. Aggregate with large absorption but small pores, often a fine-grained material, should be avoided.

Thermal Movement. The deterioration of a rock structure may be significantly affected by differences between the coefficients of thermal expansion of aggregate and the cement matrix (8 to 10×10^{-6} per °F) in which it is embedded. The use of an aggregate with a low coefficient of expansion (2 to 3×10^{-6} per °F) may lead to disintegration of the concrete, for as the temperature of the concrete is reduced the cement paste tends to shrink more than the aggregate with the result that tensile stresses are set up in the cement paste which may be accompanied by cracking. Certain limestones have coefficients of expansion of 2×10^{-6} and may cause deterioration in concrete subject to rapid changes of temperature.

Aggregate Grading. During processing at the pit or quarry, aggregates are screened into various sizes. The amount present of material of different sizes is expressed as the cumulative percentage of material passing the various sieve sizes, starting with the largest and finishing with the smallest. This cumulative percentage is plotted as a curve, the grading curve for the material, see Fig. 2.7 to 2.11. The grading of aggregates is a major factor determining the workability, segregation, bleeding, handling, placing and finishing characteristics of the concrete.

Satisfactory concrete can be made with various gradings of aggregate and there is no universal ideal grading curve. There are limits, however, within which a grading must lie to produce a satisfactory concrete, but these depend upon the shape, surface texture and type of aggregate and the amount of flaky or elongated material. Variations in the grading of sand can be the cause of wide variations in workability, strength and other properties, but the grading of the coarse aggregate has less effect.

Attempts have been made from time to time to produce an ideal grading based on the idea that if the maximum of solid particles were packed into a concrete mix then the highest

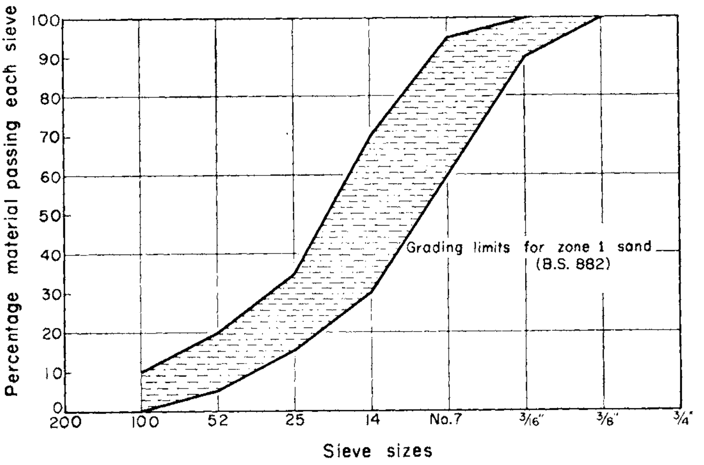


Fig. 2.7. Grading limits for zone I sand.

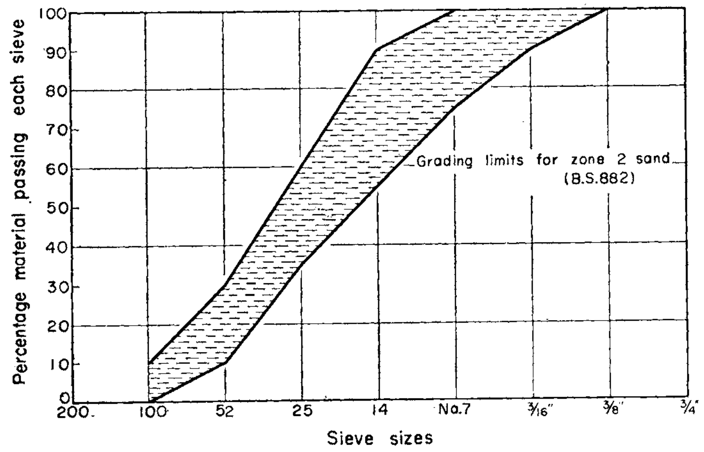


Fig. 2.8. Grading limits for zone 2 sand.

density and strength would result. However, such concretes give harsh unworkable mixes and a certain excess of cement, sand and water is necessary over and above the theoretical amount required. The importance of grading is dealt with in Chapter 3.

Large Aggregate. The use of large aggregate in concrete

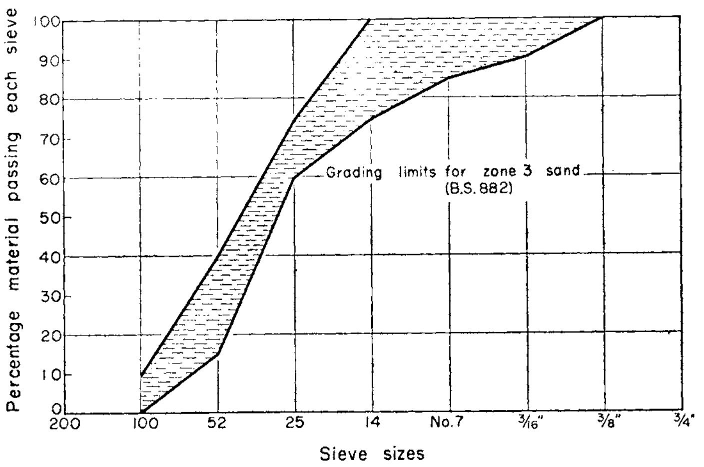


Fig. 2.9. Grading limits for zone 3 sand.

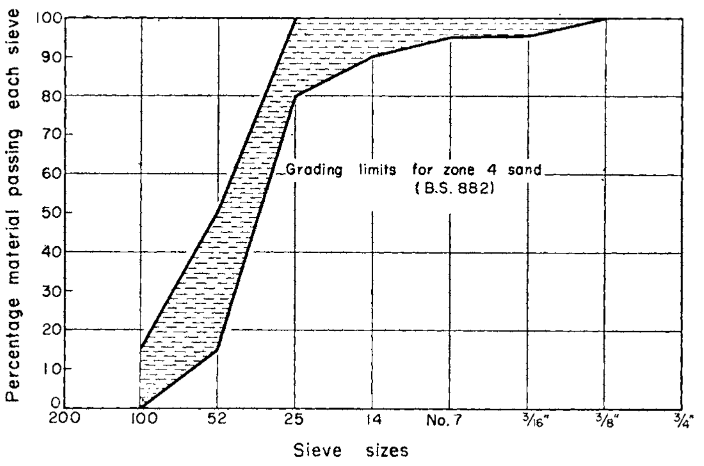


Fig. 2.10. Grading limits for zone 4 sand.

results in less cement being required to produce the same strength or workability than in a concrete made with a smaller aggregate. In mass concrete work it can be an advantage to increase the maximum size of aggregate and so reduce the heat of hydration generated within the concrete mass, whilst at the same time reducing the tendency to thermal stresses and

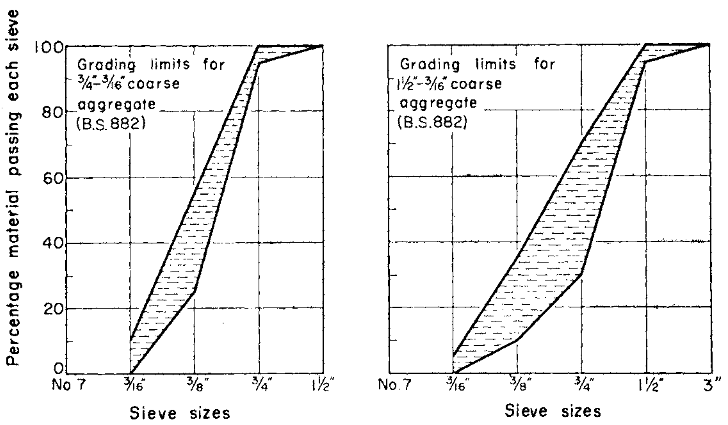


Fig. 2.11. Grading limits for coarse aggregate.

shrinkage cracks. On the other hand, mixing, handling and placing equipment in this country is geared to a maximum size of about 3 in. The maximum size which can be used is also controlled by other factors.

In reinforced concrete it should be ¼ in. less than the spacing between the main reinforcement. Where placed between narrow forms it should not be greater than ⅙ of the clear distance between the shutters. This ensures that arching will not take place, and that a satisfactory packing can take place during compaction.

Large aggregate is often more expensive because most pits or quarries are not adapted to its production.

When concrete is produced from large aggregate extra care is necessary, since the mass of the large pieces of aggregate makes them more prone to segregation. Conveyor belts, chutes and mono-rail transporters should not be used for transporting the concrete since they all tend to produce segregation; skips with full side or bottom opening discharges are suitable, but they must be large enough to hold a multiple of complete batches so as to minimize the effect on segregation of the discharge from the mixer.

The workability of concrete made from large aggregate is more sensitive to variations in the grading, so that strict control of the grading and batching of the aggregates is necessary.

The use of large aggregates is usually associated with a large batching plant producing mass concrete, so that it is economic to use three or four sizes of coarse aggregate (3–$1\frac{1}{2}$ in., $1\frac{1}{2}$–$\frac{3}{4}$ in., $\frac{3}{4}$–$\frac{3}{8}$ in. or $\frac{3}{16}$ in.) and so minimize differences in grading. When large aggregates have been used in the United States some difficulties have been experienced due to the aggregates degradating, i.e. breaking up in handling due to their own weight.

Large aggregates of 6 to 8 in. size have been used in core wall construction in concrete dams by adding them as a layer in otherwise conventional concrete and vibrating them into the concrete. There is a danger, however, in this method of construction, as there is in using plums or large pieces of rock, namely that air voids occur underneath the rock and are trapped against the side faces and not removed during vibration.

It is generally believed that the crushing strength is increased with an increase in the size of aggregate, but there is some evidence that this is not so with aggregate above $1\frac{1}{2}$–$\frac{3}{4}$ in. (Walker and Bloem, 1960).

Manufactured and lightweight aggregates

The chief manufactured aggregates are expanded shale and clay, foamed and air-cooled slag, furnace clinker and coke breeze, asbestos, bricks, and more recently, sintered fly ash. In addition other aggregates such as sawdust, wood shavings and vermiculite are used for special manufactured products.

Blastfurnace Slag Aggregate

Blastfurnace slag has been used for a number of years as a concrete aggregate, and its use as a track ballast on railways and as a roadstone has been common for an even longer period. It is used mostly in the north of England and the south of Scotland, close to the sources of supply, the pig iron furnaces producing basic iron. Because it is a by-product of pig iron manufacture its quality may vary from works to works and even from one works over a long period. The best guarantee of quality is a reputable supplier.

The main requirement for slag is that it should be stable. It is composed of various alumino-silicates of calcium and magnesium, i.e. the same minerals as are found in the slag used in Portland blastfurnace slag, but in addition it may contain residual sulphur and iron which can lead to a rapid breakdown when the slag is immersed in water. Slag may contain calcium orthosilicate in a form that is liable to undergo volume change at normal temperatures with consequent disintegration, or dusting.

The normal methods of cooling is in ladles of 5 to 15 tons capacity or in pits or moulds. It may also be tipped down slag banks. The cooling in ladles, pits or moulds yields a uniform product, but tipping into banks result in a slag with widely varying grain size and porosity. The density and structure of the slag depends not only on its chemical composition but on the rate and hence the method of cooling.

Acid slags tend to be more dense, whilst basic slags are less so because they produce more gases during cooling, but acid slags tend also to be glassy and hence more brittle than basic slags. Acid slags are therefore cooled slowly to allow crystalline growth to offset the tendency to brittleness (glassiness), whilst basic slags are cooled quickly to retain maximum density and prevent a vesicular structure caused by escaping gases.

After cooling, the slag is crushed in primary and secondary crushers. It is a tough angular aggregate with a tendency to produce harsh mixes. It has a coarse surface texture with a relatively high absorption. To obviate the difficulties which this causes, the aggregate should be maintained saturated in the stockpiles and allowance made in the mix design for free water in the aggregate.

At one time it was considered that slag aggregates caused corrosion of reinforcing steel, but it now appears that this is not so. The tendency of steel to corrode in slag aggregate concrete is no greater than with other aggregates, although there is a danger of corrosion when the sulphur content is high.

Broken Brick

Broken brick is often quite a good material, suitable for plain concrete, but its suitability depends upon the type and hardness of the brick. Some bricks contain sulphur and unslaked lime, although the amounts present in old second-hand bricks will not be very high.

Any plaster adhering to old bricks must be removed before crushing, and the bricks should be hosed down and saturated with water before use. Owing to their porosity brick aggregate should not be used for impermeable construction work.

In general, however, broken bricks are not used much for hydraulic concretes although in combination with high alumina cement they are still used extensively for heat resistant concrete.

Clinker and Breeze

Furnace clinker and breeze have been used for many years as aggregates, breeze blocks being one of the first lightweight partition building blocks. Coke breeze, which is not used for concrete work, must not be confused with breeze and clinker which are residues from the combustion of coal. The difference between breeze and clinker is that clinker is more thoroughly fused than breeze and hence is superior.

Clinker gives good results if it contains no combustible material, but failures may occur due to the lack of attention to proper selection and control and the failure to appreciate the deleterious effect of combustible material. The combustible (organic) material causes excessive moisture movement and this results in the disintegration of the concrete. British Standard 1165 specifies three grades of clinker for concrete; the best grade (Grade A) may be used in plain concrete generally, including that subject to weather, and for this grade the combustible material must not exceed 10 per cent. The two other grades of clinker are limited to interior work where the concrete will not become damp; for *in situ* concrete the combustible material is limited to 20 per cent, but is raised to 30 per cent for precast units. The crushing of clinker affects the organic content differentially, the coarse material becoming devoid whilst the fines are enriched with it. Hence if the clinker is crushed and screened, and the fines rejected, a sound aggregate may be prepared but the cost is increased.

There has been a continuing decrease in the use of both clinker and breeze which has been accentuated by the increased cost and the lack of available supplies. Clinker is in short supply because of the increasing use of pulverized fuel for boilers but breeze blocks are still, however, one of the chief partitioning blocks used in the building industry. They hold nails and form a good key for plaster.

Crusher Sand

The result of crushing rock is to produce a waste material which is finer than $\frac{3}{16}$ in. and may contain particles as fine as rock flour. It has a haphazard grading and is commonly made up of flaky particles. It is a bad material to use and leads to harshness and low workability, low strength and low durability. But the material can be processed and improved by using a proper crushing plant to improve the grading and eliminate flakiness. The rock flour and fine particles can be removed in a hydraulic classifier and a controlled grading obtained.

The use of manufactured stone sand is only economical where the material is derived as a by-product from stone crushing so that crusher screenings are transformed into a useful product.

Expanded Shale and Clay Aggregates

One of the post-war developments in concrete aggregates was the marketing of new manufactured aggregates. One of the first was a lightweight expanded clay aggregate (Leca) which consisted of rounded pellets the colour of burnt clay which, when broken open, showed a vesicular texture. The aggregate has a high absorption but, because of its rounded surface, the workability of the concrete is greater than that of corresponding gravel aggregate. Other lightweight expanded clay aggregates are also available under various other trade names.

Non-rounded aggregates are available which in appearance resemble cinder ashes, but they are inert and fairly hard. They are from clays and shales under controlled conditions and yield a uniform product. The shale is crushed to a powder and then fed with sufficient water into a pelletiser where it is rolled into pellets. From the pelletiser it is passed on a steel grid-like conveyor to a dryer to remove some of the moisture, and then on to the furnace. The furnace — which is a large oil-fired hood — raises the temperature to 1200 to 1300°C, which is sufficient to fire the carbon in the shale and cause the shale to expand and acquire a cellular structure.

The expanded clay or shale is allowed to cool and is then passed to a crushing and screening plant to be reduced to the normal sizes of aggregate, i.e. $\frac{3}{4}$ to $\frac{3}{8}$ in.

A typical chemical analysis of one sintered material is as follows:

Silica	56%
Aluminium oxide	31%
Iron oxide	5%
Magnesium oxide	0·3%
Sulphur trioxide	1·7%
Loss on ignition	1·4%

This material has a high absorption — 0·4 per cent — and a tendency to degradate slightly during mixing, but it is remarkable for its strength to weight ratio. It can be used as a structural aggregate and strengths above 5000 p.s.i. have been attained. It has a dry loose bulk density of about 35 lb/cubic ft. and a specific gravity of 1·40 to 1·80. Most of the sintered materials are available in three grades:

$\frac{3}{4}$ to $\frac{1}{2}$ in. — $2\frac{3}{4}$ yd^3/ton
$\frac{1}{2}$ to $\frac{3}{16}$ in. — $2\frac{1}{4}$ yd^3/ton
$\frac{3}{16}$ in. to dust — $1\frac{3}{4}$ yd^3/ton

The relation between density and strength of the resultant concrete is shown in Fig. 8.1. As with all lightweight materials the density increases with increasing strength.

Foamed Slag

Foamed slag is manufactured from the same material as heavy slag aggregate, the difference between the two materials being due to the method of cooling of the molten slag. To form heavy slag aggregate the molten slag is cooled slowly and uniformly, but to form foamed slag it is chilled rapidly to produce a porous structure.

Various techniques are used to achieve rapid cooling and foaming. Jets of water are combined with a stream of molten slag so that the slag is foamed and rapidly chilled whilst at the same time the finished material is free from excess water. As with heavy slag the main requirement is that it should be chemically stable. British Standard 877 gives limits for various impurities. With some processes of manufacture the slag may contain particles of iron, but these are removed by passing the material under a magnet when on its way to the stockpile.

Foamed slag aggregates are available in two sizes: coarse, approximately $\frac{1}{2}$ to $\frac{1}{8}$ in., and fine, $\frac{1}{8}$ in. down, or as an "all-in" $\frac{1}{2}$ in. down. The coarse material has a tendency to degradate during handling and in consequence the finer material is more readily available. The coarse material, however, is more desirable since for a given richness of mix a lighter, stronger and more workable concrete can be produced.

Foamed slag concrete is used for screedings to floors under granolithic and roof screeds. In addition, it has been used successfully for load-bearing walls in certain types of housing construction. Before mixing, the aggregate must be wetted down to prevent the high absorption reducing the workability during placing. If the aggregate is used dry the concrete stiffens after mixing and loses its plasticity.

Sintered Fly Ash

Fly ash is the modern equivalent of clinker or boiler ashes, and is produced by precipitating the fine dust carried out by the flue gases from boilers fired with pulverized coal. It can be used either as an aggregate or as a replacement for cement. In addition, if it is treated by pelleting and sintering it can be made into a lightweight aggregate. The ash is first pelleted with water by being rolled either in a plain tube mill or on an inclined tray. The pellets are then flash-dried to give them a hard exterior before being sintered. The sintering process, similar to that used to produce Portland cement, consists of heating the material to a high temperature, sufficient to cause the material to react and the physical changes to take place, but low enough to prevent fusion.

Fly ash contains between 5 and 15 per cent of carbon, and this can be burned to provide the necessary temperature for sintering. Little extra fuel is required to keep the process going once the carbon in the fly ash has been ignited. Combustion is maintained and the temperature controlled by a forced draught. Certain difficulties have occurred from time to time in producing a suitable round aggregate and at least one manufacturer has ceased production, but the amount of fly ash produced annually is of the order of 4 million tons so that its use as a lightweight aggregate can be expected on a continually increasing scale.

Vermiculite

Vermiculite is a lamellar material, similar to mica, chiefly used for its lightweight and insulating properties. In its natural state it is an alteration product of certain micas found in north and south America, South Africa, Australia and Japan. In the form as used it has been heat treated to expand it and has a density of 4 to 12 lb/cubic ft.

It exfoliates rapidly and extensively between 150 and 850°C, but to obtain the best product with the maximum toughness it is heated to between 650 and 850°C in either a rotary kiln or in a gravity-fed vertical kiln.

Vermiculite expands in a direction at right angles to the grain by about 15 times its original thickness. The expansion is caused by the pressure of the contained water when it is converted to steam.

Perlite, which is imported in small quantities from the Continent, is a silicious lava which, like vermiculite, can be expanded by heating. Its properties and uses are very similar to those of vermiculite.

Vermiculite and perlite, when expanded, have a vesicular structure which results in their low densities. Like other lightweight aggregates they are more porous and have a higher absorption than gravel aggregates. They are used for roofing screeds and underlay floor insulation. Where they are exposed to weather they need protection with a cement rendering.

Water

Water is one of the main constituents of concrete. It has various functions; it reacts with the cement powder, so causing it to set and harden, and it is a lubricating liquid which enables the concrete to be placed as a semi-fluid and so facilitates its compaction.

A quantity of water equivalent to about 25 per cent of the weight of cement reacts with the cement, but more water than this is required to facilitate placing and compacting. The ratio of water to cement usually varies between 0·35 and 1·0 depending upon the richness, i.e. the aggregate/cement ratio and the required strength of the concrete.

The water in excess of a water/cement ratio of 0·25 assists hydration, but it mostly causes voids and reduces the strength of the concrete. On drying, the removal of this water causes the concrete to shrink, and any soluble salts it contains crystallize in the pores and produce efflorescence and staining. Where it is important to prevent this, or where the protection of reinforcement from corrosion is important, water containing large quantities of soluble salts should not be used.

If water contains soluble organic matter or certain inorganic salts it may have an adverse effect on the cement during hydration; the increase in strength may be retarded or the final strength reduced. But if the water is fit for drinking it is suitable for mixing and curing.

In this country it is doubtful whether there is any justification for using anything other than water supplied for domestic purposes. In some situations, however, it is necessary to use sea water, and this contains soluble salts of which the most common are sodium and magnesium chloride and magnesium sulphate. The principal effect of these salts is to increase the early strength so that the 7-day strength is obtained at 3 days. The 28-day strength is usually not much affected.

Where such concrete is subject to damp conditions the salts in the concrete may go into solution and so provide a strong electrolyte for promoting corrosion of the steel reinforcement, whilst the magnesium sulphate may also attack the cement. Particular care should be taken, therefore, when using sea water for mixing, to ensure that a dense, well-compacted concrete is produced, with the minimum water content per cubic yard consistent with adequate workability.

Additives

It is expedient from time to time to change some of the properties of concrete by the addition of chemicals. Their use is seldom wholly beneficial to all the properties of concrete, so that although they improve some properties they may harmfully affect others; they are not forms of universal panacea and they should be used only when their full effect on all properties of the concrete is known. Certain additions may be made to cement by the manufacturer during the grinding of the clinker; these are principally calcium chloride in super-rapid hardening and cold weather cement, or various organic compounds used to produce hydrophobic or water-repellent cement or air-entraining agents.

Certain chemicals may be used to accelerate or retard the setting time and the rate of hardening. For example, for plugging leaks a very fast setting mortar is required; this may be achieved by mixing some high alumina cement with Portland cement (in equal proportions they will give a flash set) or by using a proprietary additive. The retarding of the set is required where it is intended to treat the concrete surface by brushing to expose the aggregate to obtain a textured finish; for this purpose the formwork may be coated with a proprietary chemical.

In general, the setting time is reduced when the rate of hardening is increased. Most accelerators are sulphate salts (except gypsum, calcium sulphate) or are alkali carbonates, aluminates and silicates; but the most common accelerator is calcium chloride. The common retarders are sugars, starches and various organic acids.

There are three main groups of additives:

(a) accelerators and retarders;
(b) workability and air-entraining agents;
(c) water-repelling materials.

In addition, fly ash is sometimes added to a mix either to replace some of the cement or to improve workability.

Accelerators

Calcium Chloride. One of the earliest and still the commonest chemical added to concrete is calcium chloride. It increases the rate at which heat is evolved during setting and hardening and increases the strength, so it is used in concreting in winter. It may be ground in with the cement during manufacture, or it may be added either as flake direct into the mixer or preferably by being first dissolved in the mixing water. Dissolving in the mixing water is more satisfactory for it ensures complete dispersal, but the extra trouble may not be warranted on a small job. Accelerating the rate of hardening reduces the setting time proportionally, and strengths are usually improved up to 7 days. In calculating the increase in strength it can be reckoned that the addition of 2 per cent of calcium chloride is equivalent to a temperature rise of 20°F. The effect is, therefore, marked at early ages and of little effect later (see Fig. 2.12).

The usually recommended proportions of calcium chloride are 2 per cent of the weight of cement, although apparently 4 per cent has been used in Russia in conjunction with 2 per cent sodium chloride and without any flash set, which according

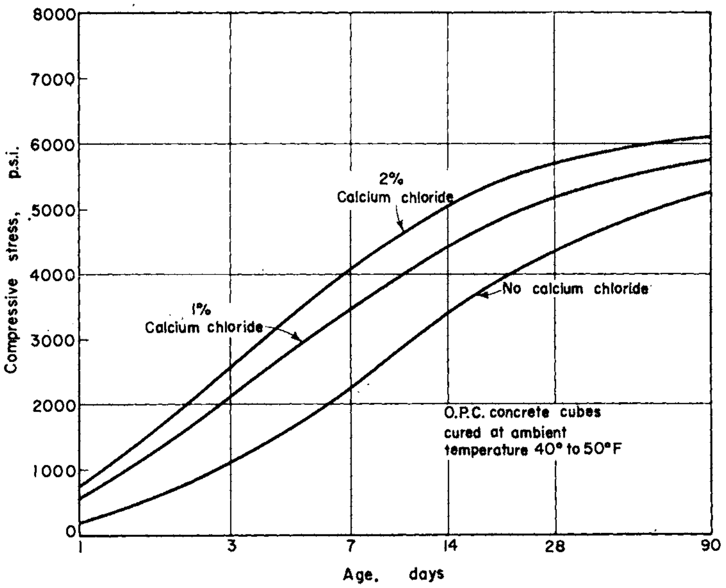


Fig. 2.12. Effect of calcium chloride on strength.

to Orchard (1958) may result if the calcium chloride is increased above 3 per cent. Early research, particularly of Abrams, demonstrated that there exists an optimum amount of calcium chloride which should be used with Portland cement. The figure of 2 per cent is close to this optimum but 4 per cent may be taken as the maximum for use under freezing conditions.

There is some disagreement as to the effect of calcium chloride on reinforcing steel, but the general opinion is that for good quality concrete well compacted in place, it has no effect, but that for poor quality concrete it may increase the rate of corrosion. Some initial corrosion occurs but does not continue with age even under damp conditions, since calcium chloride, like gypsum, ultimately combines with the aluminate in the cement. The optimum amount of calcium chloride recommended is limited by the amount that can chemically so combine. On the other hand for prestressed concrete calcium chloride should not be used; prestressing wires are prone to stress corrosion, a form of local corrosion which causes hair cracks to appear at the inter-crystalline faces. Concentrations of certain salts can facilitate the commencement of stress corrosion and calcium chloride is one of these salts.

Shideler (1952) has carried out work on the effect of calcium chloride on other properties of concrete. Expansion due to the alkali/cement-aggregate reaction is adversely affected and the resistance to sulphate attack is somewhat lowered. A further effect of calcium chloride is that it increases the workability slightly, but it has no effect on air entraining.

Other accelerators which have been used include sodium and potassium sulphates; these accelerate the hydration at a few hours, but the effect then falls off. Very rapid hydration within the first two hours is caused by the addition of sodium hydroxide.

Catalysts

The most common catalyst which has been advocated for use with Portland cement is triethanolmine. Like all catalysts its function is to promote a desired chemical reaction without itself being changed or consumed. The effect of triethanolmine is to increase the strength of cement not only at early ages (as does calcium chloride) but also at later ages. The effect is different in different cements, apparently being more effective with cements with a high tricalcium aluminate; unfortunately with some cements it can cause a flash set and a marked reduction in ultimate strength.

Retarders

Apart from calcium sulphate, most retarders are organic compounds or proprietary materials. Calcium sulphate (as gypsum or anhydrite) is added during the manufacture of cement to control the setting time, by retarding it. Gypsum combines with the aluminates to form sulpho-aluminate, but if too much is added then unsoundness is caused.

Some proprietary workability agents cause an increase in the setting time of about an hour, depending upon the mix proportions, when added in normal quantities (usually about 1 per cent or 1 lb/cwt). When added in excess, delays of up to 8 hours have been achieved even with a very rich mix in hot climates. Such materials are useful where it is necessary to cast a large block of concrete without construction joints and without fear of revibrating the set concrete.

In building works a number of proprietary materials are available which can be used where it is required to expose the aggregate. These materials are usually organic compounds. They are brushed on to the surface of the shuttering against which the concrete is to be placed to delay the skin-setting of the concrete. When the shutters are struck — usually next day for vertical shutters — the concrete surface is brushed to expose the aggregate.

The most common organic compound which delays the set is sugar. Excessive quantities may delay the set indefinitely, but small amounts have merely a retarding effect. They retard the set by delaying hydration; this causes a reduction in early strength, but this effect is not carried over to later ages; indeed, it appears that with very small quantities of sugar substantial increases in strength may be caused at later ages.

Corrosion Inhibitors

The corrosion of steel embedded in concrete takes place when the pH of the concrete is reduced appreciably below the normal figure of 11. The pH is kept at this figure by the presence of free uncombined lime, but the leaching action of waters containing CO_2 will remove it. This occurs quickly where the atmosphere is heavily charged with carbonic gases as, for example, in gas works.

The North Thames Gas Board (Lewis, Mason and Brereton, 1956) have patented a process for the use of sodium benzoate as a corrosion inhibitor to protect the steel in reinforced concrete. Sodium benzoate is a well-known inhibitor of corrosion; although it is less efficient than say sodium chromate it is safer to use. Sodium benzoate has been used in two ways: by dissolving 2 per cent with the cement in the mixing water, and by mixing 10 per cent with the cement to form a slurry. The cement slurry was then painted on to the reinforcement.

The addition of 2 per cent sodium benzoate reduces the compression strength of concrete of 5000 p.s.i. strength by 500 p.s.i., but has little effect on any other property. The sodium benzoate remains unchanged in the set concrete even after a number of years.

Workability and Air Entraining Agents

This group consists of a large number of complex organic materials — similar in that they usually increase the workability of the plastic concrete — and a number of mineral powders, such as lime, bentonite and diatomaceous earth, which when ground as fine as cement may be used as workability aids.

Surface Active Agents. The group of organic materials may be divided into dispersing agents, air-entraining agents and wetting agents, but cutting across these three groups is a general group of workability agents which may have some powers of dispersing, air-entraining and wetting. All these materials are termed surface-active agents because when dissolved in water they tend to concentrate at the boundary between the sand and cement particles and the water.

The function of dispersing agents is to prevent the flocculation of the very small particles of a powder and keep them in suspension. They find a use in many industries by preventing materials coagulating. In a cement-water mixture, dispersing agents cause the cement paste to be more liquid and to flow more easily.

A wetting agent, on the other hand, reduces the surface tension round a particle and so tends to make individual particles cohere, i.e. flocculate. Confusion arises because the use of too much dispersing agent can also cause flocculation. Confusion is worse confounded by the fact that some dispersing agents have slight air-entraining properties when added in large quantities, whilst some dispersing agents become wetting agents when their concentration in a mix is increased. To make the matter more difficult, both wetting and dispersing agents are contained in many commercial products, whilst with some products other chemicals, such as calcium chloride, are included to compensate for the retarding effect of the surface active agent, for nearly all of them are retarders.

The advantage of dispersing agents is that they reduce inter-particle attraction and hence make for more complete hydration of the cement and at the same time increase the fluidity of a cement paste by reacting on the cement particles. Air-entraining agents, however, and most so-called workability agents, react with the sand. Some additives are said to wet the cement more completely, but cement has an affinity for water and most wetting agents also entrain air, so it is difficult to say whether this really happens.

Nearly all the surface-active agents sold as workability agents or plasticizers are marketed under trade names. Many owe their effect to air entraining, but as this usually reduces strength, this fact is not often stressed. Nearly all of them are mixtures of dispersing, wetting and air-entraining agents, so that is impossible to disentangle one effect from another and no clear guide can be given as to which type should be used. By using certain products from reputable manufacturers, it is possible, however, to increase workability and effect an economy in the total cost, with little or no loss in strength.

Finely Divided Powders. Certain finely ground mineral powders are used as workability aids. Lime, bentonite, diatomaceous earth, kaolin and silica flour have all been used from time to time, whilst in the U.S. and on the Continent natural cement may also be used. Natural cement is made from a clayey limestone, but it is a more variable product than Portland cement.

These materials are all ground as fine as cement and function by increasing the amount of mortar. They are most useful in increasing the workability of harsh mixes, and may do so without it being necessary to add more water. For such mixes, they may help to prevent segregation and reduce bleeding. More usually, however, it is necessary to add more water so that the concrete strength will be reduced. The same amount of increased workability can often be produced by merely using the equivalent amount of cement.

The increase in fine material, which follows from the use of finely divided powder, generally results in increased drying shrinkage and moisture movement, but for harsh mixes which cannot be improved by altering the mix proportions, then there may be advantage in using such a powder.

Air-Entraining Agents. Most people will be familiar with air-entraining agents, for most detergents have air-entraining chemicals incorporated. This is a pity, because otherwise some detergents would be suitable as workability agents, but as air-entraining agents the same effect can be more cheaply achieved with other materials.

The early history of the use of entrained air in concrete is interesting; with the advent of fine grinding of cement, in the U.S.A., the existing cement grinding equipment became overtaxed and various grinding aids such as rosin were used. Rosin was an excellent grinding aid, but the strength of the resulting cement was low. In addition the leakage of oil in the old type of grinding units, like the Griffin mill, led to contamination of the cement with mineral oil. Such cements were condemned by many consumers.

Certain stretches of concrete roads on the eastern seaboard of the U.S.A., however, had excellent resistance to the deteriorating effects of freezing and thawing combined with the use of calcium chloride for removing ice. An investigation of the concrete showed that it had low density and was invariably associated with cement which had been contaminated by grinding aids or oil leakage. Further investigation showed that rosin and mineral oil caused a loss of strength, decreased the density, and entrained air. It was finally established that the entrained air increased the frost resistance, and led to reduced density and strength. The requirements for air-entraining agents are that they should incorporate a large number of small air bubbles which will be stable, have no tendency to coalesce or break down during compaction, and should incorporate the same amount of air with each mix, all other things being equal.

The air content of normal concrete after full compaction is usually about 2 to 3 per cent, whereas the optimum air content to give maximum resistance to freezing and thawing is about 5 to 7 per cent. Care is necessary to ensure that not too much air is entrained if strong concrete is required, because all air-entraining agents reduce the strength of concrete.

One of the earliest air-entraining agents was Vinsol resin, a by-product of the timber industry similar to rosin. The first available in this country was probably Teepol, but many others are now in use. Although some air-entraining agents have a cumulative effect when added together, some nullify each other, and so it is better to use only one agent and not mix different proprietary brands. Other materials used to entrain air include foaming agents and gas-generating agents such as aluminium or zinc powder. The amount of air incorporated by these materials may be as high as 60 per cent and they produce foamed or lightweight concrete; this, however, is a different material from air-entrained concrete (see page 300).

Factors Affecting Air Entrainment. Air-entraining agents react with the sand, or rather with that fraction between B.S. sieve No. 25 and No. 100. Coarse sand has little effect, but finer material such as that passing the No. 100 sieve, together with silt, dust and cement powder, all inhibit air entrainment. Cement has the same effect as any powder in reducing air entrainment, so that it is difficult to entrain air in rich mixes; lean mixes entrain more air than rich mixes. It also follows that the finer the cement is ground the less is the amount of air entrained. The effect of dust, as a coating on crushed aggregate such as limestone, is to reduce the amount of air entrained whilst not affecting the strength and only slightly affecting the workability.

The particle shape of the sand is of some importance. Well-rounded soft sands are more efficient at air entraining than angular, sharp sands. The percentage of sand in the mix between B.S. sieve No. 25 and 52 increases the amount of air entrained. The coarse aggregate does not have the same effect, but in general, the larger the aggregate the less the amount of air-entraining additive needed to give the same result.

Mixing time affects the amount of air entrained, too short a time reducing the amount, but as long as the mixing time is not decreased below 2 minutes there is little effect on the total amount of air. Mixing temperature has a slight effect, the higher the temperature the lower the result, but the effect is of secondary importance compared with those due to sand and cement. Fly ash (P.F.A.) has a marked effect on the amount of air entrained, depending upon the free carbon content. Fly ashes with only a moderate carbon content may double the amount of air-entraining agent required, so care must be taken when it is proposed to incorporate fly ash.

Prolonged vibration breaks down the air bubbles and reduces the amount of entrained air, particularly where large bubbles are formed as these appear to be less stable. It has been suggested (Orchard, 1958) that 50 per cent of the entrained air may be lost after vibration for 2½ minutes, but it is doubtful whether in normal concreting operation any one piece of concrete is continuously vibrated for this period, although the more intense vibration used in precast concrete can result in a reduction in the entrained air.

If air entrainment is used to provide better workability only, then the breakdown of the air bubbles during compaction is an advantage. In this country the frost resistant quality of concrete need not be so high as in the United States, so the reduction of air entrainment with vibration is not a serious problem.

In cold weather concreting, calcium chloride can be used with air-entrained concrete without any difficulty, for it has no effect on the air entrainment.

The Effects of Entrained Air on the Properties of Concrete. Air entrainment was first used to increase the frost resistance of concrete, and this effect is still one of its most important characteristics. But in this country the greatest virtue of air-entrained concrete is the ease with which it can be placed. Air entrainment improves the workability and is accompanied by less segregation and bleeding and results in a more homogeneous mix (see Fig. 2.13).

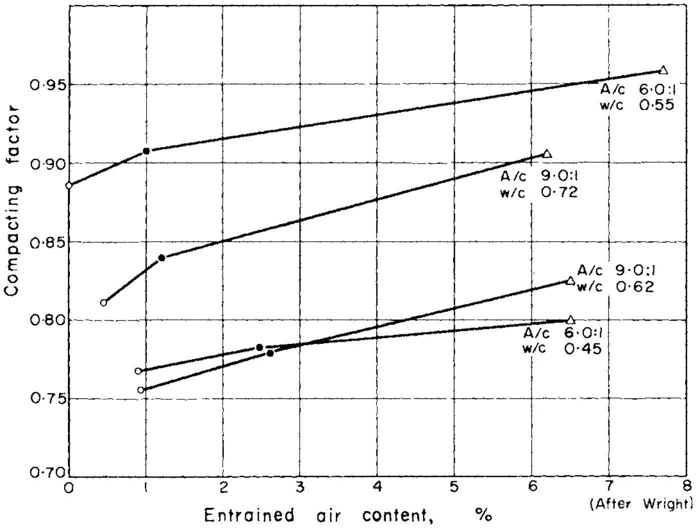


Fig. 2.13. Effect of air entrainment on workability (with 0, 0·01 and 0·03% resin).

The improvement in workability has not been satisfactorily explained but it may be imagined to be due to the lubrication of the fine aggregate by the cushioning effect of the air bubbles. By tending to separate the sand particles the air bubbles reduce particle interference. On the other hand it has been suggested that the air bubbles behave as particles of fine aggregate, which are elastic and have negligible surface friction. This would account for the oversanded appearance of a normal concrete mix in which air has been entrained, but it does not explain why a mix which appears oversanded should have a higher workability than one which contains less sand, whereas the contrary is usually the case. Air entrainment also makes a concrete more plastic, and generally improves its handling qualities.

The inclusion of air results in a loss of strength; for example, the inclusion of 6 per cent of air, whether due to poor compaction or to deliberate air entrainment, results in a reduction in strength of more than one-third (see Fig. 2.14). When an air-entraining agent is used to increase the workability then it may be necessary to compensate for the loss in strength, but since air entrainment produces a more fatty mix the amount of sand can be cut down and at the same time the amount of water can be reduced for the same workability. In this way the water/cement ratio is reduced to compensate for the loss of

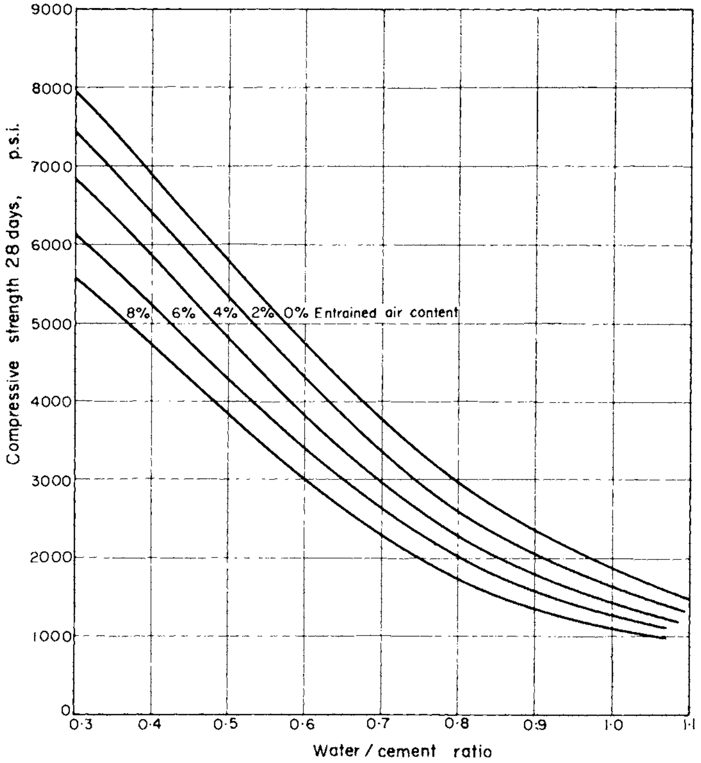


Fig. 2.14. Effect of air entrainment on compressive strength.

strength. Alternatively, a coarser sand can be used and the amount of water reduced whilst maintaining the same workability. These compensations for loss in strength can be enhanced by the addition of calcium chloride to achieve a higher early strength.

For lean mixes, for example 9:1 mixes, air entrainment results in a higher workability if designed to give the same strength as plain concrete; for mixes between 6:1 and 9:1 there is not very much difference; but for mixes richer than 6:1 the strength of air-entrained concrete is reduced if the workability is maintained the same as that of plain concrete.

Air entrainment, by making a mix more fatty, also reduces the dangers of bleeding and segregation. This improvement makes it possible to pump leaner mixes, and if the correct air-entraining agent is selected it is possible to arrange for the pumping action to break down some of the entrained air, so that the delivered concrete contains less air than originally and thus the reduction in strength due to the air-entraining agent is kept to a minimum.

Water-Repelling Materials

A number of materials are sold for increasing the water-repelling properties of concrete. These materials are usually described as waterproofing agents, but in fact no material is available as an admixture which can waterproof concrete. Some materials can make certain concretes repellent to moisture, but no material can make it impervious. Concrete of medium strength, well made and thoroughly compacted, has a permeability of 10^{-8} to 10^{-12} cm/sec, i.e. it is relatively impermeable in the same way as puddle clay is impermeable, but yet not impervious. To such concrete the addition of an integral waterproofing material is neither necessary nor advisable; unnecessary because the waterproofing material will not decrease the permeability, and inadvisable because other properties of the concrete such as the workability may be adversely affected. The concrete will, in any case, cost more.

On the other hand "waterproofing" agents still find a ready market and can be used with advantage where the concrete, because of either poor compaction, or workability, or lack of complete supervision, cannot be guaranteed to be sufficiently impervious.

Before the use of an additive can be recommended or condemned, the purpose for which it is to be used must be considered. There are two situations in which concrete is required to resist the penetration of water: one in basements and cellars where the water is under low or negligible head, and the second where the concrete forms part of a hydraulic structure and is required to hold back high heads of water. For the second case waterproofing additives are not recommended, although they may be useful in the first case to prevent the infiltration of moisture. The additives often used are discussed below. They do not include workability aids, but when considering how to make concrete more impermeable certain workability additives which do not entrain air, and hence do not decrease the concrete strength, may be used. These enable a leaner concrete to be placed with the same facility as a richer mix but without the disadvantage of extra shrinkage which results from a rich mix.

Rich concretes (3:1) are sometimes specified for water-retaining structures, but this is not the correct solution of the problem. Rich concrete shrinks more and has a greater moisture movement than lean concrete, whilst concrete richer than 6:1 does not have a much lower permeability and the density may be the same or even less. Concrete for a water-retaining structure should be a lean concrete, with high density, high workability and a low content of water per cubic yard of concrete. Most of these requirements are mutually incompatible and so it is not surprising that waterproofing agents find a ready market.

The controversy over the use of integral waterproofers probably centres round the effect of waterproofers in increasing the workability of the concrete and making it less liable to segregation in placing. In practice, the penetration of water often occurs at lean patches of concrete which result from faults in placing, such as poor compaction or poor bonding of new to old work. Such patches should not occur if the concrete is designed to suit the conditions of emplacement, but the addition of an inert filler or an organic soap may, with some materials, help to reduce the occurrence of honeycomb patches. The beneficial effect of integral waterproofers, in other than lean concrete, is due almost entirely to their effect as workability aids, but this effect can be achieved more efficiently by adding a workability agent and usually more cheaply, by re-proportioning of the concrete mix.

It would be no exaggeration to say that the design of an economic mix for structural water-retaining concrete involves the resolving of more mutually contradictory requirements than probably any other problem in concrete technology. If a concrete has a tendency to segregate or bleed, has poor workability, is too lean so as to be difficult to compact properly, or is too rich and produces shrinkage cracks, then it is unlikely to be waterproof. But in addition there is the problem of water absorption. Very few, if any, of the waterproofing or workability agents reduce the water absorption, although some of the soap admixtures, such as calcium stearate, or the various resin and organic oil compounds, are water repellent and do reduce capillary absorption.

Fine-Grained Pore Fillers. These fine-grained materials may achieve an improvement in lean concrete of poor workability by turning it into a more fatty mix at the expense of increasing the water content. They are usually divided into two classes, one of inactive materials and the other reactive materials.

Inactive Materials: Hydrated lime and chalk, clays (excluding bentonite), ground silica, talc and barium sulphate.

Reactive Materials: Bentonite, diatomaceous earths, alkaline silicates, such as sodium and potassium silicates, silico-fluorides and iron filings with ammonium chloride. These materials are chemically reactive although the action of bentonite and diatomaceous earths is more of a physical swelling of the materials; the same swelling action is achieved with iron filings by the rapid reaction with ammonium chloride which forms iron oxide.

Soaps. Various soaps are used as waterproofing agents. These are usually added as soluble soaps which react with the lime in the cement to form insoluble calcium soaps, but, of course, calcium soap may be added as calcium stearate. The reactive soaps are the alkaline soaps of soda, potash and ammonia. Usually 10 to 20 per cent fatty acid as stearate is present in the waterproofing agents. If obtained and used as chemical compounds then 0·2 per cent of soap by weight of the cement is the maximum recommended dosage. Frothing, with the consequent increase in air entrainment, may result if larger amounts are added. Soap may be added, mixed with hydrated lime; 5 to 10 per cent of fatty acid as stearate or oleate is mixed with hydrated lime and often a small amount of iron oxide. Soap may also be added mixed with calcium chloride and aluminium chloride. The effect of the calcium chloride is usually to offset the decrease of strength caused by the fatty acids.

Various Organic Materials. Besides soaps, various other organic compounds are often added. Many of these would on their own cause a decrease in strength of the concrete, so they are usually mixed with 20 to 40 per cent of calcium chloride. The organic materials used include resin, waxes, tar and bitumen, vegetable oils and fats and certain vinyl resins.

Pulverized Fuel Ash

The ash derived from pulverized fuel can be used as a concreting material, either to replace cement or as a fine aggregate.

Pulverized fuel used in many modern power stations is injected into furnaces as a suspension in air of very fine particles of coal. The ash resulting from burning consists of white glassy spheres derived from the burnt shale combined with some magnetite from iron pyrites and some unburned carbon. The carbon and magnetite give the pulverized fuel ash (fly ash) its characteristic grey colour.

The ash passes through the boiler with the flue gases and is trapped and collected by means of electrostatic precipitators. The glassy nature of the burned shale gives fly ash a chemical composition similar to other pozzolanic materials, the silica combining with the lime to give a cementing reaction.

The chemical composition of fuel ash may vary according to the nature of the coal being burned, but since many power stations burn a mixed fuel there may not be a very wide variation; on the other hand the carbon content will vary appreciably according to the type and operating conditions of the boiler. The following analysis gives the variation in composition of typical fly ash.

Silica SiO_2	38 –45%
Alumina Al_2O_3	20 –26%
Iron oxide Fe_2O_3	7 –16%
Sulphur trioxide SO_3	0·1– 2·0%
Carbon content	5 –15%

Fly ash is a fine-grained powder approaching or even exceeding the fineness of Portland cement. Its cementitious value increases as its fineness increases, the finely divided silica combining more readily with the free lime in the cement.

Fly ash results in economy when it is used as a cement replacement, and it is possible to replace up to 25 per cent of the cement by fly ash. Used in this way the heat of hydration of the cement is spread over a much longer period, so that in large masses a lower temperature is generated. By combination with the free lime the general resistance of the concrete to deterioration is increased. The shrinkage is usually reduced and the workability may be increased, although occasionally adverse effects are caused.

Fly ash may also be used, in combination with a coarse sand or gap-graded aggregate, as an aggregate to correct a grading or reduce the harshness of a mix.

The supply and marketing of fly ash is in an experimental stage and various methods are being developed. It appears, however, that apart from its use as a raw material for the manufacture of a sintered aggregate it will generally be available either ground in with an otherwise ordinary Portland cement or will be supplied in bulk in a dampened condition. Perfectly dry fly ash is difficult to handle on the site unless treated in the same manner as cement, and this, because of the need for separate silos, increases the cost. But dampened fly ash is readily handled by methods appropriate to damp sand. In such a condition it mixes readily, in a mixer, without balling or sticking. In a stockpile, however, the material can be a nuisance on a hot windy day, being readily blown about the site.

Effect of Fly Ash on the Properties of Concrete. Fly ash has certain general effects on concrete when included in quantities up to 25 per cent, but these may be altered or reversed in any particular circumstances depending upon the qualities of the fly ash under consideration.

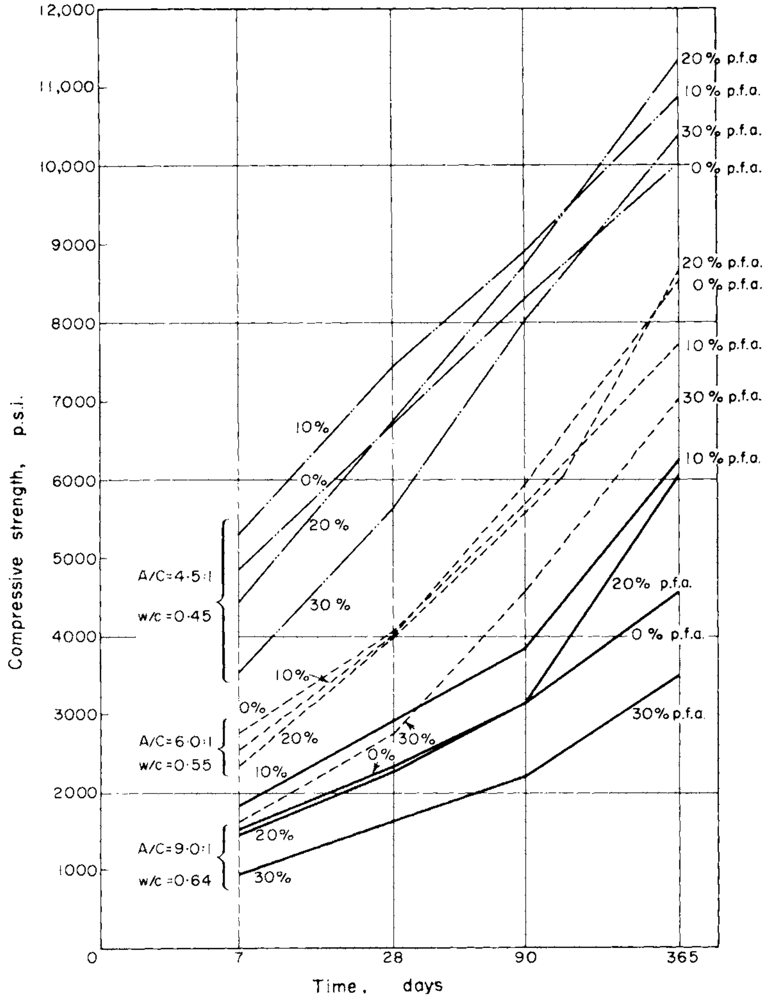


Fig. 2.15. Increase in strength with time for O.P. cement with various amounts of fly ash.

The substitution of more than 10 per cent fly ash for cement reduces the 7- and 28-day strengths. At an age of 3 months, however, much of this "lost" strength is regained, and at about 12 months the strength may be equal to, or greater than, that of normal concrete without fly ash. Intergrinding of the fly ash appears to increase the rate of gain of strength in the early stages (see Fig. 2.15 and 2.16).

The use of fly ash as a cement replacement may result in a

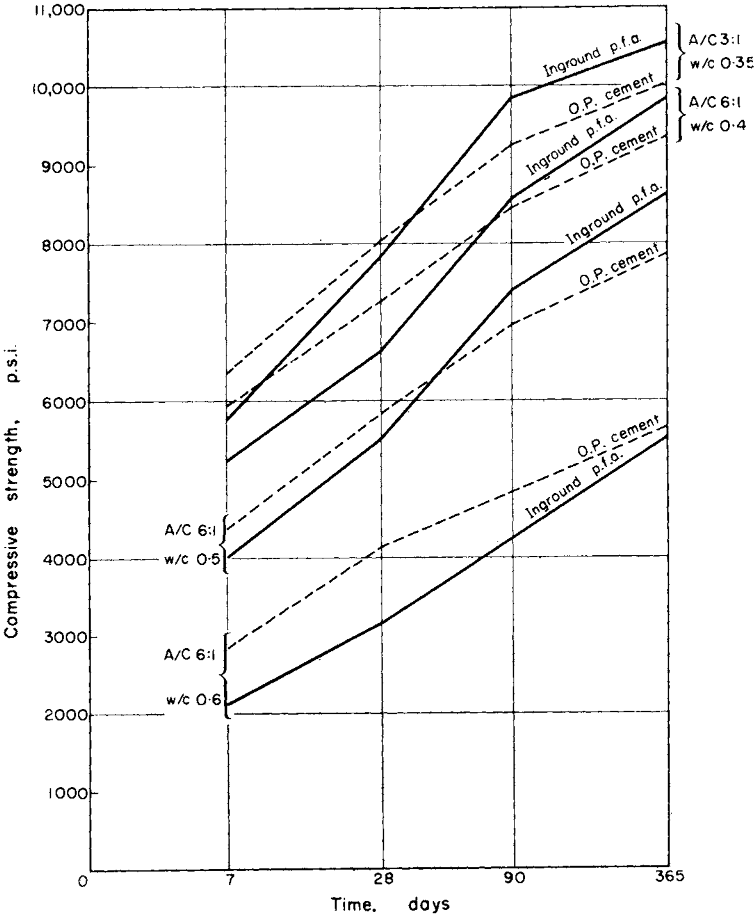


Fig. 2.16. Relationship of strength with time for O.P. cement and an O.P. cement with 20% fly ash inground.

small increase in the water requirement per cubic yard of concrete to achieve the same workability, although in any particular case this effect may be reversed, depending entirely upon the fineness of the fly ash. The use of fly ash as a sand replacement results in a greater strength than would otherwise be the case, due to the silica-lime reaction between the cement and fly ash. In addition, if used to compensate for a lack of fines in the sand there will be a reduction in the harshness of the mixed concrete and in the tendency towards bleeding and segregation. Fly ashes of low carbon content usually reduce the moisture movement and initial drying shrinkage, but this depends upon the carbon content. Fly ashes with high carbon content cause reversals of this effect and when used with an air-entraining agent result in very much larger quantities of the agent being required to achieve the same amount of entrained air.

In its effect on reducing the amount of entrained air, fly ash may be said to reduce the frost resistance of concrete. Its effect on the frost resistance of non-air-entrained concrete is not particularly significant. It causes a reduction in strength at early ages when used as a cement replacement, so that the frost resistance at early ages may be less, but by forming cementitious compounds it gradually causes a decrease in permeability so that its frost resistance at greater ages may be more than that of an equivalent ordinary concrete; the evidence at present, however, is inconclusive.

The total heat of hydration in a concrete containing fly ash as a cement replacement is not much different from that of a similar concrete without fly ash, but the rate of heat evolution of the fly-ash concrete is much less. In consequence the temperature gradients in a large mass are less, with a consequent reduction in temperature stresses. In a concrete in which fly ash is used as an aggregate, the heat of hydration will, of course, be proportionally increased.

Fly ash incorporated in Portland cement concrete increases its resistance to sulphate attack, for by reacting with the lime it reduces the amount of free lime liable to attack.

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CHAPTER 3

MIX DESIGN

Mix design is the proportioning of the various constituents of concrete to produce the desired properties in both the plastic and hardened states. The factors involved are the conditions of placing and the workability required for these conditions, the properties of the aggregates, the type of cement, any special considerations requiring a high or low aggregate/cement ratio, together with the required strength, density and shrinkage of the hardened concrete. The variations in these factors can result in concrete as different as a honeycombed no-fines concrete, a structural concrete of 8000 p.s.i. or a concrete for radiation shielding with a density of 220 lb/cubic ft.

This chapter deals with the proportioning of concretes with strength in excess of 1000 p.s.i. and densities of about 140 to 155 lb/cubic ft. Other concretes such as gap-graded, lightweight and dry-lean concretes are described in Chapter 8.

For structural concrete there are two properties which are more important than all the others: strength and workability. These properties are independent but related; the strength depends upon the type of cement and the water/cement ratio, whilst the workability depends upon the type of aggregate and its grading. Workability, however, is also dependent upon the aggregate/cement ratio and upon the total amount of water per cubic yard of concrete and so is influenced by the water/cement ratio.

The required strength of a concrete is specified from the requirements of structural design. Since the strength is more or less proportional to the water/cement ratio, then the latter can be assessed from data, such as Fig. 3.1. The difficulty in mix design arises in specifying the aggregate/cement ratio and the sizes and relative quantities of the coarse and fine aggregates; since all these factors affect the workability, the ease of handling

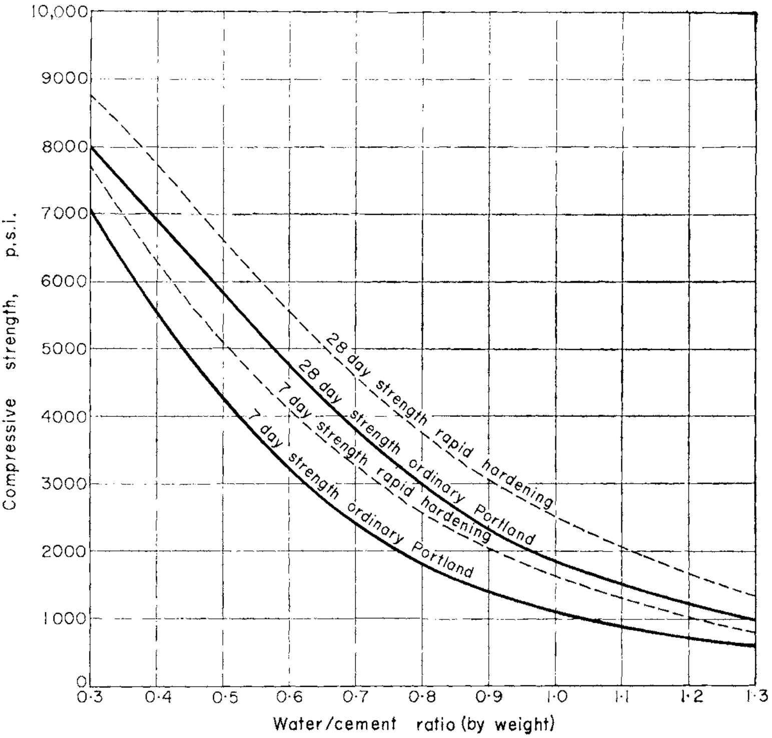


Fig. 3.1. W/c ratio strength curve.

of the wet concrete, and the density and shrinkage and to some extent the compressive strength of the set concrete, then the properties in both the plastic and hardened states must be considered. These difficulties have been overcome in a number of different methods of mix design. The following are the main ones.

Nominal mix proportions: the ratio of cement, sand and coarse aggregate may be specified by weight or volume in proportions, for example 1:2:4 or 1:3:6. This method controls the cement content and the ratio of fine to coarse aggregates. It is sometimes augmented by the specification of the water/cement ratio or of a slump.

Minimum strength. As a reaction to nominal mix proportioning a method of mix design based on strength only was adopted.

For normal reinforced concrete buildings, such a method was adequate if linked with a specification for slump and with control of the aggregate grading, particularly the sand. In mix proportioning, the sand fraction is important although the general realization of this importance is quite recent. The 1944 revision of the B.S.882 "Concrete Aggregates and Building Sands from Natural Sources" introduced two classes of sand, Class A having fairly narrow grading limits and Class B much wider limits. Class B material came to be regarded as inferior and consequently many specifications demanded the use of Class A sand, irrespective of whether supplies were readily available or whether it should be used for the particular concrete.

Following work by Newman and Teychenné, B.S.882 was revised. The revision was based upon four grading zones into which it was found that naturally occurring sands fall. None of the grading zones is superior to any other; all are suitable for making good concrete because the quality of the concrete depends upon the mix proportions. Their use, however, has meant that more care must be given to mix proportioning to produce concrete with the necessary strength and workability.

Strength and Workability. The main methods of mix proportioning in this country are based upon designing a mix to produce a concrete with a minimum strength and a required workability. The required strength is obtained by fixing the water/cement ratio and the required workability by fixing the ratio of aggregate to cement, the maximum size of coarse aggregate, and the overall grading of the coarse and fine aggregates. The aggregate/cement ratio and aggregate gradings may be determined by reference to published tables (Road Note 4 method) or by reference to graphs and tables linking the total surface area of the aggregates with the cement content (specific surface and fineness modulus methods).

Nominal mixes

Nominal mixes have played — and still play — an important part in the specification of concrete. They are specified as 1:1:2, 1:1½:3, 1:2:4, 1:3:6 and 1:4:8, these being the proportions respectively of cement, sand and coarse aggregates.

The richer mixes (1:1:2 or 1:1:3) are specified when strong concrete is required, and the leaner mixes for weaker concrete.

It has been suggested that nominal mixes were specified with little regard for strength, but this is not so. They came into use with the growth of empirical knowledge of concrete, for it was found that if concrete was mixed with sufficient water to make it plastic and easy to handle then it could be expected to achieve the required strength. The strength was not very high considering the richness of the mixes, those for ordinary Portland cement being, roughly, as follows:

1:1:2	4250 p.s.i.
1:1½:3	3750 p.s.i.
1:2:4	3000 p.s.i.

but they could be relied upon as long as the aggregates used were sound, it being virtually impossible to add too much water and at the same time maintain a plastic mix which could be barrowed and shovelled into place. The use of a nominal mix results in a wastage of materials, for only part of the potential strength of the concrete is utilized and yet undesirable properties such as excessive shrinkage might result.

Nominal mix proportions continue to be specified and in addition, to ensure some control of the strength, the water/cement ratio is usually specified; but specifying both the water/cement ratio and the aggregate/cement ratio controls the workability and may result in concrete with poor characteristics. It may be harsh, unworkable or subject to segregation or bleeding depending upon the grading and particle shape of the aggregates and the relation of the water/cement ratio to the aggregate/cement ratio.

In an endeavour to overcome some of these difficulties both the aggregate gradings and the required workability are specified. But the water/cement ratio, aggregate/cement ratio, aggregate grading and workability are all inter-related in a most complex fashion. It is only possible to specify three of the four variables, and only then if the characteristics of the cement and aggregates are known from previous experience.

Nominal mix proportions are still a suitable method of proportioning concrete for small jobs as long as the concrete is mixed with only sufficient water to produce a plastic, workable mix. For large jobs and for high-quality concrete this method has been abandoned.

Mix proportioning based on strength and workability

As previously mentioned the methods of mix proportioning for structural concrete are based on the relation between strength and water/cement ratio, and on the relation between aggregate/cement ratio, water/cement ratio and workability.

Starting with the requirements of a minimum site strength, a required workability for the conditions of placing, and a certain aggregate, there are half a dozen basic steps in mix design.

(1) First the target or design strength is decided which, with the standard of quality control to be used, will give the required minimum site strength.
(2) From the design strength a water/cement ratio is determined.
(3) From the known conditions of placing the required workability is assessed.
(4) With the known water/cement ratio and the required workability a range of aggregate/cement ratios is determined.
(5) One aggregate/cement ratio is selected which
    (a) is the most economical,
    (b) is particularly suited to the type of work,
    (c) is easily produced with the aggregates to be used.
(6) The fine and coarse aggregate are proportioned to produce the most suitable combined grading. The quantities of coarse and fine aggregate, cement and water are then determined by weight.

Strength

In designing the proportions of a mix the first step is to determine the design strength required to ensure that the minimum site strength will be achieved. The difference between the design strength and the minimum site strength will depend upon the degree of quality control to be exercised. Concrete can be proportioned only to give average values of strength, and a margin must be added to the required minimum strength to obtain the design strength; this margin may be 750 to 2000 p.s.i. and depends upon the site conditions, the degree of control and supervision and the required minimum strength.

As a first approximation, the following are suggested as design strengths appropriate to various degrees of control for different minimum site strengths.

Degree of control	Required minimum site strength at 28 days p.s.i.			
	1500	3000	4500	6000
Good	2250	4000	5750	7500
Fair	2500	4500	6500	8000
Poor	3000	5000	*	*

* These minimum strengths should not be attempted with poor control.

Water/Cement Ratio. The required water/cement ratio to produce the target or design strength depends upon the characteristics of the cement. With the same water/cement ratio, different strengths are produced by ordinary Portland, rapid hardening Portland and high alumina cements.

The water/cement ratios for these different cements are determined from Fig. 3.1 and 3.16. The mix design for high alumina cement is basically the same as for ordinary Portland, but is described separately on page 159.

Rapid hardening cement is used, in place of ordinary Portland cement, where high early strength is required. It gives, at 1 and 3 days, that strength to be expected from ordinary Portland at 3 and 7 days respectively.

Workability

The required workability of the concrete must next be determined to suit the placing conditions, type of construction and method of compaction. Concrete to be placed in a heavily reinforced beam must be more workable than concrete in massive construction. On the other hand concrete which will compact by heavy internal vibrators can be less workable than where thin poker vibrators are to be used or where some peculiarity of the work restricts compaction to hand tamping.

Suggested workabilities for various placing conditions are given below.

The various slumps, compaction factors and VB values quoted cannot be taken as the equivalent of each other, as is shown by the following values for a 1:5·5 by weight concrete using Thames Valley aggregates.

	Workability	Slump (in.)	Compacting factor	VB
Precast section (intense vibration)	Extremely low	0	0·70	above 10
Road slabs (power operated machines)	Very low	0 to 1	0·78	8–10
Road slabs (tamping screed and internal vibrators); mass foundations	Low	1 to 2	0·85	7– 8
Normal structural concrete (internal vibrators, simple sections)	Medium	2 to 4	0·85 to 0·9	5– 6
Ditto (heavily reinforced sections, internal vibrators)	High	4 to 5	0·92 to 0·95	2
Unvibrated concrete	Very high	6	0·95	1

The relation between water/cement ratio and strength shown in Fig. 3.1 is approximate because strength is related to the ratio of cement to water plus voids, with the result that if the workability is low a somewhat higher strength is achieved but if workability is high a lower strength is obtained.

Mix 1:1·9:3·6 with Thames Valley Aggregates
(water/cement ratio on saturated surface dry basis)

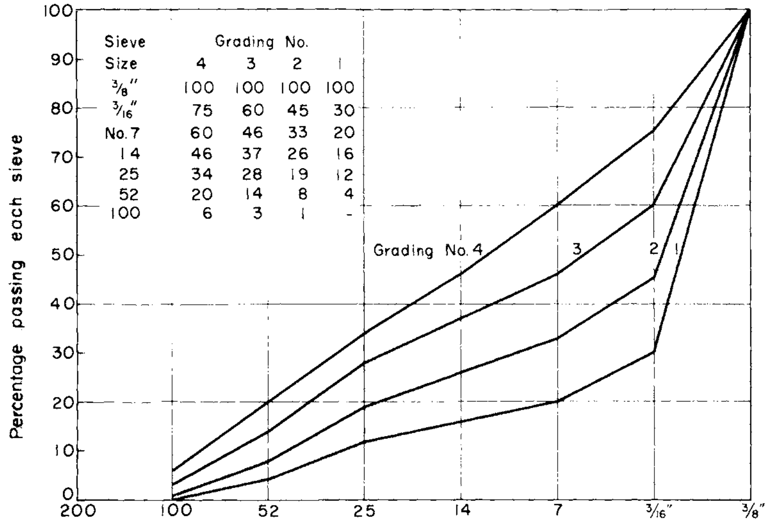
Water/cement ratio	Slump (in.)	Compacting factor	VB (sec)
0·300	Nil	0·699	Above
0·350	Nil	0·745	30
0·380	Nil	0·773	19·0
0·408	Nil	0·810	10·5
0·446	¾	0·8385	7·5
0·489	1½	0·884	5·0
0·524	2¼	0·912	3·0
0·591	4½	0·947	2·0
0·705	2	0·979	0·5

Aggregate/Cement Ratio

Having determined the water/cement ratio to produce the required strength, the aggregate/cement ratio has next to be decided and the fine to coarse material proportioned. The difficulty in deciding upon these proportions lies in knowing what the resulting workability will be.

Workability, or some measure of it, such as the compacting factor or the VB time, varies with the aggregate/cement ratio, the angularity of the aggregate, the water/cement ratio and the grading of the combined coarse and fine aggregates. Apart from the aggregate grading all the other factors can be expressed as a numerical value. For example, the angularity may vary from 1·1 to 2·6, the water/cement ratio from 0·35 to 1·0 depending upon the required strength, the aggregate/cement ratio from 2:1 to say 18:1, but the grading of the aggregate is a curve and a curve cannot easily be given a numerical value.

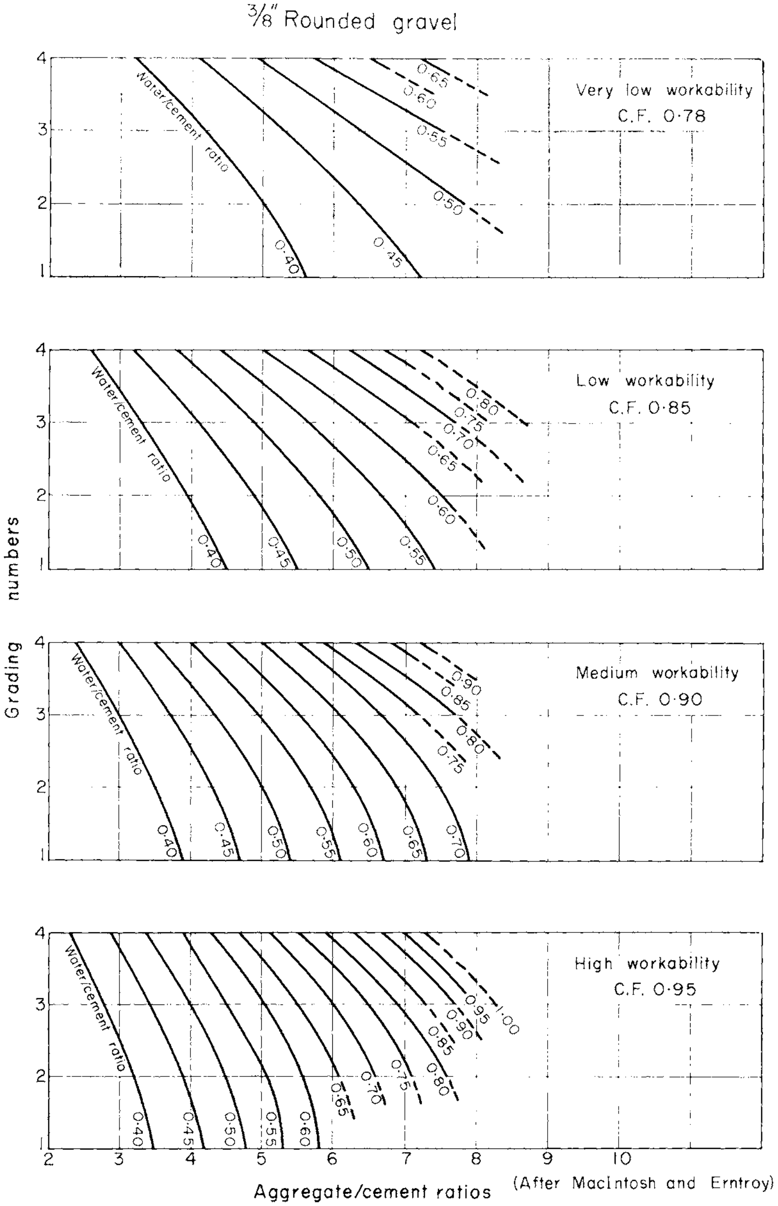
This has been solved in two ways; first the properties of concrete mixes with certain aggregates have been determined as, for example, the workability of concrete made from flint aggregate with different gradings and with different aggregate/cement ratios. The results of tests on these concretes have been tabulated so that by selecting a required workability a suitable aggregate/cement ratio can be determined, or alternatively the workability can be determined for a given ratio of aggregate to cement. This is commonly known as the Road Note 4 method, from the fact that the first basic tables were published in this country in Road Note 4 by the Road Research Laboratory. Alternatively the combined grading curve may be reduced to a numerical value in terms of specific surface or fineness modulus, and then the workability can be linked mathematically by an equation or graphically by a series of curves to the aggregate/cement ratio, the water/cement ratio and the angularity. These are the specific surface and surface factor methods.



Sieve Size	Grading No. 4	3	2	1
3/8"	100	100	100	100
3/16"	75	60	45	30
No. 7	60	46	33	20
14	46	37	26	16
25	34	28	19	12
52	20	14	8	4
100	6	3	1	-

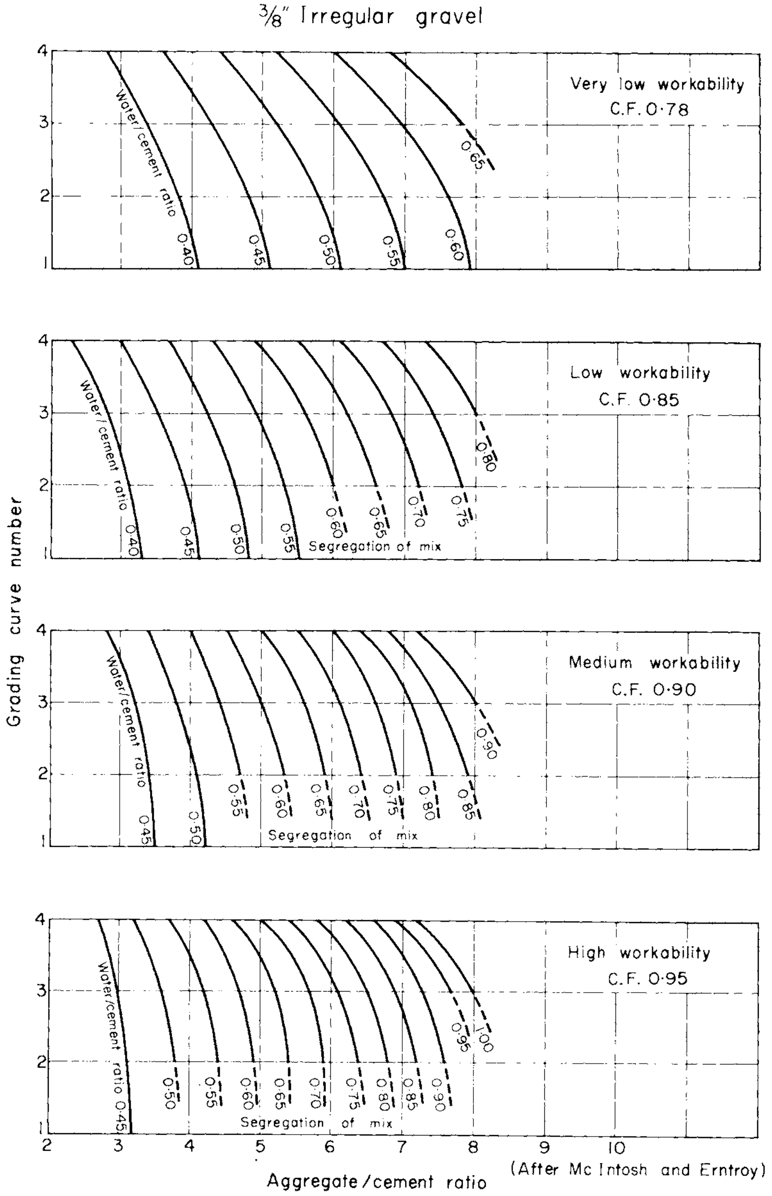
Fig. 3.2. Grading curves for $\frac{3}{8}$ in. aggregate for workability curves.

Road Note 4 *Method.* Having determined the design strength and the corresponding water/cement ratio, the approximate proportion of aggregate to cement is determined from Fig. 3.3 to 3.11 by reference to the required workability and water/cement ratio for the particular aggregate and grading which it



(After MacIntosh and Erntroy)

Fig. 3.3. Workability curves for Portland cement with $\frac{3}{8}$ in. rounded gravel.



(After Mc Intosh and Erntroy)

Fig. 3.4. Workability curves for Portland cement with $\frac{3}{8}$ in. irregular gravel.

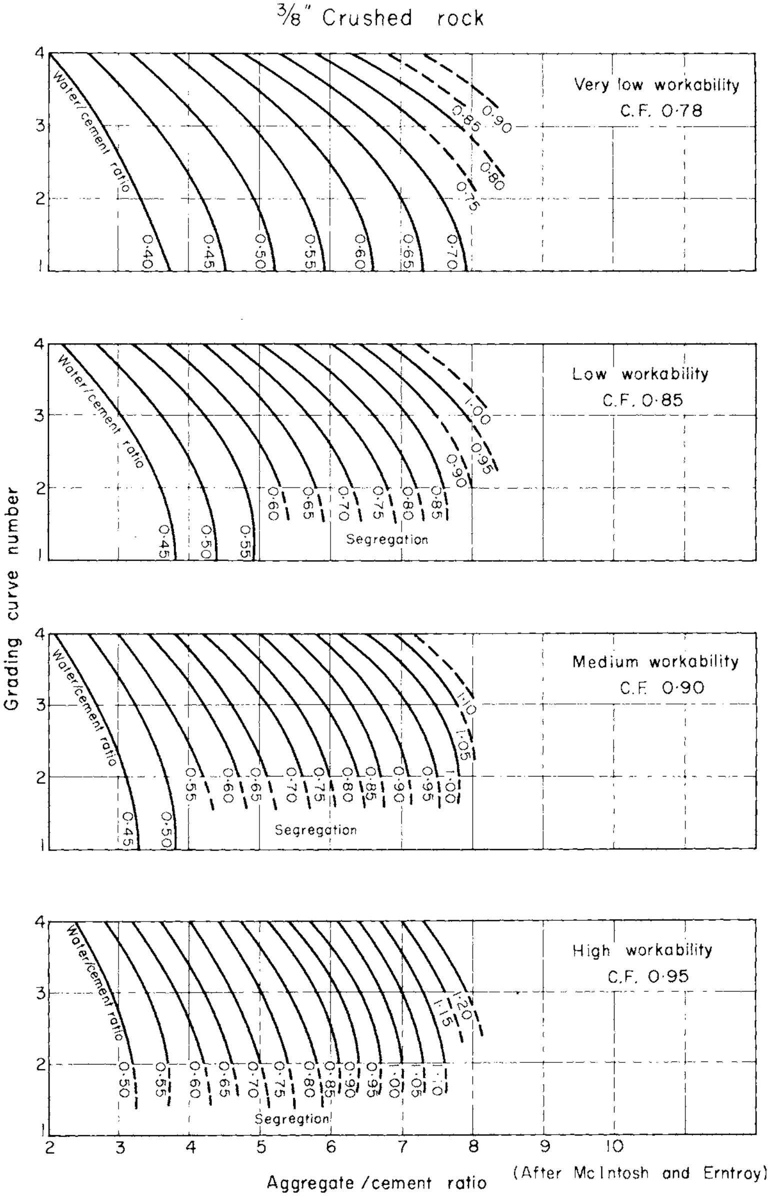
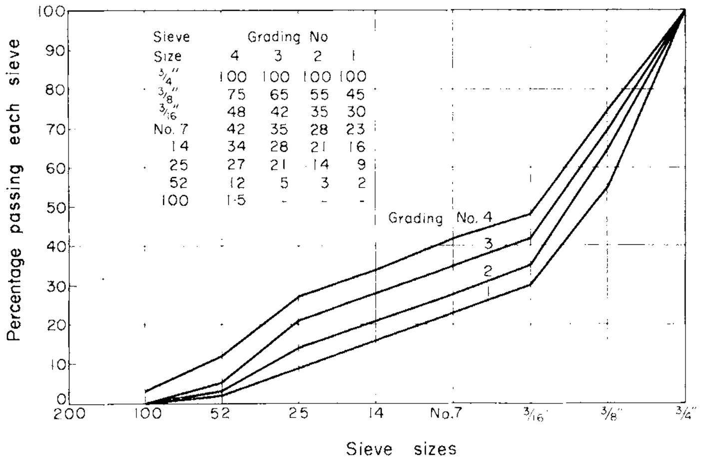


Fig. 3.5. Workability curves for Portland cement with $\frac{3}{8}$ in. crushed rock.



Sieve Size	Grading No 4	3	2	1
$\frac{3}{4}''$	100	100	100	100
$\frac{3}{8}''$	75	65	55	45
$\frac{3}{16}''$	48	42	35	30
No. 7	42	35	28	23
14	34	28	21	16
25	27	21	14	9
52	12	5	3	2
100	1·5	-	-	-

Fig. 3.6. Grading curves for $\frac{3}{4}$ in. aggregate for workability curves.

is proposed to use. The graphs are based on type gradings (see Fig. 3.2, 3.6 and 3.10) in which the amount of sand to coarse aggregate varies according to the maximum size of aggregate:

percentage of sand	*size of coarse aggregate*
30–75	$\frac{3}{8}$ in.
30–50	$\frac{3}{4}$ in.
25–50	$1\frac{1}{2}$ in.

If the aggregate it is proposed to use conforms with one of these gradings, then the workability will be similar to that given in Fig. 3.3 to 3.11. If not, then the coarse and fine aggregates must be combined so as to produce one of these gradings.

Combination of Coarse and Fine Aggregates. To produce one of the type grading curves the coarse aggregate and sand are combined in varying proportions depending upon the respective grading of these materials. A grading curve for coarse aggregate is expressed as the cumulative percentage of material passing the different size sieves; for example, 100 per cent passing $1\frac{1}{2}$ in. down to say 10 per cent passing $\frac{3}{16}$ in. sieve. This is to be combined with a grading of sand of say 100 per cent passing $\frac{3}{16}$ in. down to 5 per cent passing a No. 100. The

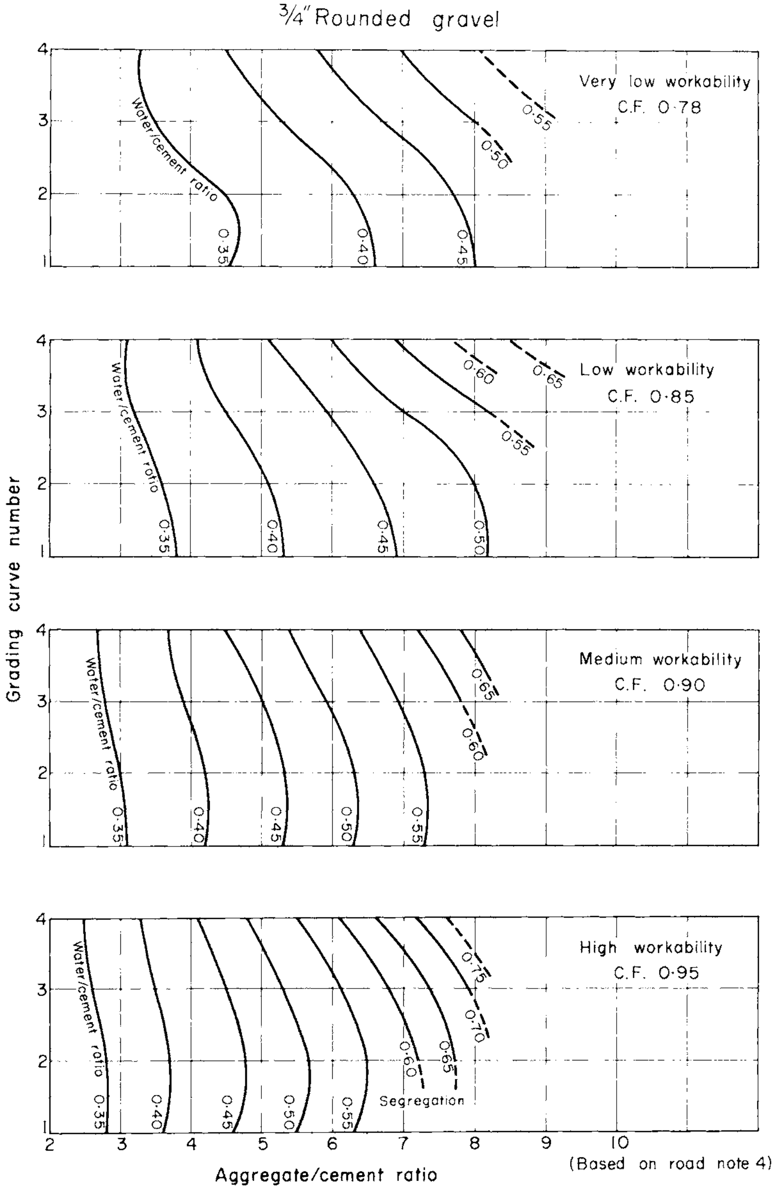
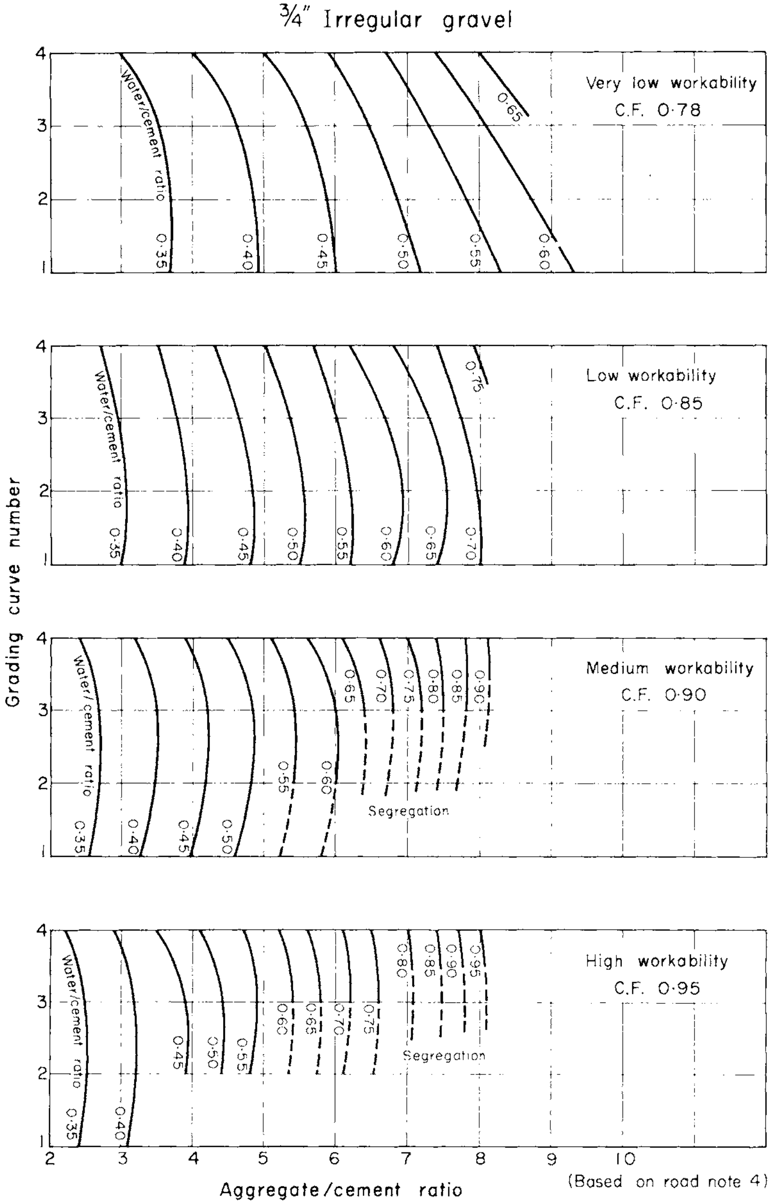
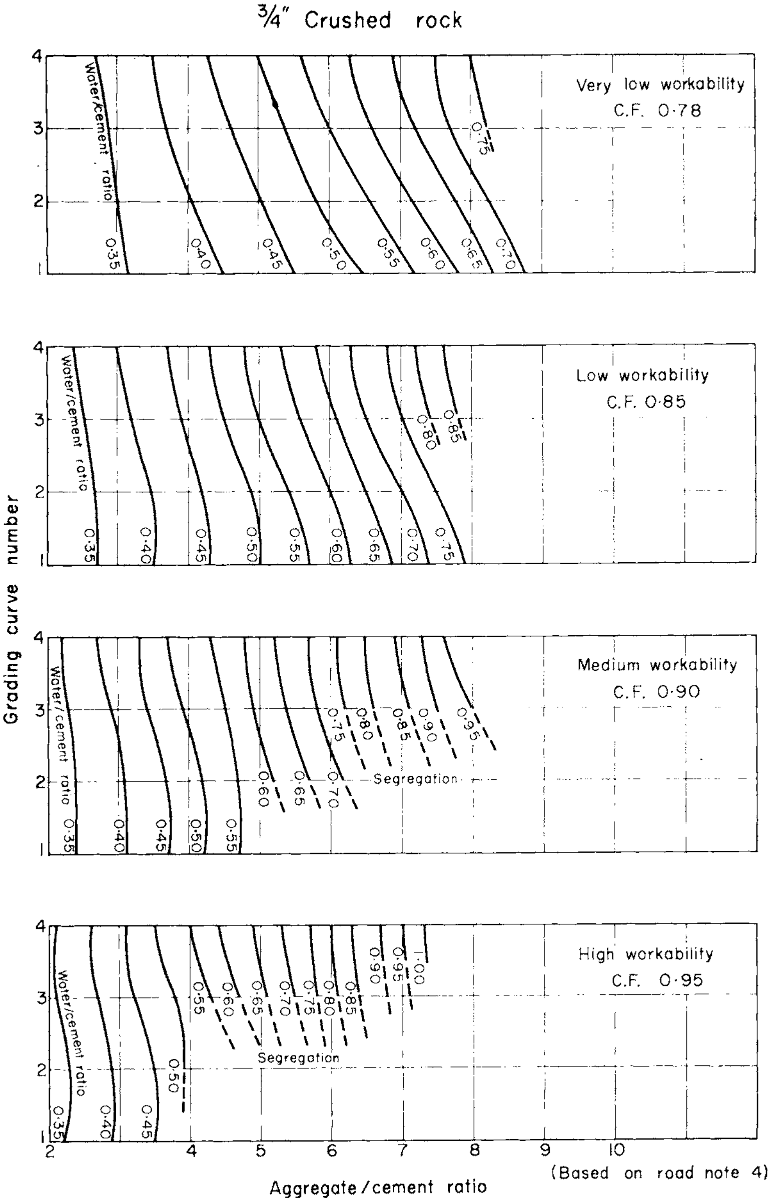


Fig. 3.7. Workability curves for Portland cement with ¾ in. rounded gravel.



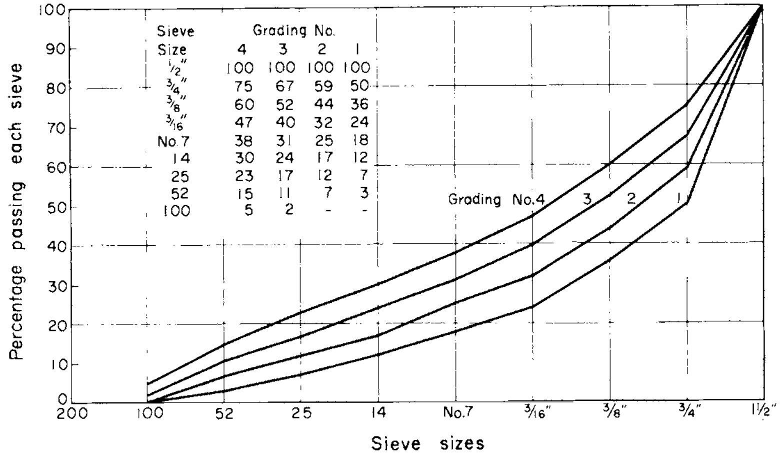
(Based on road note 4)

Fig. 3.8. **Workability curves for Portland cement with ¾ in. irregular gravel.**



(Based on road note 4)

Fig. 3.9. Workability curves for Portland cement with ¾ in. crushed rock.



Sieve Size	Grading No. 4	3	2	1
1½"	100	100	100	100
3/4"	75	67	59	50
3/8"	60	52	44	36
3/16"	47	40	32	24
No. 7	38	31	25	18
14	30	24	17	12
25	23	17	12	7
52	15	11	7	3
100	5	2	-	-

Fig. 3.10. Grading curves for 1½ in. aggregate for workability curves.

proportioning can be done mathematically but it is more simple to do it graphically, as follows.

Mark out a scale running from 0 to 100 across the bottom of a piece of graph paper, and mark out vertical scales, again running from 0 to 100, at each end (see Example 1, page 150, Fig. 3.16). Mark off on the vertical scales the sieve sizes at the points corresponding to the percentage of material passing them, coarse aggregate on the left, fine aggregate on the right, and then join by lines those points representing common sieve sizes. From all points on the left-hand side (coarse aggregate) for sieve sizes larger than $\frac{3}{16}$ in. join to the top right-hand corner, for all points on the right-hand side smaller than No. 7 join to the bottom left-hand corner.

Any vertical line will represent the proportion of fine to coarse aggregate, and the amount passing the various sieve sizes can be read off and checked against the type grading so as to give the desired proportion.

It may happen that the sand will not give exactly any of the type gradings and the resulting curve will cut across two or three of them. The aggregate/cement ratio will then have to be amended to compensate for the way in which the proposed aggregates differ from those upon which the graphs were based.

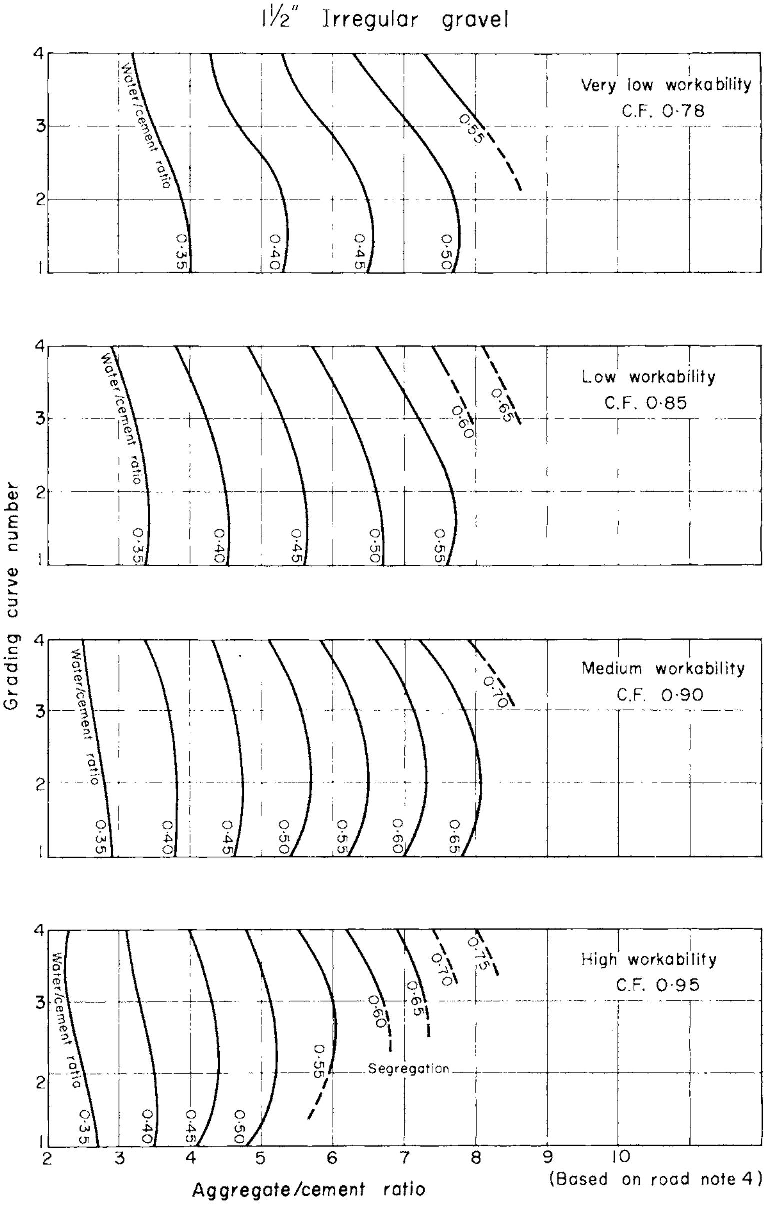


Fig. 3.11. Workability curves for Portland cement with 1½ in. irregular gravel.

This is because the relation between aggregate/cement ratio and workability is affected by:

(i) the overall grading, i.e. the grading of the coarse and fine aggregates and the ratio of coarse to fine;
(ii) the aggregate particle shape and the surface texture;
(iii) variations in the specific gravity of the aggregates when the aggregate/cement ratio is specified, in the usual way, by weight.

Aggregates with very different overall gradings can and often are used to produce concrete of all types with various workabilities and strengths. Knowledge of the workability and aggregate/cement ratios for such concretes depends directly upon previous experience or upon the carrying out of a number of trial mixes with the proposed aggregates, but the following points may be of help.

If the grading is finer than the type gradings, the mix is probably over-sanded and may be too sticky so that it will hang up in the mixer and skips. If the grading is coarser than the type gradings it may be harsh, under-sanded, and prone to bleeding and difficult to compact without causing segregation. A mix containing single-sized large aggregate but with a sand grading close to one of the type gradings will be subject to segregation.

Fuller and Thompson's Ideal Curve. The type gradings given in Fig. 3.10 are similar to a curve propounded by Fuller and Thompson which was based on the assumption that to achieve maximum density and hence maximum strength, the grading must be such as to ensure that the voids between the larger stones are filled with smaller stones and mortar, since voids in the concrete reduce the strength considerably.

A curve (Fig. 3.12) was derived whose equation is given by

$$p = 100 \sqrt{(d/D)}$$

where p = percentage of material smaller than size d
D = maximum particle size

This curve is based on the assumption that the aggregate is specially and carefully packed to achieve maximum density, and the effect of particle interference is ignored. If particle

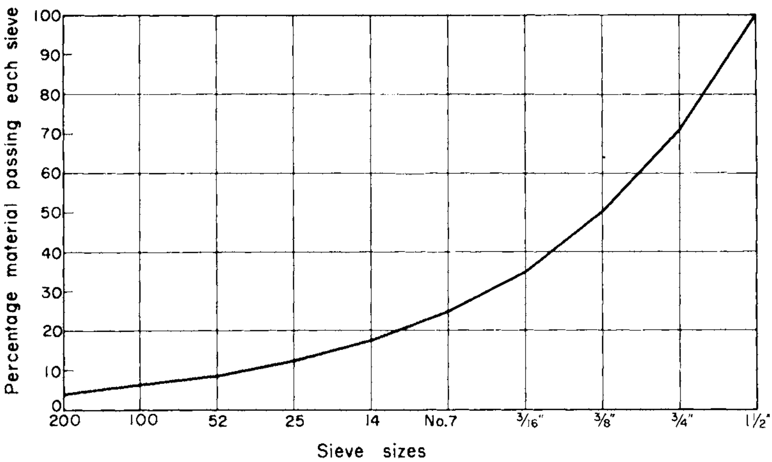


Fig. 3.12. Fuller & Thompson's ideal or maximum density grading curve.

interference is taken into account then the mathematical analysis leads to a gap-graded aggregate.

The idea of an ideal curve is now discredited and concrete is made successfully from material with gradings very different from either the ideal curve or a gap-graded material.

Fineness Modulus. In 1918 Abrams established a method of mix proportioning in which the workability was assessed by relation to the fineness modulus. The fineness modulus is a factor which is related to the specific surface of the aggregate particles. It is calculated by first carrying out a sieve analysis and then using the cumulative percentage by weight retained on each sieve as a measure of the surface area. It is thus an approximate method of calculating specific surface, but offers no advantages over specific surface in mix design and its use has been more or less abandoned.

Specific Surface

It has been pointed out that a major difficulty in mix design is that the grading of the combined coarse and fine aggregate affects the resulting workability. If the grading curve, or some property of the aggregate which is dependent upon the amount of fine and coarse material, could be expressed as a number then it could be used in an equation linking workability, water/cement ratio, aggregate/cement ratio and angularity of the aggregate. One way this may be done is by expressing the grading as a function of specific surface.

If the particles of aggregate are imagined as spheres, then for the same weight of material the surface area increases as the diameter of the spheres decreases. If the spheres are sorted into lots whose average diameter is half that of the previous lot, then for the same weight of spheres the surface area of the smaller spheres will be twice that of the previous ones. The surface area per unit weight (cm^2/g) is termed the specific surface and is a measure of the aggregate grading. (Note that in sieving an aggregate it is divided into lots of average diameter half the previous; B.S. sieves Nos. 7, 14, 25, etc. all have apertures approximately half the previous size.)

Angularity and Surface Factors

Should the aggregates to be used be all of the same shape and with the same surface texture, then it would be possible to design a mix based simply upon the specific surface and to prepare a set of charts, as in the Road Note 4 method, or a formula relating specific surface, workability and aggregate/cement ratio.

Singh (1959) has carried out work on irregular gravel and derived the following relation between the workability (compacting factor) and aggregate/cement ratio:

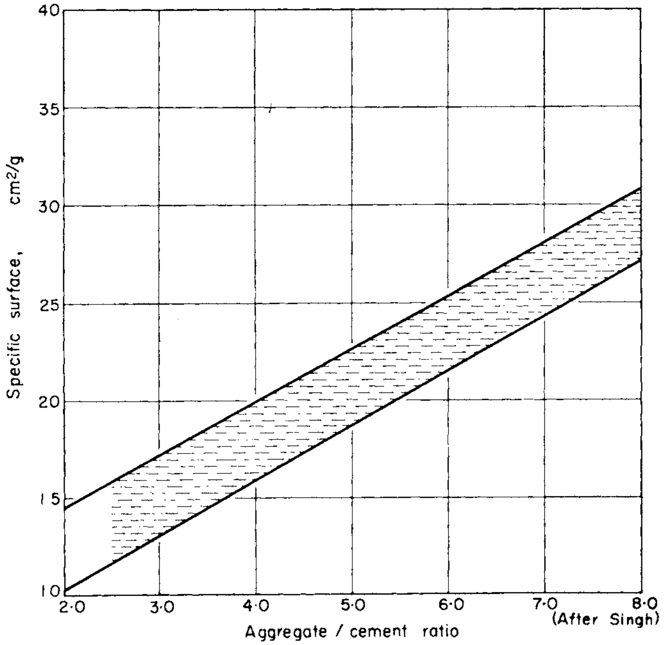
$$\text{compacting factor} = \frac{W/c}{1{\cdot}21\,P + 0{\cdot}0005\,\frac{A}{c}S_c + 0{\cdot}0604\frac{A}{c} \times \frac{W}{c}}$$

where W/c = water/cement ratio
P = water/cement ratio for standard consistence $\bumpeq 0{\cdot}25$
A/c = Aggregate/cement ratio
S_o = specific surface of the aggregate (cm^2/g), calculated from the grading curve of the aggregate

Size of material	Value of S_o (cm^2/g)
$1\frac{1}{2}$–$\frac{3}{4}$ in.	1
$\frac{3}{4}$–$\frac{3}{8}$ in.	2
$\frac{3}{8}$–$\frac{3}{16}$ in.	4
$\frac{3}{16}$–No. 7	8
No. 7–No. 14	16
No. 14–No. 25	35
No. 25–No. 52	65
No. 52–No. 100	128
No. 100–No. 200	260

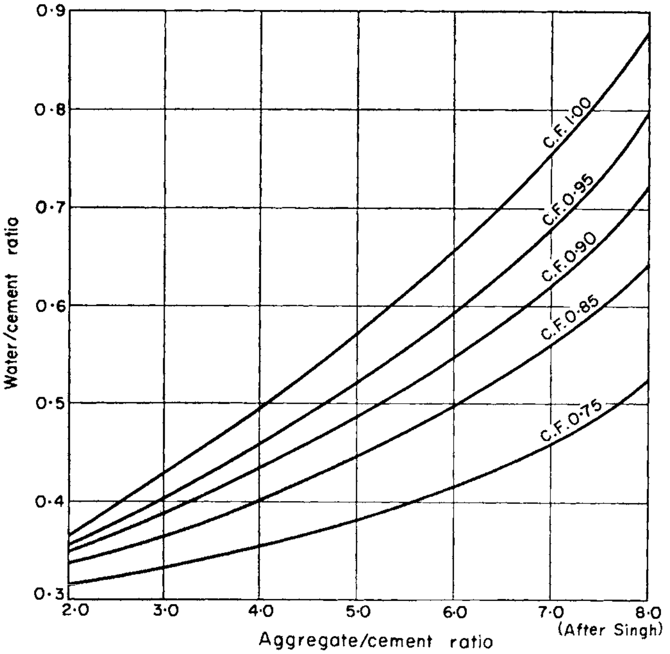
The influence of the water/cement ratio for standard consistence (P) is such that a water/cement ratio of P ($\doteq 0{\cdot}25$) is always used up in converting the dry cement powder to a fluid consistence, so that the workability is dependent only upon the amount of water added in excess of the water/cement ratio of P.

A chart for an irregular gravel aggregate is shown in Fig. 3.13 and 3.14.



(After Singh)

Fig. 3.13. Relationship of specific surface and aggregate/cement ratio for $\frac{3}{4}$ in. irregular gravel.



(After Singh)

Fig. 3.14. Workability curves for irregular gravel with mean specific surface of 15 to 28 sq. cm/gm.

The specific surface increases with a reduction in the size of material, so that the fine sand contributes very much more to the total surface area than does the coarse aggregate. The workability of a mix should therefore depend more upon the amount of cement and fine sand than upon the coarse aggregate and the coarser sand. It is well known, however, that for normal aggregates and with the types of grading usually used, the sand in the middle range (B.S. sieve No. 14 to 52) plays an important part in determining the workability, and the workability can also be increased by increasing the maximum size of the coarse aggregate; this increase is far more than could be accounted for by the small change in surface area which results from using the coarser material. In addition, the specific surface of the cement seems to be of little importance in its affect on workability, especially in lean mixes, although in rich mixes the fineness of grinding can affect the workability and in very rich mixes it may be necessary to use less sand than cement (by weight) to reduce the overall specific surface of the mix. It is necessary, therefore, to use a "weighted" specific surface, i.e. one which gives more weight to the coarser material. The following weighted values have been suggested for different sizes of aggregate:

Aggregate size	Surface factor
3–$1\frac{1}{2}$ in.	$\frac{1}{2}$
$1\frac{1}{2}$–$\frac{3}{4}$ in.	1
$\frac{3}{4}$–$\frac{3}{8}$ in.	2
$\frac{3}{8}$–$\frac{3}{16}$ in.	4
$\frac{3}{16}$ in.–No. 7	8
No. 7–No. 14	12
No. 14–No. 25	15
No. 25–No. 52	12
No. 52–No. 100	10
Passing No. 100	1

To determine the total surface factor f_s for any grading, the percentage weight of material retained on each sieve size is multiplied by the surface factor and the result divided by 1000 for ease of calculation. Murdock (1960) has suggested different values for the surface factor, as follows:

Aggregate size	Surface factor
3–$1\frac{1}{2}$ in.	$-2\frac{1}{2}$
$1\frac{1}{2}$–$\frac{3}{4}$ in.	-2
$\frac{3}{4}$–$\frac{3}{8}$ in.	-1
$\frac{3}{8}$–$\frac{3}{16}$ in.	1
$\frac{3}{16}$ in.–No. 7	4
No. 7–No. 14	7
No. 14–No. 25	9
No. 25–No. 52	9
No. 52–No. 100	7
Passing No. 100	2

To the sum determined from the products of the percentage weights of material retained on each sieve and the above surface factor is added a constant of 330, and the result is divided by 1000.

The results of these methods of calculation differ for widely varying gradings, but the result is to some extent overshadowed by the angularity factor, for it can be shown that the specific surface varies with different aggregates due to variations in the angularity.

In fact for a gravel aggregate there will be a wide variation in specific surface depending upon whether the aggregate includes crushed material, and for crushed rock upon whether a high or low reduction ratio was used in the crushing process. A knowledge of the specific surface is, therefore, not enough, and it is necessary to take into account both the angularity and the surface texture. This is done by means of a factor which is dependent both upon the angularity and to some extent upon the surface texture. This factor varies with different kinds of aggregate and also with different sizes of aggregate; for example, a different factor is obtained for quartz coarse aggregate than for quartz sand.

Shergold has measured the angularity of single-size aggregates and has expressed it as a value which is dependent on the amount of voids in the single-size material when compacted in a container. Murdock, who has developed the method of mix design described below, has used Shergold's concept of angularity but has modified it.

Mix design based on Surface and Angularity Factors. The proportioning of a mix using the surface and angularity factors is as follows. The target or design strength is decided in the manner already described on p. 126 and the water/cement ratio is determined as on p. 127. The workability required is then assessed as on p. 127 and with the known water/cement ratio and the required workability the aggregate/cement ratio is determined.

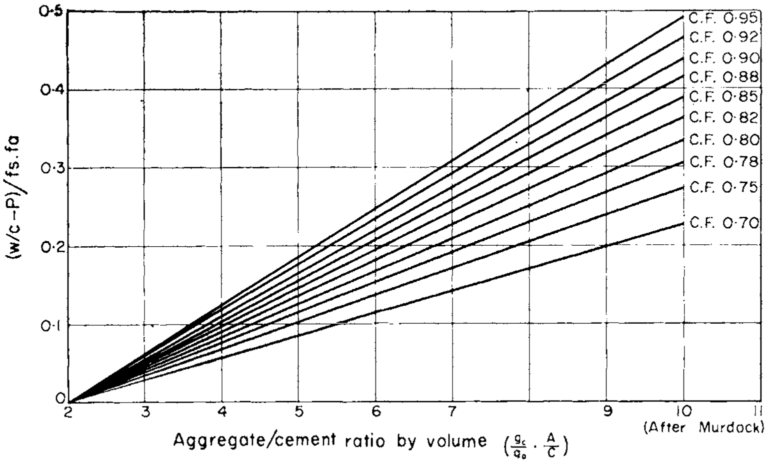
Murdock has shown that the compacting factor, which is a measure of workability, is related to the water/cement ratio and aggregate/cement ratio by the formula

$$\text{compacting factor} = \frac{7{\cdot}4\,(W/c - P)}{f_s \cdot f_a\left(\dfrac{g_c}{g_a} \cdot \dfrac{A}{c} - 2\right)} + 0{\cdot}5$$

where W/c = water/cement ratio by weight
A/c = aggregate/cement ratio by weight
f_s = surface factor
f_a = angularity index
g_a = average specific gravity of the aggregates (see p. 164)
g_c = specific gravity of the cement
P = water/cement ratio for standard consistence $\simeq 0{\cdot}25$

The figure $(g_c/g_a)(A/c)$ is the aggregate/cement ratio by volume. The apparent specific gravity of the aggregates is dependent upon the specific gravity of the coarse and fine aggregates and their relative proportions.

Before this equation can be solved, or the graph (Fig. 3.15) can be used, values of f_s and f_a must be known. This is, of course, the kernel of the mix design problem.



(After Murdock)

Fig. 3.15. Workability curves for different surface and angularity factors.

There is an infinite number of theoretical solutions but from experience Murdock has suggested that the limits for the surface factor f_s should be as follows:

	Values of f_s		
	$1\frac{1}{2}$ in.	$\frac{3}{4}$ in.	$\frac{3}{8}$ in.
Efficient pit or quarry	0·55	0·60	0·70
Not so efficient pit	0·50	0·55	0·65
Segregation likely if values below	0·45	0·50	
Mix too sticky for rotating drum mixer if values above	0·9		

The angularity index f_a depends upon the angularity of the aggregates. For single-size aggregates, for example $\frac{3}{4}$ to $\frac{3}{8}$ in. material, it is directly related to the angularity index as determined by Shergold, by the equation

$$f_a = 3f_H/20 + 1{\cdot}0$$

where $f_H = V_o - 33$
and V_o = Voids in the aggregate when compacted in a standard manner to produce maximum density.

But f_a also depends upon the grading of the coarse and fine aggregates as well as on the relative amounts of coarse and fine aggregate in the final mixed concrete. These, of course, are the things which are known only after the mix has been proportioned. It is necessary, therefore, to make preliminary estimates of the probable value of f_a.

The values of f_a can be checked later, and a correction made, if necessary, by carrying out tests on the actual materials to be used. When the tests are carried out the value of f_a can be determined from

$$f_a = 11{\cdot}05 - 15W/VG$$

where W = weight of the single-sized aggregate in grammes compacted in a cylinder of about $\frac{1}{10}$ cubic ft.
G = Specific gravity of the aggregate particles;
V = volume of cylinder (ml).

The aggregate must be used in the condition for which the specific gravity of the aggregate particles was determined, i.e. saturated surface dry or bone dry. The angularity index is determined for each of the single sizes of material, i.e. for $\frac{3}{4}$ to $\frac{3}{8}$ in., $\frac{3}{8}$ to $\frac{3}{16}$ in., $\frac{3}{16}$ in. to No. 7, etc., and the combined angularity is determined for the whole aggregate by combining the angularities for each single size in proportion to the amount present in the concrete. The value of f_a can be checked roughly, for saturated aggregate, by compacting aggregate into a cylinder of known volume and measuring the voids by then filling with a measured quantity of water. If the values of f_a are not known they can be assessed from the following table.

TABLE 3.1

VALUES OF ANGULARITY f_a

		f_a
Rounded flint gravel	$\frac{3}{4}$–$\frac{3}{8}$ in.	1·05
Slightly rounded flint gravel	$\frac{3}{4}$–$\frac{3}{8}$ in.	1·44
	$\frac{3}{8}$–$\frac{3}{16}$ in.	1·87
Irregular flint gravel	$\frac{3}{4}$–$\frac{3}{8}$ in.	2·08
	$\frac{3}{8}$–$\frac{3}{16}$ in.	2·47
Angular granite	$\frac{3}{4}$–$\frac{3}{8}$ in.	2·62
Angular crystalline limestone	$\frac{3}{4}$–$\frac{3}{8}$ in.	2·53
Quartz sand	$\frac{3}{16}$ in. – No. 7	2·47
	No. 7 – No. 14	2·47
	No. 14 – No. 25	2·25
	No. 25 – No. 52	1·62
	No. 52 – No. 100	1·84

With the values of f_s and f_a, a solution can be obtained for the equation for the compacting factor, given above, which it is convenient to re-arrange as follows:

$$\text{Aggregate/cement} = \frac{g_a}{g_c}\left\{\frac{(W/c - P)}{f_s \cdot f_a} \cdot \frac{7{\cdot}4}{(\text{C.F} - 0{\cdot}5)} + 2{\cdot}0\right\}$$

The value of $(W/c - P)/(f_s \cdot f_a)$ can be determined from Fig. 3.15, but there still remains the value of g_a/g_c. The specific gravity of cement (about 3·14 for Portland cement) can be determined by experiment, but g_a is not known until the proportioning of the coarse and fine aggregate has been determined. Its value ranges from about 2·4 to 2·8 with an average value for flint gravel of about 2·55 and for crushed rock of about 2·65 to 2·7. These figures may be used for a first approximation. The value of the compacting factor is inserted in the formula and the aggregate/cement ratio by weight is then determined.

Examples of mix design

Example No. 1 (*Road Note* 4 *Method*)

Concrete mix required for normally reinforced concrete beams and floors, using $\frac{3}{4}$ in. irregular gravel aggregate and $\frac{3}{16}$ in. Zone 2 sand to give a minimum site cube strength of 3000 p.s.i. at 28 days. Concrete to be transported by side-opening skip and compacted by immersion vibrators. Normal building site, fair control.

Design strength: Minimum site strength 3000 p.s.i. at 28 days. Fair control: design for an average strength of 4500 p.s.i. at 28 days (see table on page 126).

Water/cement ratio: From Fig. 3.1 for a design strength of 4500 p.s.i. a water/cement ratio of 0·58 will be required using ordinary Portland cement. Rapid hardening cement might be required for early stripping of shutters or during colder weather.

Workability: For normal reinforced concrete beams, reference to the table on page 127 shows that medium workability is required, with a slump of 2 to 4 in. or a compacting factor of 0·85 to 0·9.

Aggregate/cement ratio: From Fig. 3.8 it will be seen that the aggregate/cement ratio can vary from:

6·6:1 for grading No. 1 and a compacting factor of 0·85

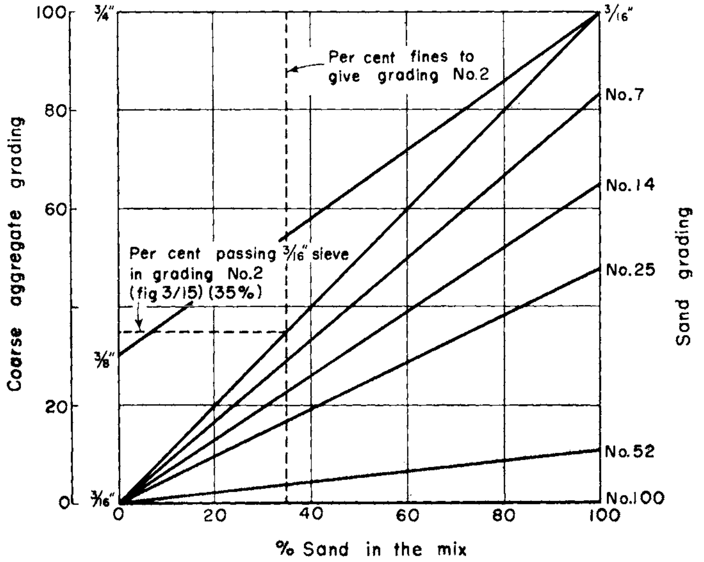
6·1:1 for grading No. 4 and a compacting factor of 0·85

to

5·8:1 for grading No. 2 and a compacting factor of 0·90

5·5:1 for grading No. 4 and a compacting factor of 0·90.

The most economical mix from these results is a mix with an aggregate/cement ratio of 6·6:1, a water/cement ratio of 0·58 and with aggregates proportioned to grading No. 1 in Fig. 3.6.



To obtain a combination of coarse and fine aggregate to give combined grading No. 2, the amount on the $\frac{3}{16}$" sieve must be 35%. The combined grading is then:

Passing $\frac{3}{4}$"	100%	No. 7	29%
Passing $\frac{3}{8}$"	55%	No. 14	23%
Passing $\frac{3}{16}$"	35%	No. 25	17%
		No. 52	4%

Fig. 3.16. Proportioning of fine to coarse aggregate.

It would probably be better to use a slightly richer mix, say 6·2:1 with a water/cement ratio of 0·58 and grading No. 2. This will give a mix with a compacting factor between 0·85 and 0·90, and grading No. 2 will ensure a less harsh mix than No. 1; the mix will be more cohesive and should, therefore, produce a slightly better finish, whilst the increase in workability will facilitate discharge from the side-opening skip.

Proportioning of fine to coarse aggregate: the next step, having determined the aggregate/cement ratio, is to proportion the fine to coarse aggregate. The grading of the fine and coarse aggregates are assumed to be as follows.

Grading of $\frac{3}{4}$ in. irregular gravel:

passing $\frac{3}{4}$ in. sieve	100 per cent
passing $\frac{3}{8}$ in. sieve	30 per cent
passing $\frac{3}{16}$ in. sieve	0 per cent

Grading of $\frac{3}{16}$ in. Zone 2 sand

passing $\frac{3}{16}$ in. sieve	100 per cent
passing No. 7 sieve	84 per cent
passing No. 14 sieve	65 per cent
passing No. 25 sieve	48 per cent
passing No. 52 sieve	11 per cent
passing No. 100 sieve	0 per cent

These are to be combined to give Grading No. 2 of Fig. 3.6. The gradings are plotted on graph paper, coarse grading on the left and the sand grading on the right, with 0 to 100 across the bottom.

Since the amount of material required to pass the $\frac{3}{16}$ in. sieve to give Grading No. 2 is 35 per cent, then from the graph the percentage of sand is 35 per cent. The proportion of sand by weight, therefore, is

35% of 6·2 = 2·16 (where 6·2 is the aggregate/cement ratio). The concrete proportions are then 1:2·16:4·04 with a water/cement ratio of 0·58.

Example No. 2 (Road Note 4 Method)

Concrete mix required for shell roof construction. Minimum site cube strength required is 4000 p.s.i. at 28 days. Shell roof construction will not be more than $2\frac{1}{2}$ in. thick, so use $\frac{3}{8}$ in. material for coarse aggregate and $\frac{3}{16}$ in. down sand. Concrete will be required to compact easily, but must not slump on the roof slopes.

Design strength: Good control will be required for the construction of a shell roof. From the table on page 126 it will be seen that the allowance over the minimum site strength of 3000 p.s.i. is 1000 p.s.i. and for 4500 is 1250 p.s.i. For good site control allow 1250 p.s.i., i.e. design for 5250 p.s.i. for a minimum site strength of 4000 p.s.i.

Water/cement ratio: From Fig. 3.1 the water/cement ratio for a design strength of 5250 p.s.i. is 0·55.

Workability: From the table on page 127 a low workability will be required with a compacting factor of about 0·85. The mix should be made fairly cohesive so that it will not slump easily.

Aggregate/cement ratio: Figures 3.3, 3.4 and 3.5 are the workability curves for $\frac{3}{8}$ in. aggregate. From the curves for low workability (compacting factor of 0·85) it will be seen that with a water/cement ratio of 0·55 the aggregate/cement ratio for crushed rock or irregular gravel varies from 4·2 to 5·3 with grading No. 2 or 3.

Grading No. 1 would produce a mix with a tendency to segregate if the workability were higher than 0·85, and grading No. 4 would produce a rather "sticky" mix with $\frac{3}{8}$ in. aggregate. A $\frac{3}{8}$ in. rounded gravel has not been considered because it is not easily obtainable. A $\frac{3}{8}$ in. crushed rock is best avoided, if possible, as it is sometimes flaky due to the high reduction ratio which is often used in crushing. For $\frac{3}{8}$ in. irregular gravel the aggregate/cement ratio would be 4·9 to 5·3, depending upon the grading.

When the gradings of the $\frac{3}{8}$ in. material and the sand are known, they are proportioned in the manner described in example 1 and the mix proportions thus determined.

Example No. 3 (*Road Note* 4 *Method*)

Concrete mix required for mass concrete blocks. Maximum size of aggregate to be $1\frac{1}{2}$ in. material (larger material is not easily available). Concrete to have a 28-day strength of 1500 p.s.i.

Design strength: Minimum site strength 1500 p.s.i. The design strength will vary from 2250 p.s.i. for good control to 3000 p.s.i. for poor control (see table on page 126).

Water/cement ratio: From Fig. 3.1 this is equivalent to a water/cement ratio of 0·91 to 0·80.

Workability: The table on page 127 gives a desirable workability for mass foundations of 0·85.

Aggregate/cement ratio: There is only one graph for $1\frac{1}{2}$ in. material and that is for irregular gravel (Fig. 3.8). From this figure it will be seen that for a compacting factor of 0·85 the data does not go beyond an aggregate/cement ratio of about 8·0:1. The mix will have an aggregate/cement ratio in excess of this, perhaps 9·0 or 10·0:1, but further design of the mix must be based on trial mixes. In this connexion, note the tendency to segregate with increase in workability (curves for compacting factor of 0·95).

NOTE: Because of the relatively low strength and hence high water/cement ratio, the sand content may have to be slightly higher than normal.

When material other than $1\frac{1}{2}$ in. irregular gravel or all-in ballast is used on work requiring a higher strength, then an assessment of the probable workability can be obtained by direct proportioning from the workabilities of other aggregates, for example: workability of $1\frac{1}{2}$ in. crushed rock =

$$\frac{\text{workability of } \tfrac{3}{4} \text{ in. crushed rock} \times \text{workability of } 1\tfrac{1}{2} \text{ in. irregular gravel}}{\text{workability of } \tfrac{3}{4} \text{ in. irregular gravel}}$$

Example No. 4 (*Surface Factor Method*)

Concrete mix required for reinforced concrete structure. Size of members will allow the use of $1\frac{1}{2}$ in. irregular gravel with $\frac{3}{16}$ in. down natural sand. Minimum compressive strength at 28 days to be 3000 p.s.i.

Design strength: Minimum site strength 3000 p.s.i. With fair control, the design strength will be 4500 p.s.i. at 28 days (see table on page 126).

Water/cement ratio: The water/cement ratio to give a design strength of 4500 p.s.i. at 28 days will be 0·62 (Fig. 3.1).

Workability: The concrete should have medium workability, say a compacting factor of 0·85 (see table on page 127).

Aggregate/cement ratio: The aggregate/cement ratio can be determined only when the angularity and surface indices of the aggregates are known. It may be assumed that the value of f_s is 0·55 (see page 147) and the value of f_a is 2·2 (a mean value from the table on page 148). Also in the formula for aggregate/cement ratio is the value of the specific gravity of the aggregate; for flint gravel this may be assumed to be 2·60.

The value of the aggregate/cement ratio is then

$$= \frac{2\cdot60}{3\cdot14}\left\{\frac{(0\cdot62 - 0\cdot25)}{0\cdot55 \times 2\cdot2} \times \frac{7\cdot4}{(0\cdot85 - 0\cdot5)} + 2\cdot0\right\}$$

Using Fig. 3.15 then

$$\frac{(w/c - p)}{f_s \cdot f_s} = \frac{0\cdot62 - 0\cdot25}{0\cdot55 \times 2\cdot2} = 0\cdot305$$

For a compacting factor of 0·85 the value of $A_v = 8\cdot40$, and hence

$$\frac{A}{c} = \frac{2\cdot60}{3\cdot14} \cdot 8\cdot40 = 6\cdot95$$

The sand and coarse aggregate which it is proposed to use are proportioned to give a value of f_s of about 0·55 using the surface factor figures given on page 144.

Example No. 5 (*Surface Factor Method*)

Concrete mix required for large very heavily reinforced concrete structure. Crushed rock aggregate and natural sand to be used. Minimum site cube strength at 28 days to be 4500 p.s.i.

Size of Aggregate: Very heavily reinforced section; therefore ¾ in. aggregate will be the maximum size of coarse aggregate (because the structure is large it is better not to use ½ in. or ⅜ in. coarse aggregate as the maximum).

Design strength: Minimum site strength 4500 p.s.i. Assume good control and let the site agent know this assumption has been made. Design strength for good control from table on page 126 is 5750 p.s.i.

Water/cement ratio: From Fig. 3.1, for a design strength of 5750 p.s.i. at 28 days a water/cement ratio of 0·52 will be required.

Workability: The concrete must have good workability to be easily placed between heavy reinforcement, and a VB of 2 sec or a compacting factor of 0·95 will be required (see table on page 127).

Aggregate/cement ratio: Value of f_s for ¾ in. material, say 0·60 (see page 147).

Value of f_a for rounded gravel and sand: 1·8
for irregular gravel and sand: 2·2
for crushed rock and sand: 2·5
(see table on page 148).

The values of $f_s \times f_a$ are therefore, 1·08, 1·32 and 1·50.
Values of $(w/c - 0{\cdot}25)/(f_s . f_s)$ are 0·25, 0·205 and 0·180 for a compacting factor of 0·95; the values of A_v are then 6·0, 5·3 and 4·9.
If the specific gravity of gravel is 2·5 and of crushed rock is 2·6, the aggregate/cement ratios are: rounded gravel 4·8
irregular gravel 4·3
crushed rock 3·9
With the grading of the proposed material known, the proportions of fine and coarse aggregate are determined and the values of f_s and f_a checked. A trial mix would be essential to determine whether there is any tendency of these rich mixes to segregate because of the high workability.

The combination of single-sized aggregates

Where it is intended to use single-size coarse aggregates and sand, these have to be combined to produce the required overall grading.

Example: It is required to combine the following materials to give grading No. 2 (Fig. 3.10) for 1½ in. material.

Grading of 1½ in. material:

passing 1½ in. sieve	100 per cent
passing ¾ in. sieve	14 per cent
passing ⅜ in. sieve	3 per cent

Grading of ¾ in. material:

passing ¾ in. sieve	95 per cent
passing ⅜ in. sieve	7 per cent
passing $\frac{3}{16}$ in. sieve	2 per cent

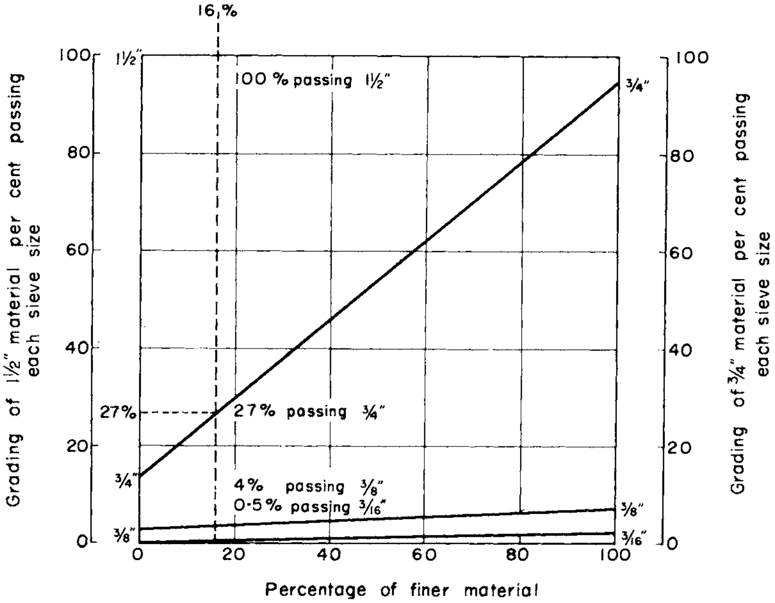


Fig. 3.17. Combining 1½ and ¾ in. aggregate.

Grading of ⅜ in. material:

passing ½ in. sieve	100 per cent
passing ⅜ in. sieve	96 per cent
passing 3/16 in. sieve	10 per cent

Grading of sand:

passing 3/16 in. sieve	100 per cent
passing No. 7 sieve	84 per cent
passing No. 14 sieve	60 per cent
passing No. 25 sieve	44 per cent
passing No. 52 sieve	24 per cent
passing No. 100 sieve	5 per cent

These materials are combined as follows. The 1½ in. and ¾ in. materials are plotted as shown in Fig. 3.17. From Fig. 3.15 it will be seen that for grading No. 2, 59 per cent passes the ¾ in. sieve, and 44 per cent passes the ⅜ in. sieve; thus

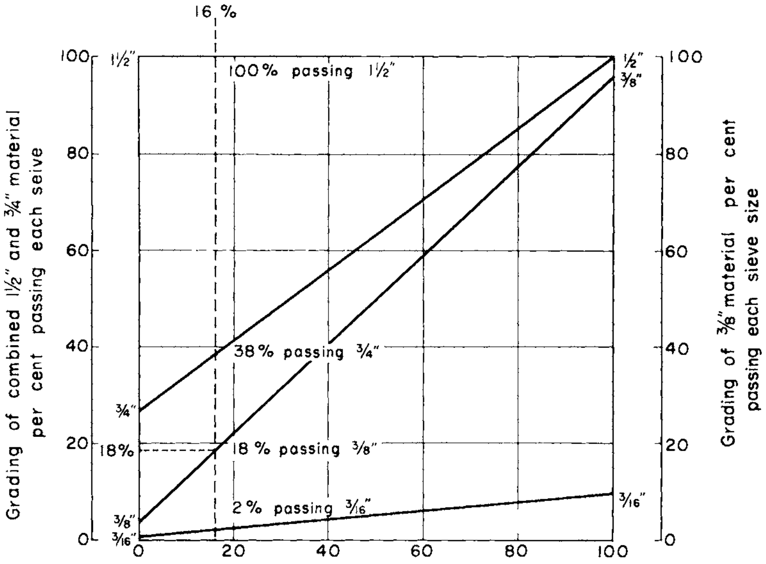


Fig. 3.18. Combining $\frac{3}{8}$ in. material with combined $1\frac{1}{2}$ and $\frac{3}{4}$ in.

15 parts in 56 (100 – 44) i.e. 27 per cent must pass the $\frac{3}{4}$ in. sieve. To produce this, 16 per cent of the $\frac{3}{4}$ in. material must be combined with 84 per cent of the $1\frac{1}{2}$ in. material.

This gives a new grading for the combined $1\frac{1}{2}$ in. and $\frac{3}{4}$ in. material, as follows:

passing $1\frac{1}{2}$ in. sieve	100 per cent
passing $\frac{3}{4}$ in. sieve	27 per cent
passing $\frac{3}{8}$ in. sieve	4 per cent
passing $\frac{3}{16}$ in. sieve	0·5 per cent

This grading is plotted in Fig. 3.18 and the grading of the $\frac{3}{8}$ in. material is plotted on the right-hand side of this graph. Again for grading No. 2, from Fig. 3.10 there is 44 per cent passing the $\frac{3}{8}$ in. sieve and 32 per cent passing the $\frac{3}{16}$ in. sieve; to produce this, 12 parts (44 – 32) in 68 (100 – 32) i.e. 18 per cent must pass the $\frac{3}{8}$ in. sieve. Thus 16 per cent of the $\frac{3}{8}$ in. material, must be incorporated into the grading.

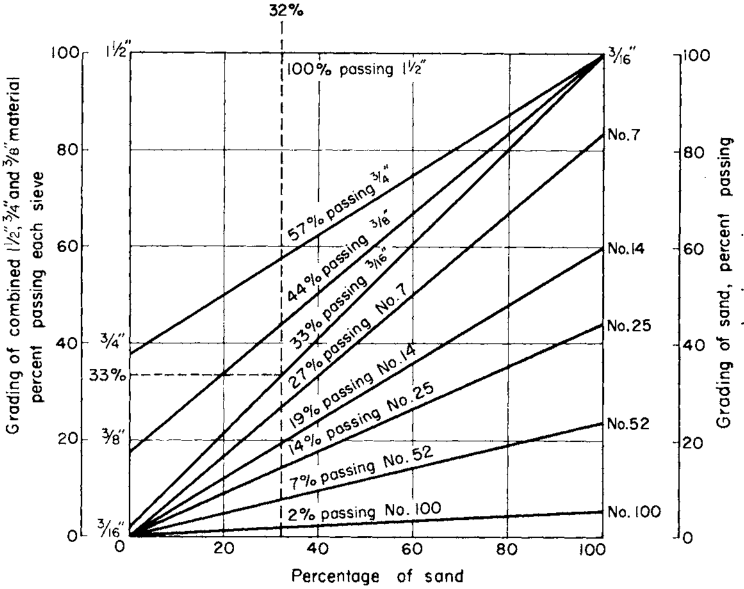


Fig. 3.19. Combining sand with combined 1½, ¾ and ⅜ in material.

This gives a new grading for the combined 1½ in., ¾ in. and ⅜ in. material, as follows:

passing 1½ in. sieve	100 per cent
passing ¾ in. sieve	38 per cent
passing ⅜ in. sieve	18 per cent
passing 3/16 in. sieve	2 per cent

This grading is plotted on Fig. 3.19 on the left-hand side, the grading of the sand being plotted on the right-hand side. Further reference to the grading No. 2 of Fig. 3.10 shows that 32 per cent of the sand must be combined as shown, and this gives an overall combined grading close to that of grading No. 2. The values for grading No. 2 are shown in brackets.

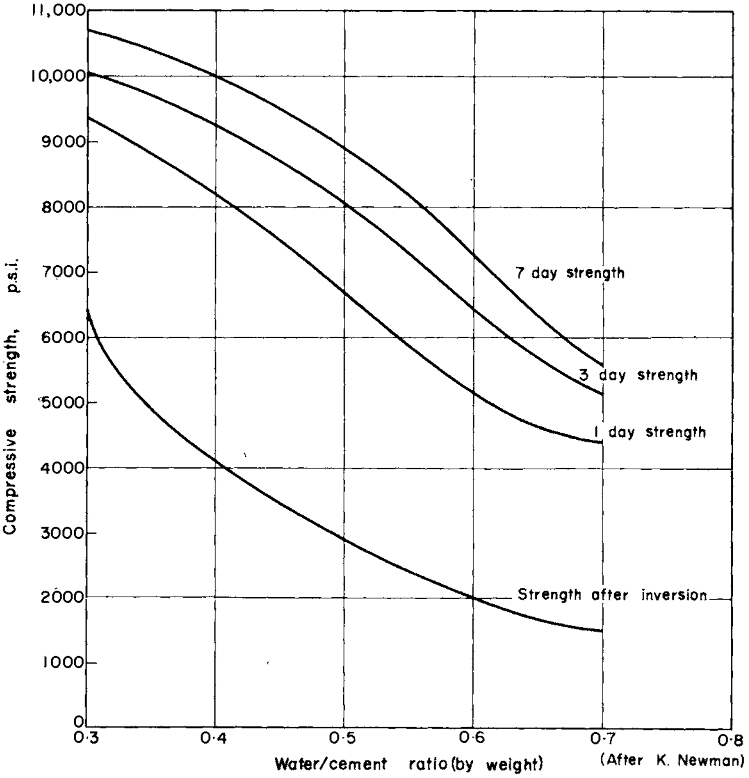
passing 1½ in. sieve	100	(100) per cent
passing ¾ in. sieve	57	(59) per cent
passing ⅜ in. sieve	44	(44) per cent
passing 3/16 in. sieve	33	(32) per cent
passing No. 7 sieve	27	(25) per cent
passing No. 14 sieve	19	(17) per cent
passing No. 25 sieve	14	(12) per cent

passing No. 52 sieve	7	(7) per cent
passing No. 100 sieve	2	(—) per cent

Mix design for high alumina cement

The mix design for high alumina cement has, for many years, been based on nominal mix proportions, but as a result of work carried out by Newman it is now possible to design high alumina mixes in the manner described above under the Road Note 4 method.

The strength attainable with high alumina cement and its relation with the water/cement ratio is given in Fig. 3.20. The



(After K. Newman)

Fig. 3.20. Relationship of compressive strength and water/cement ratio for high alumina cement.

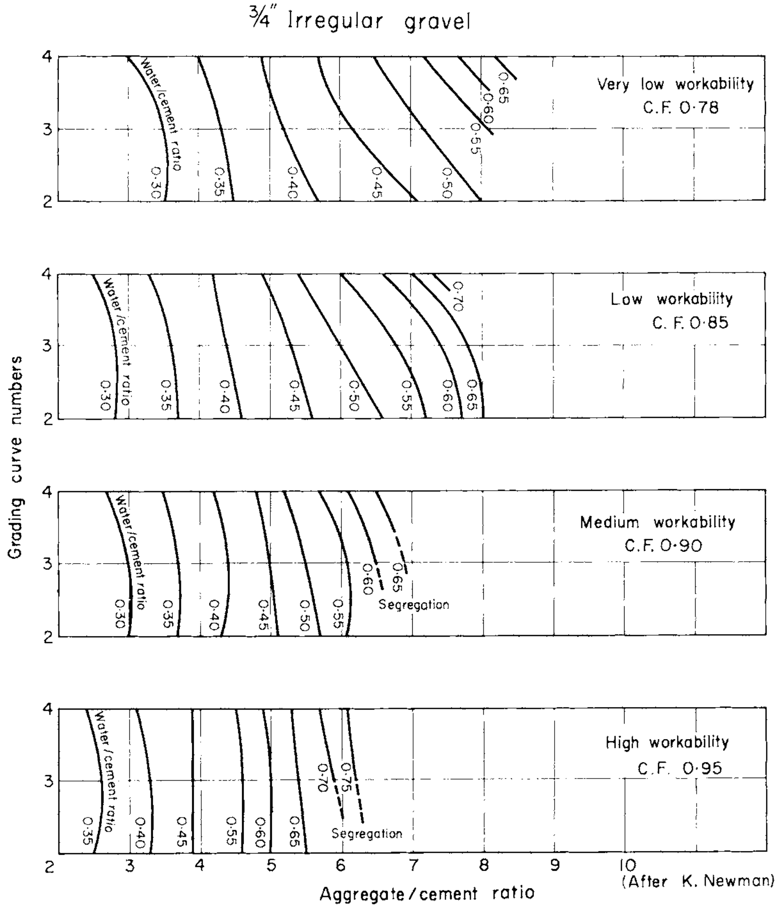
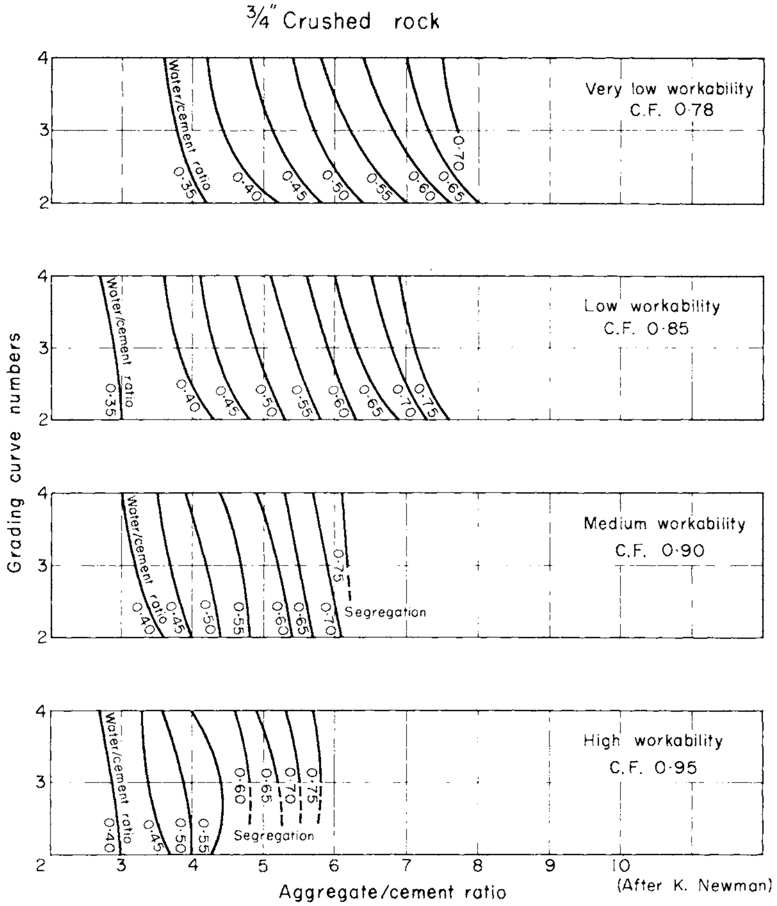


Fig. 3.21. Workability curves for high alumina cement with ¾ in. irregular gravel.

workability, aggregate/cement ratio and water/cement ratio for the three type gradings (Nos. 2, 3 and 4 in Fig. 3.6) are given in graphical form in Figs. 3.21 and 3.22.

With the information from these graphs the method of proportioning a mix is the same as that for ordinary Portland cement (pages 125–129) with the modification that since extra sand is generally required then type grading No. 1 is not



(After K. Newman)

Fig. 3.22. Workability curves for high alumina cement with ¾ in. crushed rock.

included, as mixes with this proportion of sand are liable to segregation.

High alumina cement is subject to reversion and loss of strength if kept moist at temperatures of about 80°F and above; the loss of strength which occurs is shown in Fig. 3.20.

Trial mixes

Once the basic proportions of a concrete have been determined it is expedient to confirm these by a trial mix and, if necessary, to carry out further adjustments.

A trial mix consists of mixing together the designed proportions of cement, aggregate, water and admixture, if any, and of measuring the workability and the strength of concrete cast from the mix.

Strength is based on effective water/cement ratio, which is determined on the basis of saturated surface dry aggregates. This is a condition which is difficult to achieve although it could be approximated to by using dry aggregates and adding an extra amount of water equivalent to that which the aggregate is known to absorb. But to ensure that absorption of the aggregate does not affect strength or workability, wet aggregates should be used in the trial mix. The moisture content and absorption of the aggregates are determined and the amount of water necessary to give the required effective water/cement ratio, is calculated.

If the total moisture content of the aggregate is less than the absorption, a quantity of the mixing water is added to the weighed aggregates and left to stand, in the mixer, for twenty to thirty minutes. This ensures that the cement paste in contact with the aggregates does not have a reduced bond due to absorption of moisture from the paste by the dry aggregates.

The amounts of materials are accurately weighed, and mixed, the mixing water being added gradually during the mixing and the appearance of the mix continuously observed.

After mixing the compacting factor, VB or slump is measured, whichever is the most suitable for the particular concrete. The measurement should be made about 10 minutes after mixing or such other time as is appropriate; for example, immediately after mixing when the concrete is to be controlled by workability tests at the mixer, or half an hour after mixing or some other interval as is appropriate where the placing time is protracted. When using ready-mixed concrete it is necessary to determine what workability is required at the mixer so as to ensure that it will have the correct workability for placing, when it arrives at the site; i.e. the loss in workability during transit must be determined.

When the trial mix has been carried out, it may be obvious that the workability is not as great as was anticipated. This may be adjusted by increasing the richness, i.e. adding amounts of cement and water, keeping the water/cement ratio constant.

If the mix is unworkable due to harshness then it may be improved by adding water, cement and sand in such proportions as to keep the water/cement and aggregate/cement ratios constant. This has the effect of increasing the proportion of fine to coarse material. If the mix has the appearance of over sanding denoted by excessive stickiness, then water, cement and coarse aggregates are added, again keeping the water/cement and aggregate/cement ratios constant but decreasing the ratio of fine to coarse material.

If the mix is excessively workable but appears to contain the right amount of fine to coarse material, then the mix is made leaner by adding fine and coarse aggregate in the same proportions as previously used. This reduces the richness but maintains the water/cement ratio constant.

Some of these adjustments can be carried out during the course of a single trial mix, but it is usually easier and quicker to make up two or three separate mixes, adjusting each one from the results of the previous mix. It is not usual to require more than three mixes for normal gravel or crushed rock aggregates.

After trial mixes, concrete cubes are cast so that confirmation can be obtained that the calculated effective water/cement ratio will result in a compressive strength of the right order, say within 250 p.s.i. of the design strength. Cubes are usually cast by compacting on a vibrating table to which the cube moulds are clamped. During the vibration the behaviour of the mix should be noted, together with the ease of compaction and any tendency to bleed or segregate. Depending upon the urgency of the work it may be possible to wait until 7-day compression strengths are available; alternatively a method of accelerated curing may be used to obtain an early indication of the potential strength.

The quantities of materials per cubic yard of concrete

When the mix proportions (by weight) have been determined the quantities of materials for 1 cubic yd of concrete can be calculated.

The weight of cement per cubic yard of concrete is given by

$$\frac{62{\cdot}4 \times 27 \,.\, g_a \,.\, g_c\,(1{\cdot}00 - V_a)}{g_c\left[\frac{W}{c}\,.\,g_a + \frac{A}{c}\right] + g_a}$$

Where g_a = average specific gravity of the aggregates
g_c = specific gravity of the cement (about 3·14)
V_a = amount of voids per cubic yard (say 1·5 per cent)
$\frac{W}{c}$ = water/cement ratio
$\frac{A}{c}$ = aggregate/cement ratio

This formula reduces to

$$\frac{1660}{\frac{W}{c} + \frac{A}{c}\cdot\frac{1}{g_a} + 0{\cdot}319}$$

When air entrainment is used then V_a may be 5 to 7 per cent, so that a figure of 0·06 must be used in the formula. With mix proportions of 1 :*n* :*m*, the quantities of fine and coarse aggregate by weight are *n* and *m* times the weight of cement respectively.

The average specific gravity of the aggregates in the above formula is determined from a knowledge of the specific gravity for the coarse and fine aggregates. With the proportions of 1 :*n* :*m* the average specific gravity is given by

$$g_a = \frac{n \times \text{S.G. of fine aggregate} + m \times \text{S.G. of coarse aggregate}}{n + m}$$

The quantities calculated in the above manner should be checked by an independent calculation. An alternative method of calculation by absolute volume of materials is as follows.

With a mix proportion by weight of $1:n:m$ the absolute volumes of cement, fine and coarse aggregate and water for 1 cwt of cement of specific gravity 3·14 are:

$$\text{cement} = \frac{112}{3{\cdot}14 \times 62{\cdot}4} = 0{\cdot}572 \text{ cubic ft}$$

$$\text{sand} = \frac{n \times 112}{\text{S.G. of sand} \times 62{\cdot}4}$$

$$\text{coarse aggregate} = \frac{m \times 112}{\text{S.G. of coarse aggregate} \times 62{\cdot}4}$$

$$\text{water} = \frac{\frac{W}{c} \times 112}{62{\cdot}4}$$

$$\text{air voids} = \frac{\Sigma \times \%\text{ air voids}}{100}$$

$$\text{total volume} \quad \Sigma \quad \text{cubic ft}$$

where W/c = water/cement ratio, and the air voids are about $1\frac{1}{2}$ per cent for normal concrete and 5–7 per cent for air-entrained concrete.

The required quantities per cubic yard of concrete are obtained by dividing 27 cubic ft by the total absolute volume Σ cubic ft.

$$\text{Then} \quad \text{weight of cement} = \frac{27 \times 112}{\Sigma}$$

$$\text{weight of sand} = \frac{n \times 27 \times 112}{\Sigma}$$

$$\text{weight of coarse aggregate} = \frac{m \times 27 \times 112}{\Sigma}$$

$$\text{volume of water/cubic yd.} = \frac{\frac{W}{c} \times 27 \times 112}{10.\Sigma} \text{ gal}$$

Ordering materials

It is usual in the north of England and Scotland to order sand and coarse aggregate by weight. In assessing the quantity to order, the weight must be increased by a percentage equivalent to the average weight of water contained in the aggregates, which is about 2 to 4 per cent for gravel aggregates and 4 to 6 per cent for sand. When the sand is delivered straight from the washing plant it may contain 12 to 14 per cent. The free water in crushed rock may be very small, even nil.

In the south of England aggregates are ordered by volume in cubic yards of material. The volume of aggregate required is calculated from the weight by dividing by the dry loose bulk density and an allowance must be made for bulking of the sand; this will depend upon its moisture and grading, but it is prudent to allow for about 25 per cent bulking (see Fig. 3.23).

In addition to these various allowances the amount of

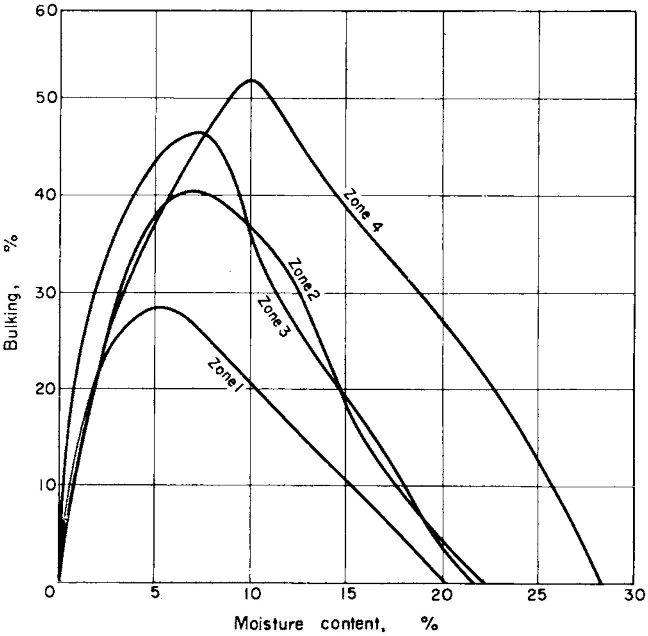


Fig. 3.23a. Effect of moisture content on sand bulking.

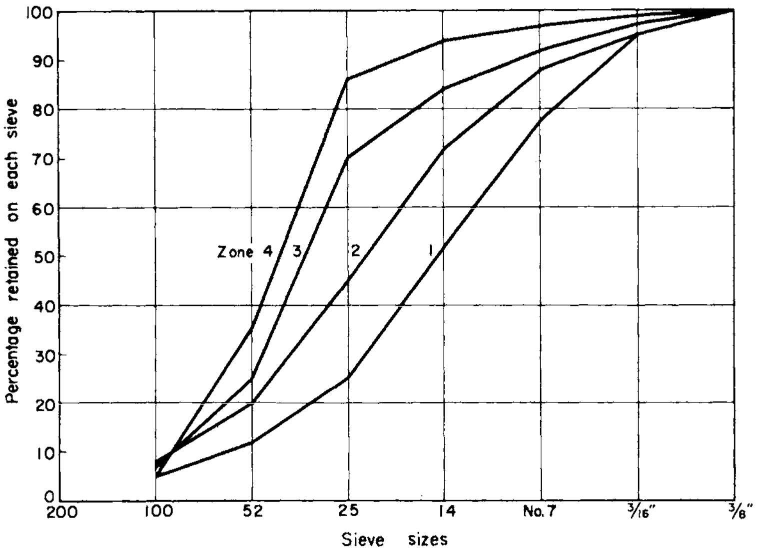


Fig. 3.23b. Zone gradings of sand used in bulking test.

wastage must be taken into account. This is often taken as 5 per cent but may vary from 2 to 7 per cent depending upon the site conditions.

Typical dry bulk densities for various aggregates are as follows:

Quartz Sand	96 to 102 lb/cubic ft
Flint Gravel	
$1\frac{1}{2}$–$\frac{3}{16}$ in.	89 to 94 lb/cubic ft
$\frac{3}{4}$–$\frac{3}{16}$ in.	85 to 90 lb/cubic ft
Crushed Rock*	
$1\frac{1}{2}$–$\frac{3}{4}$ in.	80 to 90 lb/cubic ft
$\frac{3}{4}$–$\frac{3}{8}$ in.	77 to 90 lb/cubic ft
$\frac{3}{8}$–$\frac{3}{16}$ in.	75 to 85 lb/cubic ft

* Low values for limestone.
High values for granite and dolerite.

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CHAPTER 4

MANUFACTURE OF CONCRETE

Handling materials

Aggregates

The purpose of correct handling is to receive, proportion and deliver materials as cheaply as possible in the condition in which they are required; whilst in addition, it is essential to ensure a supply of clean material at a minimum cost and wastage with the material free from contamination.

The handling and batching of concreting materials varies according to the materials and the quantities to be used. On a small site the aggregate may be simply a heap of sand and another heap of $\frac{3}{4}$ to $\frac{3}{16}$ in. gravel. These may be handled and roughly proportioned by the shovelful — a method of little value but still used with the cement delivered and proportioned by the bag. On the large site, however, the coarse aggregate may be supplied in four or more single sizes, the sand being handled by conveyor belts. The aggregates will be discharged from hoppers automatically controlled to give the required grading, weigh-batched and fed with the weighed cement and weighed water to a large mixer.

In rugged and difficult country on a large job a different set-up may be required, including an aerial ropeway to transport the aggregates and the mixed concrete. The large quantities to be handled require expert knowledge and it is often profitable to sub-let the winning of aggregates on such sites to a specialist firm, who will then deliver the material in much the same way as a commercial supplier. Between these extremes there are a number of different plants and methods of handling the materials.

The handling of aggregate is controlled by the method of supply and delivery. On the majority of jobs the aggregates are supplied in 5 cubic yd tipper loads; even on some large jobs they are delivered ultimately by tipper lorry, even though the size of the job has warranted the exploration and development of separate sources of aggregate.

On a few jobs, principally large concrete dams, the rock may be brought straight from the quarry and crushed and screened at the site and then fed by belt conveyors to stockpiles and thence to the batcher and mixer. On many jobs it is economic to stockpile aggregates into single sizes, for example $1\frac{1}{2}$ to $\frac{3}{4}$ in., $\frac{3}{4}$ to $\frac{3}{8}$ in., $\frac{3}{8}$ to $\frac{3}{16}$ in., and there may be two types of sand, and a stockpile of fly ash.

On small jobs at least two stockpiles will be required, one for $1\frac{1}{2}$ to $\frac{3}{16}$ in. coarse aggregate and one for sand. Except for the roughest work all-in ballast cannot be recommended since this material is usually taken as it comes, with excessive variations in sand content and with hardly one batch of material resembling the next, but see dry lean concrete p. 308.

Where a site is limited in area, as building work in cities often is, saving in the handling and storage of aggregate may be made by having it delivered pre-mixed. A pre-mixed aggregate is one which has been formed by recombining and mixing the aggregates at the pit or quarry to produce the required grading. Reliance is placed on the supplier to produce the required grading, but those suppliers who undertake this work realize this also, so that no trouble occurs and the method can be economic even on large jobs. Where a supplier has not previously supplied by this method he usually overestimates his cost and the extra price per ton of aggregate may then make it uneconomic.

The aggregate supplied to a site is deposited in stockpiles, which are usually areas marked off and boarded with timber, iron, or precast concrete boards. Where there are differences in ground level it is sometimes possible to make the stockpile in the form of a gravity-feed hopper and feed direct to the mixer.

The area around a batching and mixing plant is usually limited, and even on large jobs the quantities of concrete being produced call for proportionally larger stockpiles, so that there is never sufficient room. If materials of the same size from different pits are being delivered then the problem becomes chronic, for either separate piles for aggregates from each pit must be established or, if the material from the different pits is combined, a digger must be used to "haymake" the aggregate to obtain some semblance of constant grading. The stockpile should be large enough to hold a few days supply, depending upon the delivery conditions, but in any case only one stockpile for each type and size of material should be established otherwise the material will have to be double-handled which adds considerably to the cost. Sometimes twin stockpiles are constructed, aggregate from one pile being used while the other is draining. This is done in an attempt to control the moisture content of the aggregate as used. In general it is not worth the extra cost.

On a small site the area available is always too small and only a limited reserve of aggregate can be maintained. The aggregates are tipped direct into the correct bin and shovelled from there to the swing weigh batcher, which may be stationary or may be mounted on wheels on a short length of track. This system makes more room available for aggregates around the mixer. There is available, as an alternative to the swing weigh batcher, a mixer with an integral weigh hopper. The material is shovelled to the hopper and there weighed directly, but the site round an integral weigh batcher is usually congested and the aggregates become contaminated. Hoppers are very useful but a difference in level of about ten feet is required. If this is provided by a basement then the aggregate is tipped into the hopper and fed to the batcher at basement level. Alternatively the materials may be tipped in to bunkers or a stockpile and fed to the hopper by a mechanical digger.

Transportable hopper units and storage bins with combined weigh batchers are available with two or three bins. These are simple to move and erect; they can be towed behind a lorry and are useful on small or medium size jobs.

From a large stockpile the aggregates may be fed to the weigh batch hoppers by crane, fitted with clamshell grabs, or by dragline. In operating such a stockpile it is necessary to avoid a core of material which is never used and is left undisturbed until the pile is run down, as such material becomes contaminated with dust and other materials. It is better to arrange for the stockpile material to be continually removed.

This can be done by constructing a recovery tunnel, built before the stockpiles are created. The stockpiles are established over the tunnel and they feed through draw-off gates to a conveyor belt which travels the length of the tunnel. The conveyor delivers the aggregate to a second conveyor or a bucket elevator which raises the material to the hoppers. At the top the aggregate is delivered by a system of chutes to the required hopper.

Various other types of equipment are available for different sizes of work. For example, on a medium-size job it may be advantageous to use a hand-operated drag-line bucket which works from a winch mounted on the mixer. The control for the winch is mounted on the handle of the scraper bucket. The aggregates are grouped radially around the mixer and the scraper pulls the material either to the skip hoist of the mixer, if it is of the type which incorporates an integral weigh batcher, or to an enclosed bucket elevator which raises it to a hopper.

Where the scraper loads direct to the weigh batcher, the experience of the operator enables him to deposit the correct weight of aggregate in the mixer skip. Using two sizes of coarse aggregate and one of sand the scraper is able to load well within the batching time.

Cement

Cement is handled either in 1 cwt paper bags or in bulk, bulk cement being any cement which is not packed in paper bags, sacks, or containers of such a weight that when full they can be lifted by hand. Different methods of handling are required for site work from those in use in factories producing precast concrete, but bulk handling for most jobs consists of transporting the cement to the site in tank lorries and discharging into the site silo. Occasionally, for example in work overseas, the 400 lb steel drum has to be used, but usually it has to be broken down and the cement re-handled. The 400 lb drum is economic only where the wastage from bag cement will be excessive and the quantity does not justify bulk shipping.

The 1 cwt multi-ply paper bag is standard throughout the country. Its cheapness and lightness make it sufficiently adaptable to cover all conditions of use. Compared with hessian or cloth bags, which are liable to damage and have to be returned after use, the paper bag is easier to use and more simple to dispose of afterwards. No other method has yet been discovered which is superior and which can cover all the conditions of use in the same way. The only trouble likely to occur in site use is in the proper storage of the cement to ensure its freedom from damp. Cement will partially set under damp conditions, become lumpy and take on what is known as "air set". Such cement cannot be adequately mixed and, if used, results in low strengths because it is partially hydrated. To avoid these troubles storage must be watertight and moisture proof, and so arranged that the cement first in the store is the first out. Occasionally hot cement may have to be dealt with. The heat is derived from the grinding of the clinker, and makes the manual handling of the cement bags difficult. All that need be done is to allow the cement to cool. This is especially necessary in hot weather when the use of such hot cement can result in a false or premature set of the concrete.

In using bagged cement the proportions of the concrete mix and the size of the mixer should be arranged so that the quantity of materials charged into the mixer are based on units of 1 cwt of cement. This ensures that full bags only are used, for it is difficult, if not impossible, to split a bag of cement and still maintain consistent concrete.

Bulk Handling. The handling of cement in bulk in site work is now quite simple. Bulk supplies can be used with ease on jobs large enough to justify the erection of a cement silo, and since silos can be obtained in small sizes on hire and are easily transported, they are economic even on small jobs. On most jobs the cement arrives in pressure container lorries from which it is pumped to the cement silo. Deliveries every few days or even more frequently, if necessary, can usually be arranged so that the silo capacity required is not large and a storage problem does not arise.

The site cement silo is positioned adjacent to the mixer, and on the smaller models a weighing bucket is incorporated with the discharge mechanism. The required quantity of cement is weighed into the bucket which is then run out on rails suspended from the silo. The bucket then discharges into the mixer hopper. On large central batching plants the mechanism is more complicated but the principle is the same. Arrangements are usually made on large plants for the cement to discharge into the mixer continuously with the aggregates and water so as to increase the mixing efficiency.

The usual type of pressure container lorry is arranged so that it can be tipped for discharge and the cement is forced out by an air pressure of about 10 p.s.i. This is sufficient to aerate the cement and elevate it to a height of about 40 or 50 ft. Aeration reduces the cement density and causes it to travel in suspension with the compressed air in much the same manner as a liquid. It breaks down any arching action and promotes a steady flow, thus making charging or discharging a simple matter. The delivery operation is free from nuisance due to dust, and 5 or 10 tons of cement can be discharged in a few minutes. On jobs using large quantities the cement may be delivered by rail or road. Special wagons are available which can be off-loaded from rail wagons to road haulage and delivered to the site from the nearest railhead.

In special circumstances various other forms of cement handling are used besides aeration by compressed air. Bucket elevators, belt conveyors and special types of chain and spiral conveyors are all used for moving and conveying cement, but most of them have their application in cement works and precast concrete product factories and are little used on the site.

Batching materials

The batching of materials is the measuring of the required quantities of cement, aggregates and water to produce concrete. The cost of concrete depends upon proper batching; obviously the addition of more cement than is required makes the concrete more expensive, and in addition the cost of placing the concrete may be increased by variations in workability due to inaccurate batching.

The method of batching must be related to the size and importance of the job. On a small job with, say, a $5/3\frac{1}{2}$ mixer there will be no special requirements beyond the use of a swing weigh-batcher, and even this may be unnecessary when the concrete is required merely to provide site concrete or a clean level surface on which to carry out other building operations.

When the strength of the concrete is important or its quality must be controlled, then proper batching is necessary. Volume batching is usually decried but first-class work can be produced if a mechanical volume batcher, such as is incorporated in a continuous mixer, is used and when the man responsible for the plant operation is fully competent and has had sufficient experience.

Volume batching of cement is difficult to carry out accurately because cement may weigh from 75 to 100 lb/cubic ft depending on its compactness. This difficulty is overcome by weigh-batching on to continuously moving belts, a system which incorporates the advantages of weight batching with that of continuous production.

Volume batching by gauge boxes is fairly satisfactory if the gauge boxes are well made and have a small area to volume ratio. They are never used on site unless supervision is very strict, and since they suggest that a measure of control is being used when in fact it is non-existent, their use should be prohibited.

Large errors can occur in other methods of volume batching, such as using hoppers marked off along their sides.

Batching should be by weight, and preferably mechanical. This applies also to the measurement of the water, for on most sites the first thing which goes wrong with a mixer is the volume feed of the water. The measuring devices for water on most mixers are usually very poor.

The type of batching plant to be used and its simplicity or complexity depend upon the total quantity and the throughput of materials to be achieved.

The simplest type of swing weigh-batcher and the tipper-hopper mounted on a short section of rail has already been mentioned, as also has the type of weigh-hopper which is an integral part of the mixer. These types of hopper are usually speedy enough to keep a 10 cubic ft mixer operating normally with two men loading, as long as the men do not have to lift the aggregates too high when shovelling. Waist-high is the maximum that can be maintained with continued efficiency.

The integral skip weigh-batcher when lowered to the ground is most convenient for hand loading. When lowered it is detached from the mixer and rests in a weighing machine, which is either of the springless balance or hydraulic type. The materials are simply shovelled in or are loaded by a "hand" scraper.

When cumulative weigh-batching is used — as is usual with small weigh-batchers — then because of the nature of the materials the cement, being light and "fluffy", is usually weighed last. In consequence any errors in the weighing of the aggregates tend to be corrected on the cement weight. This has the effect of doubling the error in the aggregate/cement ratio. When the cement is weighed separately the water/cement ratio remains within the errors of the control on the machinery and the error in aggregate/cement ratio is halved. It is advantageous, therefore, to use either 1 cwt bags of cement or to use a cement silo which incorporates a separate weigh-hopper for the cement.

When the accuracy of control or the throughput quantity is sufficient to warrant it, the weighing of the aggregates is split between different weigh-hoppers. The weighing of the coarse aggregates is separated from that of the sand; two separate hoppers may be used for coarse aggregates and a further hopper for sand, together with a hopper for cement with the water also weighed. At the same time, by means of an electrical resistance probe, a correction can be made for the moisture content in the sand both as regards the amount of sand and the amount of water. In very large plants with high rates of production the time taken to weigh may control the production cycle. To reduce the batching time, aggregates may be weighed separately in different sizes by means of preset controls.

Even with weigh-batching large errors can occur unless the weighing plant is adequately maintained. The usual site batching plant incorporates a spring-balance type of weighing machine. Errors in this type of equipment may arise due to coating of the equipment with cement dust and fouling with spilled mixtures of cement and aggregates.

The large types of batching plant incorporate beam and jockey-weight weighing machines, which are usually accurate within 1½ per cent, but regular maintenance is necessary to maintain this accuracy.

Mixing and placing

The purpose of mixing concrete is to ensure that the various materials are thoroughly worked into a consistent and uniform mass in which all the ingredients are equally distributed.

There are three main types of concrete mixer in general use: the batch mixer, the continuous mixer and the paving mixer. The batch mixer is the most important, and of this there are three types; the tilting drum, the non-tilting drum and the open pan mixer. For a number of years these three had separate functions. The tilting drum was used for small portable mixers on small sites, the non-tilting drum for most other mixers from the largest to the smallest job, and the open pan mixer for rich dry concrete.

Most mixers will mix a wet mix satisfactorily with some degree of efficiency, but great difficulty used to be experienced with rich dry mixes for prestressed concrete or harsh dry mixes such as are used for pavement construction. With the continued use of such drier and harsher mixes, attention had to be given to the design of mixers for handling a wider range of concretes, so that with modern batch mixers there is not now the same simple distinction between the three types.

Non-Tilting Drum Mixer. Probably more concrete has been made with non-tilting drum mixers than with any other mixer. At the same time many are inefficient, they discharge a fatty mix at the beginning and a lean mix at the end of their discharge; they take too long to mix and too long to discharge. In design there has been little progress for a number of years and yet they continue to give valiant service.

The mixer is essentially a short cylindrical drum which rotates about a horizontal axis. The drum is fitted with fixed blades set at angles. These blades pick up the materials, carry them to the top of the drum as it rotates, and allow them to fall freely and so mix together. The actual size and shape of the blades, their angle of set in relation to the drum and their peripheral speed are important matters which affect the efficiency of any individual machine. The material is charged into the mixer through a chute or hopper. After mixing the concrete is usually discharged by inserting a retractable chute into the mixer drum, which catches the concrete as it falls and discharges it. This method helps to produce lack of uniformity of the discharged mix; when the discharging chute is pushed into the drum the material forms a heap on it, and larger material falls over the sides of the heap and back into the bottom of the mixer, so producing a mild form of size segregation. The result is that at the end of discharge it contains more large aggregate than at the beginning.

In one type of non-tilting drum mixer the material is discharged by reversing the drum. This moves the material out on a spiral set of blades through the cone end of the mixer and produces a more uniform mix.

The non-tilting drum mixer varies in size from ¼ to 2 cubic yd capacity, but the ½ and 1 cubic yd mixers are the most common; where a capacity greater than 1 cubic yd is required the use of twin 1 cubic yd mixers gives extra flexibility.

Tilting Drum Mixer. The tilting drum mixer in the shape of an open-ended round based cone was one of the first mixers made. For a long time it was restricted to simple portable mixers, i.e. 3½ and 7 cubic ft mixers whose efficiency was low. A number of manufacturers have now produced larger versions for central batch mixing and the 1 cubic yd sizes and above are quite efficient.

The mixer is loaded and discharges through the same end. During charging and mixing the end points upward at an angle. With the small portable machines the charging is usually manual, but with the larger mixers a cone hopper or chute is used to charge in the materials from the weigh-batcher hoppers. In some of the newer designs an integral weight batcher is incorporated together with an automatic water dispenser which injects the required quantity of water under pressure. The blades in the mixer lift up the material, part of which falls on to the inclined surface and then slides back down into the body of the mixer whilst the rest falls freely; by this means an efficient mixing action can be obtained, but the angle at which the drum operates is critical, and should be between 20 and 30°. If the angle is too steep the fine material tends to remain near the base and segregation may be caused.

Discharging of the small mixer and of some of the newer mixers is simple. The drum is up-ended and the material discharged. On the newer and larger plants the drum is up-ended by a hydraulic control, but on the small mixer it is achieved by rotating a hand-wheel which turns the drum over. As long as the free fall is small, segregation does not occur and a discharge of uniform concrete is obtained. This type of mixer has been used in the large sizes for mixing aggregates of 6 and 8 in. maximum size.

Where two or more mixers are used on one job they can be arranged without difficulty to be charged by a single batch weigher, and to discharge direct on to one or more wet hoppers.

There also exists a design of tilting drum mixer which consists of two cone ends. The material is charged into one side and discharged from the other, somewhat after the style of the non-tilting drum type; this type suffers from the disadvantage that the operator cannot easily watch both the charging and discharging, however, and in addition it is more difficult to arrange a single batching plant to serve twin drums.

Tests carried out on tilting and non-tilting drum mixers have shown that for sizes up to 14 cubic ft the non-tilting drum mixer is more efficient than the tilting drum mixer, and the type of non-tilting drum mixer which discharges by reversing the drum rotation has a higher efficiency.

Unfortunately the effect of the mix design and the characteristics of any particular mixer may cause a reversal in the general efficiency. The set and size of the blades, for example, can make a particular tilting drum mixer relatively efficient, while again the size of the mixer also has an effect, the modern large-capacity tilting drum mixers being amongst the most efficient.

Pan Mixers. The paddle or open-pan mixer consists of a circular pan which rotates about a central axis. Inside the pan, mounted off centre, is a rotating paddle. The rotating pan carries the materials round with it, while the rotating paddles mix and stir them. In the turbo-pan mixer the pan remains stationary and the paddles counter-rotate at speed on an axis which moves round the pan. The materials are charged into the open pan from a hopper and mixed by the action of the paddles. After mixing the concrete is discharged through a trap door in the bottom of the pan. Discharge is effected by blades which guide the material to the discharge opening.

The pan mixer is probably the most efficient mixer for all concretes other than wet or highly workable mixes. It is of particular value for mixing high-strength or gap-graded concretes, because the positive mixing by the rotating paddles prevents any balling or loss of fines due to sticking in the pan. Its disadvantages, apart from its relatively low efficiency in dealing with wet mixes, stem from its general shape and method of discharge. For small jobs or where the concrete is to be barrowed the bottom discharge is less convenient because the mixer must be mounted on a platform 6 to 8 ft above ground level, and the extra height above ground at which the mixer must be mounted may lead to some difficulties in the loading of aggregates into the batching hoppers. On large jobs it is usually necessary to install a small conveyor chute to prevent troublesome double-handling of concreting skips. On exposed sites strong winds may cause some troubles with cement dust and cause loss of cement during charging of the dry materials.

Operating a Mixer

With medium-size mixers larger than 5/3½ and fitted with a loading hopper, which is normal, the time allowable for hand loading the hopper controls the time required for the complete cycle of mixer operation. With say a 10/7 mixer the ideal time cycle is some 2½ min, which allows for the hopper being loaded.

With a 5/3½ mixer, the time spend loading the drum is necessarily additional to the machine's minimum operating cycle and should, therefore, be kept as low as possible.

A non-tilting drum mixer requires about two minutes to mix, which is the time it takes for the water to work through the materials. With such a mixer the water is usually discharged in bulk by the quick emptying of the water tank. To prevent the dampened material sticking to the blades the flow of water should be started just before the charging of the cement and aggregates. As they drop into the back of the mixer, these materials push the water to the front. The mixing time is then the time required for the water to work through the mix.

In mixing dry-lean concrete with a 16:1 aggregate/cement ratio and a water/cement ratio of about 0·5 very little water — in fact sometimes no water at all — is needed if the aggregates have a high water content, and in consequence 30 sec mixing may be all that is necessary. The mixing time for an open pan mixer and for a large modern tilting drum mixer is not more than $1\frac{1}{2}$ min even with relatively dry mixes, and for turbo-mixers may be as small as 30 sec.

To obtain thorough and quick mixing the correct charging of the materials is important. Ideally all the materials should be charged uniformly over the same period. The water should be injected under pressure continuously with the other materials, but this is not usually possible. The efficient charging of the materials increases in importance with the size of the mix, but with modern plant the means of controlling the charging time has been improved on the larger mixers.

On some mixers the water tanks are inefficient, their discharge system often does not permit of any adjustment, and the water is injected in one fierce gush. On large mixers, the water tanks are often calibrated to discharge not less than 10 gal, whereas with dry-lean concrete, as already mentioned, very little water is required.

The mixer must be charged only to its rated capacity. There is a tendency to charge in more material than can be properly mixed when using lightweight aggregate and, with heavy aggregates for reactor shields only about half the normal volume of materials can be mixed per batch.

Additives such as workability agents should be charged into the mixer automatically where possible, without reliance being placed on the mixer-driver's memory. If the mixer-driver fails to add the admixture the concrete will usually be stiffer and look harsher, whereupon he will tend to add more water and so produce weaker concrete.

To obtain a thoroughly mixed concrete it is essential that the mixer is operating efficiently and is thoroughly maintained. This requirement may appear to be so obvious as not to require stating, but the most frequently occurring troubles with mixers stem from poor or bad maintenance of the machines.

If the mixer is not cleaned properly after use its efficiency will be seriously reduced, the mixing will be poor and the time taken to discharge will be increased. Due to bad maintenance the cut-off valve of the water tank often leaks, allowing a small continuous discharge during the whole of the mixing period.

The mixer must be operating properly, with the drum or paddles rotating at their correct speed. The blades in a rotating drum must not be coated or clogged with old cement, nor must they be excessively bent or worn. The mixer must be set level; a batch mixer mixes inefficiently and a continuous mixer incorrectly if not set level, and in addition the usual water gauge operates incorrectly. The mixer should be laid out so that the mixer-driver can see into the mixer drum and into both sides of a non-tilting drum mixer. On a large plant involving twin drums this means careful layout to ensure that the drums discharge to the required place.

The first batch of concrete into a mixer must be used as a primer. It is usually enriched with an extra 10 per cent of cement and sand, or a cement mortar is first charged in. If the first batch corresponds with the start of concreting in a wall or column then an increase in richness (by reducing the coarse aggregate to half the normal figure) will take care of priming the mixer.

If the first batch uses sand and coarse aggregate stored in the hopper overnight then it will be extra wet (the water having drained to the bottom of the hopper) and care is necessary to achieve consistent concrete.

The driver should be instructed to work to constant workability gauged by inspection and checked by, say, the automatic workability apparatus. A good mixer-driver can do this and achieve consistent results.

Variations exist between batches in some small tilting drum mixers and in nearly all non-tilting drum mixers, due to some of the cement and sand from two consecutive batches sticking up between the blades and then discharging in the next batch.

In the following batch the fines again tend to accumulate, and so on. This produces one batch deficient in fine material, the second nearly correct and the third batch grossly oversanded.

The amount of water used and the workability affect the amount of fines sticking in the mixer. When a mix is fairly rich and somewhat dry, the amount of material retained in the non-tilting drum mixer may be more than one-quarter of a batch. When the next batch is charged in, then the mixer becomes too full and spillage may occur. The accumulation of material in a mixer is a defect which varies from mixer to mixer and, for any one mixer, with the mix proportions.

Conveying concrete

The methods of conveying concrete from the mixer to the point where it is to be placed must ensure that the concrete is quickly and cheaply transported and that it does not change its properties by drying out, by segregating, or by bleeding. After the concrete is mixed care is necessary to prevent it segregating into its constituent parts and the use of the wrong method of conveying can do this.

Concrete from large, single- and double-drum mixers is often discharged into a wet hopper to facilitate its distribution, and from the wet hopper into trucks, dumpers, skips, buckets or conveyor belts to be conveyed to its required position. Alternatively it may be discharged from the mixer direct to the bucket or skip or into the bowl of a concrete pump or pneumatic placer.

Concrete from small mixers is usually discharged into barrows or concrete prams but on some sites dumpers, monorail transporters, boom transporters or powered barrows similar to small dumpers may be used. Where concrete is produced by a central plant for a number of buildings being constructed on one site then various forms of transport may be combined. For example, concrete may be loaded direct to skips for one building, to a pneumatic placer for another part of the site, and to a wet hopper for subsequent transport by dumper to a third part of the site.

The choice of any particular form of transport more often depends upon what is available than on any other factor, but even in such a case, as well as when a free choice is available, it is essential to appreciate the characteristics of each form of transport and its effect on the concrete.

Barrows and Prams. Wheelbarrows are in common use on site work and are well suited to moving small quantities of concrete. They can be wheeled up and down planks and on scaffolding boards, can be easily handled by one man, and can be accommodated in the usual materials hoist. They hold about $1\frac{1}{4}$ cubic ft of wet concrete but nearly 2 cubic ft of dry concrete. Thus they can accommodate only part of a mixed batch. The time required to position and fill successive barrowloads usually controls the number of batches produced per hour. Because most mixers discharge richer concrete at the beginning than at the end, the contents of one barrowload differ slightly from its neighbour. This usually makes little difference, however, because of the remixing which occurs during placing.

Powered barrows and concrete prams are in use in various capacities up to $\frac{1}{2}$ cubic yd. The larger sizes are really four-wheeled light dumpers. Powered barrows and prams are suitable for moving medium quantities as long as the ground is not too soft, and is fairly level.

Boom Conveyor. The use of a light steel boom for delivering concrete on small sites, for example in housing construction, has been advocated from time to time and has been adopted on some sites. The advantages of the boom, which may carry 15 cwt and span 40 to 50 ft, are that it can span most house sites, the labour required to move the concrete is small, and the time taken to erect or dismantle and move the boom by half a dozen men is less than an hour.

Full advantage of a boom can be taken only when the mixer can be sited centrally in the right position. The boom will not work on a hill site and cannot accommodate large changes in level. Its use is restricted mostly to concreting the foundations for houses.

Conveyor Belts. These can be used to move concrete short distances, and to elevate it 20 or 30 ft or more without difficulty. They cannot be used for moving wet or very workable mixes, and on steep inclines there is a tendency for segregation to occur as the belt passes over the rollers. Segregation also occurs as the material is discharged, the coarse material being thrown forward and the fine material dropping back under the end of the belt. If the belt discharges to a wet hopper some remixing takes place during the discharge from the hopper.

Short conveyor belts, mounted on a turntable, are sometimes used to convey the mixed concrete from a pan mixer with bottom discharge to a wet hopper or to skips.

Dumpers and Trucks. Dumpers and trucks are the easiest and cheapest method of transporting quantities of concrete over a site where the placing area is not covered by cranes, or where the quantities of concrete, or the distance it has to be conveyed, are against the economic use of pumps or placers. For transporting concrete on roads and runway contracts, tipper lorries may be used for distances of 5 to 10 miles. In fact in some countries on the Continent open trucks are used even for supplying ready-mixed concrete.

All trucks and dumpers tend to affect the concrete adversely as they convey it, because of the jolting over the ground. If the concrete is too wet segregation may be caused, whereas if it is too dry it may be compacted and be difficult to discharge. However, the major portion of any segregation which occurs takes place when the concrete is loaded. A large conical heap is formed on the bed of the tipper lorry and this leads to segregation. This trouble does not occur to the same extent with dumpers, probably because of the hopper shape of the dumper body.

The lorry or dumper may discharge directly into place when the area is large, although it may be necessary to discharge on to a spot board and then shovel the concrete into place. On airfield construction work where dry-lean rolled concrete and paving quality concrete are used the usual transport from a central batching plant is by 3 cubic yd open tip lorries, the lorry discharging straight into the paving machine. There is usually not much room available in road construction work, and specially constructed tip lorries may be used. These have a cone end which discharges on to a chute in the same way as do ready-mixed concrete lorries.

Dumpers and trucks, together with skips and buckets, form the main methods of conveying medium or large quantities of concrete from the mixer to the point of placing. Unfortunately with concrete of good workability there is always the tendency to segregate wherever concrete is transported by wheeled vehicles. To reduce segregation the mixer should be sited as near to the areas of large concreting operations as possible; this will also reduce the cost of handling.

Monorail Transporter. On building work which extends over a large area the monorail transporter is useful. It consists of a single rail supported on short cross beams, upon which travels a jubilee skip. The skip will carry about $\frac{1}{3}$ cubic yd of concrete at 3 to 5 m.p.h. It is powered by a petrol engine and can be arranged to haul a similar skip behind itself. The rails are laid in 12 ft straights and in curves of 12 ft radius.

The monorail will transport concrete over long distances easily and with the minimum of labour. Gradients of 1 in 20 can be negotiated without difficulty, and the transporter can be arranged to stop automatically at the mixer for filling and at the placing point for discharging. It has the disadvantage that unless adequate usage is obtained from it, the labour and cost involved in setting up the rail and moving it into new positions may be greater than moving the concrete by dumper or powered concrete pram.

The jolting of the jubilee skip over each rail joint causes segregation in wet mixes, and compacts dry concrete, making it difficult to discharge and place.

Skips and Buckets. On civil engineering works skips and buckets are the traditional methods of moving concrete, and their use in building work has extended with the adoption of tower cranes. The skip or bucket is lowered on to the ground, filled with concrete, and then lifted and swung over to the position for placing by the crane. The concrete is discharged from the bucket two or three feet above the placing position. Buckets and skips of various capacities are available, from about $\frac{1}{2}$ to 8 cubic yd. Where they are filled direct from the mixer they should have a capacity sufficient for a complete batch. Even when a wet hopper is in use it is better to use buckets or skips with a capacity which is a multiple of the batch size in order to reduce the effects of segregation to a minimum.

There are three or four different types of skip and bucket. There is the square, hopper-shaped skip with bottom or side discharges; these are generally of $\frac{1}{2}$ to $1\frac{1}{2}$ cubic yd capacity, and are usually fitted with single or twin radial gates; these are useful for handling concrete of good workability. The side discharge is particularly useful for concreting in framed buildings, but sticky or harsh mixes are handled only with difficulty.

The circular bottom-opening bucket of 1 to 4 cubic yd capacity is a very useful piece of equipment. It usually has steep conical sides with a single roller gate which is easily operated. It can be discharged either from the crane hook or can be landed and discharged. It will handle all types of mixes, including sticky or harsh ones.

Special skips are available for underwater concreting, fitted with metal or canvas covers to protect the concrete whilst it is being lowered under water. One type of skip is so arranged that it can be discharged only by a diver, whilst another is designed to discharge without a diver. With this latter type as soon as the skip touches the bottom it releases the bottom doors. As the skip is then lifted up, these swing open with the weight of concrete which discharges on to the bottom protected by the door flaps, which thus prevent it from mixing with the water. Other types of skips or buckets are available for concreting in confined spaces or for passing through air locks.

The troubles experienced with skips and buckets are associated with the discharge of the concrete. The discharge opening is generally too small, and relatively dry concrete tends to stick in the container, expecially in skips with side discharge.

When only part of a site is covered by cranes, other forms of transport may be used in conjunction with a skip or bucket. For example, the bucket may be loaded on a lorry and filled at the mixer or wet hopper, transported to within the crane's radius and there lifted, discharged and re-loaded on the lorry. Alternatively the concrete may be moved by dumper or placer to within the crane's radius and there discharged into a skip. Overhead cableways have been used with success for distributing skips of concrete in the construction of large dam projects (Lambert, 1949). Cableways have the advantage that they can operate without causing any segregation of the concrete, and once installed they can compete both in speed and in cost with other forms of conveyance.

Pumping Concrete

Pumping is an excellent method of delivering large quantities of concrete from a central mixing plant on a site which is fairly flat, or where a delivery pipe can be laid with few bends. Not all concretes can be pumped, although in practice the range of consistence of concretes that can be pumped is wide; they must all have sufficient cement mortar to lubricate the concrete and prevent blockages of the pipeline, however.

A concrete pump is a single cylinder ram pump fitted with inlet and outlet valves which operate alternately. It has a conical hopper for receiving the concrete, although in some models this may be replaced by a paddle type mixing hopper. The common size of pump is 6 in. and this can pump 20 cubic yd of concrete per hour, which is equivalent to the delivery, on a three-minute cycle, of a cubic yd mixer. Concrete pumps, however, like all plant which deals with concrete, suffer from breakdowns, and a more realistic average delivery would be 15 cubic yd per hour. The pump works as follows: on the suction stroke of the ram, the outlet valve is closed by a rod operated on a cam whilst at the same time a second rod opens the inlet valve and allows the concrete from the delivery hopper to be drawn into the body of the pump. On the delivery stroke the inlet valve is closed, the outlet valve opened, and the concrete rammed forward through the outlet valve into the pipeline. The pump works on a cycle of about 1¼ sec, i.e. about 45 strokes per min.

Regular maintenance is essential, for although a pump is simple in principle, a number of refinements are necessary to deal with the abrasive nature of concrete. The piston head, for example, incorporates cup-washers so as to ensure that the piston cylinder is kept free from cement mortar, and a water flushing system is incorporated. If these washers are not properly maintained then either water gets into the pipeline from the flushing system and mixes with the concrete or the piston and cylinder are scoured by cement and sand.

Recently a double acting pump has been introduced of lighter construction than normal. It has two rams which operate alternately in separate sleeves joined at a Y junction. The pump stroke can be varied to suit pumping conditions.

A 6 in. pump is capable of delivering concrete 1000 ft horizontally or up to 125 ft vertically. One foot height is equivalent to 8 ft on the flat, and an 11¼° bend is equivalent to 5 ft on the flat. The layout, for sites involving both horizontal and vertical travel, should be designed to use a minimum number of bends; 90° bends can be used but troubles arise due to the tendency of the pump line to kick at each stroke of the pump; sharp bends also tend to blow apart at the joints. The kicking, jolting action in a pump line means that it must be adequately supported. It must not be tied to or supported on shuttering or scaffolding used for other purposes.

Any rise in the pipeline should be as steep as possible to ensure that the required height is gained as quickly as possible. In other words long slow rises should be avoided; these cause trouble with all but very fatty mixes, as they lead to wet segregation of the concrete.

Pumpable Mixes and Pumping Technique. The ideal mix for pumping is probably within the range 3:1 and 5:1 with a sand content of about 40 per cent and a water/cement ratio of 0·45 to 0·6; in other words a fatty mix with excess sand, very workable and with no tendency to segregate or bleed. On the other hand mixes as lean as 8:1 with poorly shaped aggregates can be pumped using the double acting pump and a workability agent, but dry, harsh or very wet mixes will not pump. The maximum size of aggregate which can be pumped through a 6 in. pipeline is nearly 2 in., but fewer troubles occur if this is limited to 1½ in.; similarly the maximum size for a 4 in. pipeline should be ¾ in.

It is not usual to pump rich mixes, since these are not often placed in sufficiently large quantities to demand the use of a pump; no difficulty is experienced, however, unless they are relatively dry. Mixes which will pump easily usually flow easily into the bowl of the pump, the pump being self-feeding. If a man has to be employed to push the mix into the bowl, or if the mix tends to segregate, then trouble in pumping can be expected.

Blockages are sometimes due to the concrete not being fatty enough, i.e. not having enough sand to ensure that the ram pushes it through the pipe. Mixes which do not contain enough sand pack tightly into a mass which then has to be cleaned out by hand. Sometimes a blockage or a partial stopping in the pipeline can be removed by hammering the pipe with clump hammers, but as with using a placer the number of men necessary to hammer the pipe is a direct reflection upon the efficiency of the whole operation.

In the operation of a concrete pump there are certain rules of thumb to be observed. First the pump line must be lubricated. This usually consists of a flush of water followed by mortar grout before the first batch of concrete, whilst in addition the first batch is made a little wetter than the remaining batches. If a line is to be shortened, and it is always better to work back to the pump, it must be done quickly to ensure that the concrete is not allowed to remain stationary too long, as otherwise blockages occur. When a line is to be lengthened during pumping it must be done carefully by only one or two pipes at a time; otherwise blockages may occur.

When pumping is completed the line must be blown out. This is done by using a paper plug, made from well-soaked old cement bags. The plug is driven through the pipe by compressed air. Care and experience is necessary in such cleaning to ensure that only sufficient air pressure is used to keep the plug moving, and that the pipeline is not under high pressure when the remains of the concrete and the plug are ejected. If, for some reason, the line cannot be cleaned by blowing through a plug, it is necessary to resort to lengthy hand cleaning and flushing out with water. As with all processes using machinery to deliver concrete, the concrete must be delivered before the initial set takes place; about an hour can be allowed for the concrete to remain in the pipe without moving, but any longer period carries the risk that the concrete may "freeze" in the pipe, i.e. it may set, with the consequent danger of losing some of the equipment.

Pneumatic Placers

A pneumatic placer is an excellent method of delivering medium or large quantities of concrete. The cost of delivery is small when the quantity which can be delivered without moving the pipeline is large. It may be compared directly to pumping, with which it shares some advantages and disadvantages. Delivery lengths are similar to those for pumping, and similar considerations as to layout of the pipeline and the effects of bends and rises apply equally to placers.

The Placer. The placer was developed for discharging concrete in tunnel linings by blowing the concrete behind the shutters; correctly used it is satisfactory, but has a tendency to cause segregation and this is accentuated by poor operation in rock tunnels. It consists essentially of a steel container in the shape of an inverted cone, fitted with a charging hopper at the top and a discharging pipe at the bottom. The top is closed by a sealing cone.

The method of operation is as follows. A batch is charged into the container. The top sealing cone is cleansed by compressed air and then closed. Air pressure is introduced into the top and at the same time by a lead-in pipe at the bottom. The air pressure at the top keeps the sealing cone closed and provides a push behind the body of concrete. The air inlet at the bottom acting on only a small amount of concrete pushes it along the discharge pipe to the end where it is ejected into a discharge box. This is a steel container into which the concrete is shot horizontally. It contains a baffle plate and a discharge opening at the bottom through which the concrete falls. A discharge box is not needed where the discharge end of the pipe is buried in the concrete or in lining tunnels.

In addition to the placer, pipeline and discharge box an adequate air-receiver is required to provide a volume of air at the required pressure of about 110 p.s.i. Sizes of receivers are linked to the capacity of the placer and the length of discharge; for example, a ½ cubic yd placer using a 4 in. pipe 300 ft long will require about 150 cubic ft receiver and a 225 cubic ft/min compressor.

As with pumping, a placer is capable of delivering concrete up to 1000 ft horizontally or up to 140 ft vertically. For the successful operation of a placer pipeline there should not be any bends within the first 50 ft or so of pipe if the discharge pipe is long. The total number and sharpness of bends should be a minimum, but at the same time if the concrete has to be lifted the riser pipe should be steep and near to the placer so as to take advantage of the higher air pressure.

The usual sizes of pipe are 4 and 6 in. diameter. With a 4 in. delivery the aggregate should be restricted to all material passing a $\frac{3}{4}$ in. sieve, and this can be increased to $1\frac{1}{2}$ in. with a 6 in. pipe. As with pumping, the pipeline must be primed, usually with a batch of soft mortar or an over-sanded rich mix of concrete.

Operation. The operation of a placer, like that of a mixer, is simple, but if its operation is deputed to the less intelligent of the labour force then there is a lowering of its efficiency and an increase in stoppages due to bad maintenance and poor operation.

Blockages can be caused by stopping the placer abruptly during the discharge of a batch or by attempting to move too large an aggregate through too small a placer. If blockages do occur then they can usually be cleared by maintaining the air pressure and hammering the pipe at the site of the blockage, the position of the blockage being easily located by "ringing" the pipe with a small hammer. If this is of no avail then the pipe must be broken down and the blockage cleared by hand. Fortunately the remainder of the pipeline is usually empty, as opposed to pumping where the pipeline is always full.

Placing concrete

Concrete should be properly placed to ensure that it can be well compacted into a homogeneous mass. Improper placing results in serious defects such as segregation, bleeding and honeycombing. These can arise either because of a lack of knowledge of or a complete disregard for the requirements of good placing. Besides avoiding segregation, proper methods of placing will prevent distortion of the shuttering and movement of the reinforcement. Concrete is analogous to a heavy emulsion of materials of different specific gravities; improper handling, therefore, results in the separation of the coarse and fine materials. Unrestrained dropping, steep chuting and the horizontal flow of concrete in the shutters should not be permitted. Concrete is sometimes placed between vertical shutters by simply allowing it to drop regardless of the height. This results in the concrete rebounding on the reinforcement and the sides of the shutters and separating into its constituent parts. At the same time the steel is prematurely coated with mortar which may dry before it is finally covered with concrete. When concrete is to be placed between vertical shutters and the free fall exceeds 5 to 8 ft, it should be placed in its final position by a tremie pipe, because it can be dropped considerable distances through such a vertical pipe without difficulty and without harmful segregation. Properly used such a pipe will add little to the cost of placing and will prevent honeycombing with the consequent unsightly patching having to be done later. If the tremie is supported on light cross-timbers, it can be moved along the wall as concreting continues.

Concrete should be placed in the formwork close to its final position. Movement of concrete in a horizontal direction usually results in a differential movement of the coarse and fine aggregates, so that leading the concrete along the forms with a vibrator may result in segregation. Furthermore, dumping in large quantities at any point and allowing it to flow again causes segregation and also results in poor compaction within the centre of the concrete mass.

The depth of any one layer of concrete should not be greater than 12 to 18 in. depending upon the congestion of reinforcement, but in mass concrete work with continuous concreting operations the depth of the layer is controlled more by the rate of delivery of the concrete than by any other factor. In such mass work high-powered 4 in. vibrators can adequately compact layers at least 2 ft thick. In the concreting of slabs and road or airfield pavements, the discharge from the dumper, truck or placer is usually only a foot or two above the surface being concreted, whilst to ensure economy and speed of operation the concrete is dumped continuously over the area, so that no segregation takes place.

Relatively thin walls and columns in buildings are a source of trouble; the concrete may sometimes be dropped 12 ft or more into an area which cannot be properly inspected, with the result that the concrete is placed with little control. Besides rebounding on the side shutters, when it hits the bottom of such a section it usually forms a conical heap down the sides of which the large aggregate rolls, producing a harsh concrete devoid of fines which no amount of vibration can compact and resulting in segregation and honeycombing on the finished surface. If it is necessary to concrete walls 8 ft or more in one lift, then panels should be left out of one side of the shuttering so that the free fall can be restricted and the vibrator in the concrete can be properly controlled. Concrete that is allowed to slide down a steep chute or is discharged from the end of a belt conveyor will segregate on falling off unless a stop baffle is incorporated, and even then some segregation may occur.

For the lower section of the first lift in a wall or column, especially where the main reinforcement laps with the starter bars, it is often best to reduce the quantity of coarse aggregate in the mix by half so as to provide about 6 in. of richer concrete which will bond properly against the old concrete. It is considered that this solution is a better one than the usual requirement of a layer of mortar, which so often is a wet grout which weakens rather than strengthens the concrete.

Under-water Placing. Placing concrete under water is to be avoided wherever possible. Where there is no alternative the concrete must be placed without disturbance, as otherwise it will become mixed with the water. It is not possible to compact or vibrate concrete placed under water so the concrete must be self-compacting, i.e. wet enough to flow under its own weight but free from segregation and bleeding.

Apart from the use of pre-packed or grouted concrete there are three methods of placing concrete under water. They are by dropping through a tremie pipe, using a bottom opening skip, and dumping in bags. Concrete placed by a bottom opening skip or by tremie forms a layer of laitance on the surface of each lift. If, for some reason, the concrete has been disturbed more than usual during placing the laitance may be excessive. It must be cleaned off before the next lift, but wherever possible the concrete pour should be continued to above water level to avoid the occurrence of horizontal joints.

Concrete placed under water is usually rich in cement, and 4:1 aggregate/cement ratios are common.

Under-water Placing by Tremie. Placing concrete under water by a tremie pipe consists of dropping the concrete through the pipe in such a way as to keep the pipe full of concrete and prevent the concrete mixing with the water.

The skill in using a tremie lies in ensuring that the concrete flows down the pipe continuously, so that the pipe never becomes empty, otherwise the water will rush in and prevent successful concreting. To start concreting, the tremie pipe, with its hopper on top, is lowered until it nearly touches the bottom. A plug of cement bags is pushed into the top of the pipe and the hopper filled with concrete. The concrete pushes the plug down and the hopper is maintained nearly full of concrete. Eventually the concrete will cease to flow so the tremie is slowly lifted up. This will start the flow again. If the flow becomes too rapid the tremie is lowered quickly.

Ordinary 6 in. diameter concrete pump or placer pipes make a satisfactory tremie. A wet hopper to regulate the flow to the tremie hopper is usually necessary. In concreting large areas tremie pipes at 12 to 15 ft centres will be necessary. They may be moved laterally to extend the area of concreting, but care must be taken to keep them full of concrete whilst this is done. The tremie pipe is simple to use for large unobstructed areas to be filled with mass concrete, but lateral obstructions make concreting difficult when they restrict the flow of the concrete.

Under-water Placing by Bottom-opening Skips. Just as when using a tremie, concrete placed by skip must be dumped with the minimum disturbance. The skip must rest on the bottom before the doors are opened, and the type of skip which opens when it reaches the bottom is an advantage. When the bottom doors are opened the skip is raised gradually to allow the concrete to flow out without disturbance. The skip should always be filled to capacity, and unless a special underwater skip is used a cover should be placed over it to eliminate any agitation of the surface of the concrete while the skip is lowered through the water.

Dumping in Bags. Concrete may be placed by dumping in bags. The bags are placed in position by a diver in much the same way as sand-bag walls are built. The bags are bonded together and may be used to form a retaining wall in place of shuttering where a tremie or bottom-opening skip is to be used.

Canvas bags are also used to lower concrete to a diver when he is to place it in confined spaces which do not warrant the use of a tremie.

The compaction of concrete

The compaction of concrete is the process whereby the amount of voids is reduced to a minimum and the particles of aggregate are constrained to pack more closely together so as to achieve the maximum potential density and strength from the concrete.

Before the advent of mechanical vibrators this could be achieved only by hand ramming, punning and spading. Old specifications for concrete often included clauses dealing with such hand tamping and ramming; these clauses were often most detailed and of great length, illustrating that the engineers responsible were most concerned about compaction. Hand placing as normally carried out to-day is a relatively inefficient and an expensive method of producing a dense concrete free from large air voids. Concrete may have to be made wetter than desirable when hand compacted.

In the early days of concrete construction earth-moist mixes were used almost exclusively; they were deposited in thin layers and were well rammed using a large amount of labour. This produced good concrete, and since labour was cheap a satisfactory concrete could be produced. Occasionally hand compaction is still necessary, but because of high labour costs, the materials are now cheaper than the labour and, therefore, when hand compaction must be used a mix richer than normal is necessary.

The invention of reinforced concrete made it impossible to place earth-moist concrete by ramming. To pack the concrete around the steel to ensure adequate bonding it was necessary to use wetter mixes. To achieve high strengths, however, concrete must be made relatively dry, the density increased and the amount of voids in the concrete reduced to a minimum. The proper compaction of dry harsh mixes can only be achieved mechanically, the most successful mechanical tool being the vibrator. Concrete displays an entirely different property when vibrated; the surface friction between adjacent particles is reduced, the concrete becomes plastic, and it behaves like a heavy liquid.

Vibration of Concrete

Apart from certain specialist construction it is now doubtful whether the compaction of concrete by hand should be permitted. Vibrators, whether internal or external, are available in all sizes to suit all jobs, and earth-moist concrete which cannot be compacted by vibrators is required on very few jobs, the main exception being perhaps packing in underpinning work.

Concrete is vibrated by the insertion of a vibrating mass into it (see Plate 6) or by the application of a vibrating mass to it, or by clamping a mould filled with concrete to a vibrating table and vibrating the whole. Concrete which is to be compacted by vibrators must have been properly proportioned, or segregation and bleeding may occur. It is usually less workable and has a lower sand content than one suitable for placing by hand compaction.

Vibrators were first used in this country in about 1902 when during the extension of a foundry building the foundry vibrators were used to compact the concrete. In 1917 Freysinnet used pneumatic hammers to compact concrete. In 1927 Denian of France patented a method of direct vibration by internal vibrators and so replaced the previous shaking of the formwork together with rodding and spading to induce compaction.

In site construction work internal vibrators are used almost exclusively; external or form vibrators are only an adjunct, to assist surface compaction. In the manufacture of precast concrete, however, form vibrators or table vibrators are generally used.

In the theoretical investigation into vibration Stewart recognized three separate phases in the process of compaction, but for practical purposes using internal vibrators only two

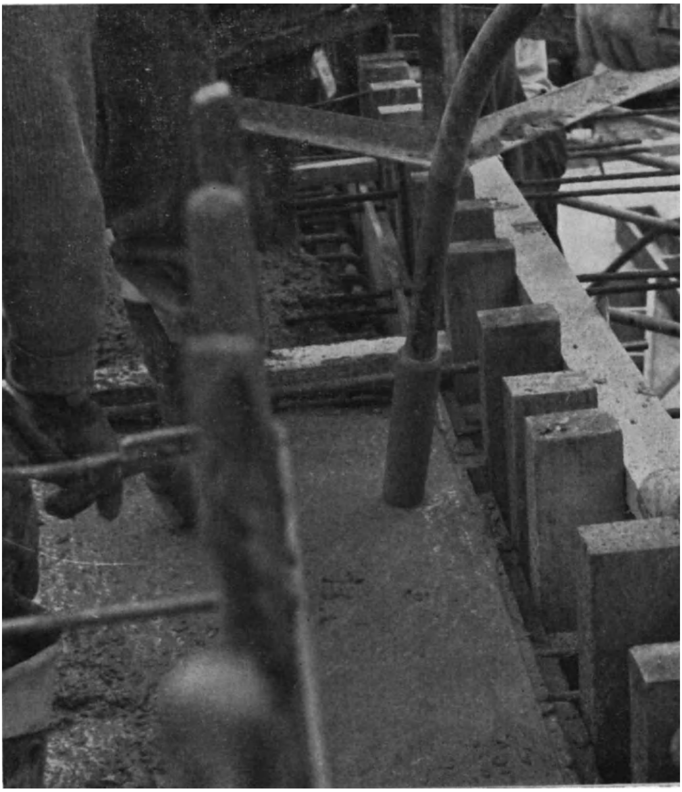

Plate 6. Compacting concrete around congested reinforcement by internal vibrators.

phases need be considered and these are easily recognized by visual inspection. The first is the initial collapse of the deposited concrete; the loosely packed concrete subsides, the arching action of the larger particles is broken down, and the mass gradually becomes like a viscous fluid.

The second phase is de-aeration in which the entrapped air bubbles are forced upwards and the voids are reduced to a minimum. If this phase is prolonged, segregation may take place with the gradual sinking of the large aggregate to the bottom and with the finer materials and cement slurry being drawn towards the vibrator.

Investigations carried out to determine the best combinations of amplitude and frequency for internal vibrators have suggested relatively low-frequency, high-amplitude vibrators are best suited to dry concretes. High-frequency, low-amplitude vibration has the greatest effect during the first phase of compaction, causing more rapid collapse and subsidence of the loose uncompacted concrete but low-frequency vibration has a greater effect in the second phase causing a more rapid expelling of the entrapped air. On the whole, however, it is probably better to use a high-frequency, low-amplitude vibrator since with this a greater degree of compaction will be achieved during the period of vibration commonly allowed in site work. Very little attention has been paid to the acceleration force of the vibrators but for satisfactory compaction the acceleration must be greater than some critical value which varies with the mix, but is about 4 *g*. Where the whole mass of concrete is subject to vibration, as on a table vibrator, attention must also be paid to the inherent stability of a mix. With some mixes there is a tendency for the concrete to rotate in the mould, sucking in air on one side and pumping it out on the other. This difficulty is not met on site work using internal or shutter vibrators.

The use of vibrators to achieve compaction results in the full strength of the concrete being achieved by reducing the air voids. A greater strength and density can also be achieved because of the ability of vibrators to handle less workable concrete. The higher strength results from the total amount of water per cubic yard being reduced and the concrete made leaner whilst maintaining the same water/cement ratio. Alternatively, keeping the aggregate/cement ratio constant, the water/cement ratio can be reduced which again results in a higher strength.

Although the correct use of vibration will produce, either directly or indirectly a better and usually cheaper concrete, it is sometimes suggested that there is an overall increase in cost because the shutters have to be made heavier and more watertight to resist the greater pressure and prevent bleeding. Although this is difficult to refute, the cost of formwork depends more upon the number of uses, its handling ability and also the ease of erection and dismantling. If shutters are properly constructed to make the total cost, including labour and materials, a minimum, then it will usually be found that they are of sufficiently high standard for vibrated concrete without costing any more.

Revibration. Occasionally references are made to the revibration of concrete, and as to whether it should be permitted. Concrete which is subject to vibration whilst still plastic but after it has been compacted in place may be said to be revibrated. Partially set concrete should not be disturbed unless the disturbance is deliberate and controlled.

The revibration of partially set concrete which comes about by chance is likely to cause harm to the concrete. Revibration can be used when it has been necessary, for some reason, to place a concrete wetter than required and it is desirable to increase the strength to the maximum attainable. If the concrete is too wet when first placed, however, continued vibration will result only in segregation and a weakening of the concrete.

The concrete may be compacted and left for a period of up to 4 hours and then revibrated. This period allows some hydration of the cement and on revibration there is an increase in both density and strength. The increase may be from 10 to 40 per cent of the non-revibrated concrete (see Fig. 4.1). The

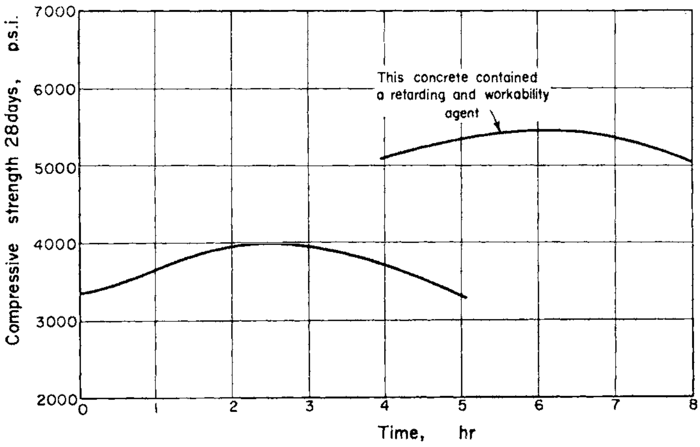

Fig. 4.1. Effect of revibration on strength of two concretes.

increase depends upon the original strength of the concrete and the time of revibration, the maximum increase usually occurring about 2 hours after initial compaction; after 4 hours, revibration causes a decrease in strength unless the setting and hardening has been delayed by a retarding agent (see Fig. 4.1).

Vibrators

Vibrators are of two general classes, internal and external. The external vibrator is usually a vibrating machine which is clamped to the formwork, but there are special types used in slab and paving construction in which the vibration is applied to the top surface of the concrete.

Internal Vibrators. Internal vibrators are the more common. They consist of a high-speed rotating element enclosed in a suitable casing; the element being out of balance, the high-speed rotation imparts a vibration to the whole of the head.

The rotation is produced in one of two ways; by a flexible drive from an electric or petrol motor, or by a direct coupled electric or air motor mounted in the head of the vibrator.

For most work vibrators of 1 to 4 in. diameter are suitable, a 2 in. vibrator being used for ordinary reinforced concrete beams and columns and a 4 in. vibrator for more massive work. Where the reinforcement is very congested a thin poker vibrator may be required to penetrate between closely spaced bars.

Current practice tends towards the use of a high-frequency vibrator of 9000 to 10,000 c.p.m. although vibrators up to 13,000 and 14,000 c.p.m. are available. High-frequency vibrators have an effective vibrating range in reinforced concrete of between 2 ft and 4 ft 6 in. Unfortunately the power consumption of a high-frequency vibrator is always higher than an equivalent low-frequency 3000 c.p.m. vibrator, and at the same time maintenance is usually greater for higher-frequency vibrators.

To achieve high frequencies of the order of 9000 c.p.m., different mechanical methods are used. The simplest is to run the vibrator from a flexible shaft rotating at high speed. This allows a choice of prime movers and the vibrating head is simple, but the high-speed flexible drive shaft is a source of weakness, and requires careful use and maintenance. To overcome this weakness the shaft can be run at about 3000 r.p.m. and high-frequency vibrations induced by a step-up gearing in the head of the vibrator. The construction of such gearing in the head means that the gears are subject to extra wear due to the transmitted vibration. The type with a motor in the head also suffers similarly; no flexible shaft is required, but the use of a built-in electric motor involves precision engineering with the consequent necessity for careful use and maintenance.

Where compressed air is freely available, as is usually the case in tunnel work, the pneumatic vibrator is suitable. This is more robust than the comparable electric model and is an efficient tool. It is not generally used merely because of the necessity to provide a separate compressor.

Most mechanical troubles are overcome in vibrators which have a slow-speed flexible drive shaft and in which the vibrations are induced by a loosely held rod which is free to wobble within the vibrator casing. Rotating this rod causes it to strike the inside of the vibrator casing, so causing high-frequency vibrations. With some models, however, it is necessary to knock the end of the vibrator when it is first switched on to cause it to vibrate, and this can lead to damage in use.

External Form Vibrators. Four types of external form vibrator are available, the usual type consisting of a high-speed rotating element which is out of balance, and produces vibrations of 3000, 6000 or 9000 c.p.m. Besides this type there is the pneumatic turbo-motor, the frequency of which depends upon the air pressure, but more than 12,000 c.p.m. can be reached with some Continental machines. Another air-driven vibrator is the reciprocating air motor which can operate up to 5000 c.p.m. but both this and the electro-magnetic type of electrically driven vibrator are seldom used.

External vibrators should be used only where it is impossible to use internal vibrators, or where these are to be supplemented by extra vibrators to produce a good surface finish. The principal direction of vibration should be horizontal, so the vibrator should be mounted vertically. Downward vibration is less efficient and tends to shake the shutters apart. Shutter vibrators should have a high frequency with a low amplitude to reduce the wear on the shutters to a minimum, as too large an amplitude causes excessive wear.

The efficient compaction of the concrete depends upon the successful transfer of the vibration from the external vibrator to the concrete. The shutters should be as stiff and as light as possible, because a small mass vibrates more easily than a large one. If the formwork is not stiff enough it will tend to flutter and so cause pumping of the concrete in the shutters, and this entrains air. The formwork must not be rigidly bolted to an immovable mass, otherwise the vibrations will break the shutters; for example, precasting moulds must not be rigidly bolted to the floor but must be supported upon rubber mountings.

The Operation of Internal Vibrators. In describing the two main types of vibrator some indication has been given of the way they should be operated, but no hard and fast rules can be laid down because the proper use of a vibrator is learned only by experience. The following are a few general points. Internal vibrators of 2 in. diameter should be inserted into the concrete at 2 ft centres; smaller vibrators should be used at closer intervals. The vibrators should be inserted to the bottom of the lift and if possible into the top of the previous lift to ensure complete bonding of the new concrete. Where the previous lift has hardened so that this cannot be done, the next lift should be less than usual and the concrete must be well compacted to bond with the previous lift. If the set concrete is older than about 4 hours but less than 16, it might be damaged during the vibration of the new concrete; up to 2 hours, however, such vibration will merely cause revibration of the old concrete and may lead to an actual improvement in its strength and density, because revibration helps to remove entrapped air from around the aggregate and causes further compaction.

The amount of vibration necessary to effect complete compaction is best determined by experience. Vibration is usually complete, however, when the cement mortar is brought to the surface and air bubbles no longer appear; this gives the concrete a shining appearance which disappears rapidly after the vibration ceases. If there is any doubt about whether the vibration is sufficient, it is generally better to give the concrete more vibration. The dangers of over-vibration are less than the evils of insufficient vibration; the evils of under-vibration may be easy to see in the finished structure, see plates 7 and 8.

Plate 7. Faulty construction caused by poor compaction.

In theory it is possible to continue vibration until the large aggregate separates out and sinks to the bottom. In practice this would take so long, with other than wet mixes, that it is seldom likely to happen. If segregation takes place with normal amounts of vibration then it is a sure sign that the mix was too wet and was badly proportioned. The remedy is to reduce the amount of water and not the amount of vibration.

Where reinforcement is heavy it may be difficult to apply sufficient vibration. In congested reinforcement it is better to

Plate 8. Poor compaction of workable concrete (Note nib where concrete has flowed between shutter joints)

place the concrete in the middle of the reinforcement and vibrate it to the outside of the forms, rather than to try to vibrate the concrete from the outside inwards. Vibration of the reinforcement has little effect; fears that the vibration when transmitted along the steel will break the bond between steel and concrete are unfounded, and contact between vibrator and the reinforcement causes no damage. In heavily congested reinforcement it may be advantageous to use the reinforcement itself to spread the vibration forces into the wet concrete but it must be remembered that tying a poker vibrator to a steel bar usually damages the vibrator.

Surface Vibrators. Besides internal and form vibrators, there is in use a third type — the surface vibrator. This is used to apply surface vibration to a slab, and to finish off slabs previously compacted by immersion vibrators. A number of large special machines have been developed for laying concrete to form roads and pavements, these being usually of either American or Continental origin. They are self-propelled and travel on rails or road forms. The concrete is delivered to them from the batching plant by lorry or dumper, and the machine spreads, internally vibrates, screeds and surface vibrates the concrete producing a finished concrete slab at rates of up to 10 ft/min. The larger machines will completely finish a 27 ft wide slab in one operation, requiring only the application of a curing membrane.

On smaller jobs vibrating screeds are used, while on floor slabs compaction may be by pan or power float.

Vibrating Screed. A vibrating screed consists of a screed board with handles at each end and with a vibrator mounted in the middle. The vibrator is usually a petrol-driven self-contained unit with a frequency of about 3000 to 4000 c.p.m. and a small amplitude of 0·01 in. Screeds with large amplitudes are difficult to hold and guide.

Curing

When the concrete has been mixed, placed in position and compacted, it must be cured at an adequate temperature to ensure that proper hydration of the cement takes place and the concrete hardens and gains strength. Concrete contains enough water to hydrate the cement when first placed in position, but under the influence of sun and drying winds this moisture may be dried out and the hydration of the cement prematurely curtailed.

In addition the strength of concrete is dependent on the temperature and the length of time for which it is maintained. Sufficient time is essential, therefore, to achieve full strength. Proper curing involves the preservation of the moisture content in the concrete and the maintenance of a suitable temperature.

Water. Cement combines chemically with approximately 22 to 25 per cent of its own weight of water during hydration (water/cement ratio 0·22 to 0·25). Concrete is made with water/cement ratios from 0·35, so that at the time of mixing it contains enough water to hydrate the cement. But in thin sections, such as floor and road slabs, retaining walls and thin beams, the concrete may be subject to rapid drying on the surface, and this by suction pressure will draw water from the interior of the concrete. The concrete can then become sufficiently dry for hydration to cease. If drying occurs when the concrete is green — within the first few hours of setting — then capillaries can be formed in the concrete and its permeability and resistance to frost be adversely affected.

The water in the concrete can be retained either by replacing that removed by hot sun or drying winds, or better still by preventing evaporation taking place. The most efficient curing is attained when the concrete is kept under water. This can be achieved in road and airfield construction by ponding, i.e. building a small bank of earth or clay around the area of concrete to be cured and filling with water. On most sites such a method is not practicable because the banks are easily broken, and it is difficult to clean off the mud after the concrete has been cured.

A continuous spray of water provides very efficient curing, and can be obtained from perforated plastic hose such as is used for watering lawns. The coverage from one hose is limited and the method is not suited for large areas, but it may be used for curing floor slabs. The quantity of water used, however, can be quite large, and this may cause interference with other building work being carried out on lower floors.

On many jobs the curing water is provided by spraying intermittently by hand. The drying concrete readily takes up water, but in curing the first day or two is critical, and since periodic spraying is a haphazard affair then curing may be only partially effective.

Evaporation of the water already in the concrete may be prevented in a number of ways. The concrete may be covered with damp sacks, hessian or sand, and these are all successful so long as they do not dry out. An alternative method is to cover the concrete with an impervious film; polythene sheeting has been used for floor slabs. Water tends to evaporate from the concrete and condense on the underside of the sheets, so they must be kept down at the edges to prevent the wind blowing underneath. This also applies to semi-pervious materials such as tarpaulins or waterproof paper.

Evaporation can also be prevented by spraying the concrete with a sealing compound to seal the surface and so prevent moisture escaping. There are many such materials on the market, with various efficiencies, but there are two general types, a clear and a pigmented material. A uniform and complete coverage of the concrete surface can be more easily obtained with the pigmented material, but even so it is difficult — if not impossible — to obtain an impervious membrane with one sealing coat. The clear material causes little discoloration and may be used with advantage where the concrete is under cover. For road slabs and other concrete exposed to the weather the pigmented material is better because it is easier to see whether complete coverage is obtained. The pigment is weathered away in a few weeks. The pigment is usually white or aluminium colour, because these colours reflect the sun and help to maintain the concrete at a more uniform temperature.

Bituminous paints are used to form an impervious seal, especially in tunnel, pipe and culvert work where they also provide some protection against corrosion. Bituminous paints are not as suitable for road slabs because of their colour. Being black they readily absorb heat, so that when the sun shines the temperature in the slab rises rapidly and this can cause cracking, especially in green concrete. But in this country, with its temperate climate, cracking does not often occur, while on the other hand bituminous paints undoubtedly prevent evaporation by drying winds. On airfields, however, bitumen may be softened and become tacky by fuel spillage, so its use is somewhat restricted on this account.

Structural concrete is protected by the shutters on most of its surfaces for the first 16 hours after casting, but after that when the side shutters are stripped — or before if subject to winds in dry weather — it may need covering with wet hessian. Floor slabs should be covered with wet hessian, damp sand or damp sawdust.

Thin sections need more attention than large ones to prevent drying out for the first 3 to 7 days. Mass concrete takes a long time to dry, but rapid drying of the surface can cause crazing and surface cracking. On surfaces subject to erosion or abrasion this reduces the resistance of the surface to deterioration, and the surface of floor slabs which have been allowed to dry out soon after casting will have a greater tendency to dusting. If new concrete which has crazed is kept wet continuously for 7 to 14 days, much of the cracking will heal due to autogenous healing. In hot dry summers extra care and protection is required to prevent evaporation and to keep the concrete wet. Intermittent spraying with water is successful when the weather is damp, but during the occasional hot summer such methods are inadequate. In hot climates the concrete must be covered immediately it has been cast; otherwise plastic shrinkage cracks develop before the concrete has set.

Temperature. Satisfactory curing can be attained within a wide range of temperatures. Concrete gains little strength below 50°F and the temperature should be above this. Because of the variations in temperature between summer and winter it is necessary to cure for about 7 days in winter as opposed to say 3 days in summer. These periods are only approximate and obviously depend upon the actual ambient temperatures.

On site work, even in hot countries, the maximum surface sun temperature is probably about 120°F. This temperature has no deleterious effect on Portland cements although it may cause inversion and loss of strength in high alumina cements. Such temperatures can cause plastic shrinkage if the concrete is not prevented from drying out.

There is evidence that temperatures above 150°F will cause some reduction in the ultimate strength, although high-strength concrete can be produced by steam curing under pressure at temperatures of 220°F. Steam curing is used mostly in the production of precast concrete, as described below.

Temperature changes in the concrete induce thermal stresses, so that the ideal curing temperature is the average temperature at which the concrete will remain during use. Such ideal conditions cannot be attained and in some cases where concrete is in use in cold climates it would require an excessive period for curing. The curing temperature is controlled only when concrete is cast in winter, and this is described under winter concreting. The vast majority of concrete is cured at the seasonal average temperature. In summer months spraying with water and covering with wet hessian helps to keep the concrete temperature constant, and by evaporation slightly below shade temperature; covering with a heat reflecting white curing membrane will also help to reduce the concrete temperature. This is shown in Fig. 4.2, where the resulting lower

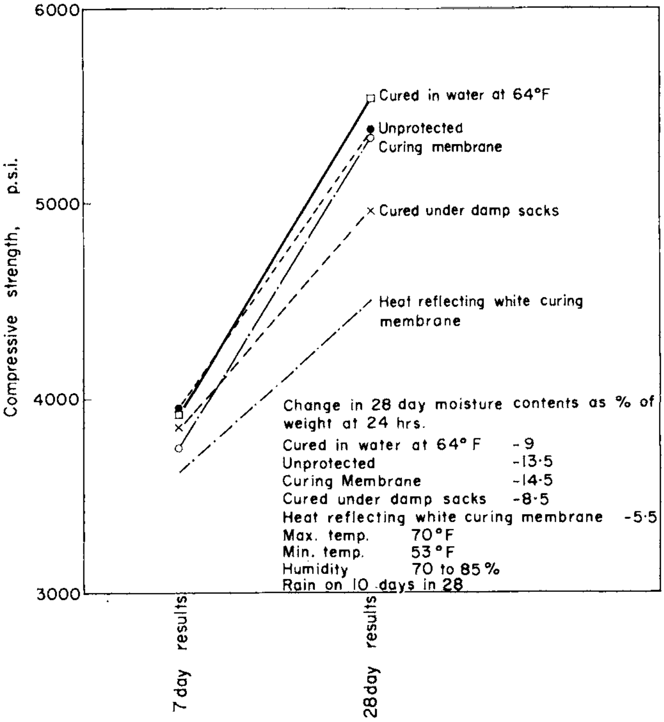

Fig. 4.2. Effect of curing conditions on strength during warm damp weather.

maturity has resulted in a lower strength for the concrete covered with a white membrane.

The heat of hydration contributes to the temperature of the concrete in mass work and can result in high temperature differences within the mass with consequent overstressing which may result in cracking. This is a problem which can be solved only by a combination of satisfactory mix design with proper construction and curing. The concrete should have a low cement content and be made with a low heat cement. In addition it may be necessary to arrange the construction so as to dissipate heat as speedily as possible and to incorporate special curing arrangements and use circulating water to keep down the temperature in the mass.

Steam Curing of Concrete

Steam curing is used to accelerate the rate of gain of strength in the manufacture of precast concrete products. It reduces the time taken for curing and so permits early release of the concrete moulds, thereby increasing the production rate and reducing the cost.

The strength of concrete is related to its maturity, defined as the product of time and temperature. A given strength may be achieved by curing for a long time at a low temperature or a short time at a higher temperature, so that it is reasonable to increase the curing temperature if the curing time is to be decreased. Concrete gains strength more rapidly at higher temperatures whilst in addition the time-temperature gradient of the concrete affects the final strength, so that a predictable strength cannot be determined exactly from the maturity relationship. In addition, steam curing does not always produce an exactly predictable result. Some types of Portland cement have, under commercial treatment, responded better than others, whilst in some plants certain optimum temperatures or special curing cycles have been found to produce the best results.

There are two different methods of steam curing, which vary only in the method of applying the heat and preventing the concrete from drying. There is the high-pressure steam process, which requires specially constructed steamtight chambers where pressure of steam above atmospheric pressure can be maintained. This process is necessarily a batch process. Then there is the low-pressure method in which the steam is maintained at or slightly above atmospheric pressure and which may be either a continuous or a batch process.

High-pressure Process. In this process temperatures of 120–160°C are usual and the curing period is short. There is a rapid increase in strength owing to the higher temperatures, but with certain aggregates a lime–silica reaction may take place and the strength developed may be in excess of that predicted from the maturity. The equipment involves a high capital outlay, however, and since the concrete is cured in batches there is much wastage of steam and heat so that the process has a low thermal efficiency. Dense aggregates reduce the penetration of heat due to their greater heat capacity, and in consequence precast members made with such aggregates will take longer to heat up. The size of the precast concrete member will also affect the rate of heating and the amount of heat required. Larger units require more careful control of the temperature rise to guard against cracking caused by differential stresses due to high temperature gradients.

Low-pressure Process. This process is continuous and the concrete units are cured in a steam tunnel in the same manner as bricks are manufactured in a tunnel kiln. The units are stacked on trolleys and travel continuously through the tunnel. They are first heated by waste steam and then they enter the high-temperature section where they are cured for the required period, followed by a longer cooling period where the heat given off is re-circulated to pre-heat the fresh units entering the steam tunnel. The low-pressure process may, of course, be used as a batch process carried out in a battery of curing chambers. The efficiency of such a battery is higher than that of a single chamber, but because it is more difficult to re-circulate and re-use waste heat the efficiency is lower than that of the continuous process.

Effect of Steam Curing on the Properties of Concrete. Steam curing may begin as soon as the concrete is cast and compacted into the moulds. A waiting period is not necessary, but care must be taken to ensure that the rise in temperature is not excessive; a rise of 20 to 30°F per hour is often used but the concrete should not reach 212°F until 5 to 6 hours after mixing. Too rapid a rise in temperature during the first few hours may lead to a lower final strength, and in fact a very high temperature gradient in fresh concrete may lead to excessive expansion and disruption, probably due to some interference with the normal process of setting.

Provided there is no disruption, steam curing under normal commercial conditions results in the concrete continuing to gain strength on subsequent storage. In high-pressure curing the effects due to the cement hydration are almost entirely obscured by the lime–silica reaction. Most aggregates contain silica which reacts under hydro-thermal conditions with the lime in the cement and increases the total strength. Foamed slag and expanded clay aggregates result in particularly large increases in strength under high-pressure curing. Limestone aggregate, on the other hand, does not contain silica, and may give a lower strength after high-pressure steam curing than would otherwise be expected.

High-pressure steam curing results in an increased resistance to attack by sulphates and in a reduction in the initial drying shrinkage and the moisture movement. This increased resistance is probably due to the increased strength and impermeability resulting from the steam curing and the reduction in free lime by its reaction with the silica in the aggregate. Steam curing at atmospheric pressure has little effect.

Low-pressure steam curing has little effect on the moisture movement of concrete although drying shrinkage may be slightly reduced owing to the drying out of the concrete on removal from the kiln.

The mix proportions have little effect on the efficiency of steam curing. Calcium chloride and other admixtures may be used with steam curing when necessary.

Winter concreting

The stoppage of concreting in winter due to freezing temperatures may result in extra costs where such stoppage is unplanned, although on some jobs it is cheaper to stop work than to adopt all the precautions necessary to ensure the proper conditions for curing the concrete. In this country it is only on about 10 to 12 days per year that the temperature actually falls below freezing. Many specifications for concrete call for the work to be stopped should the temperature fall below 35 to 40°F, but where necessary concreting can be carried out during much colder weather so long as the concrete is maintained above, say, 50°F, i.e. warm enough to ensure that proper curing continues.

At temperatures below 40°F concrete sets and hardens only slowly. At freezing temperatures new concrete may be disrupted because such concrete has little strength and the growth of ice crystals breaks down the gel structure of the set cement. The concrete is weakened permanently, if not entirely broken up. For successful winter concreting it is necessary to ensure that the fresh concrete never freezes and secondly to ensure that it cures properly, at a temperature of above 50°F, for the first two or three days. In countries where very cold weather is experienced all winter, then successful concreting can be carried out by freezing the concrete immediately it is deposited. It is maintained in this state until the spring when it is carefully thawed out and allowed to set and harden. This process has been used in Russia but it is significant that it is never used when temperatures alternate between freezing and thawing — a winter condition typical of this country.

The maintenance of proper curing conditions so that the concrete will attain adequate strength depends upon the mass of concrete and the method of construction. The temperature of the concrete may be maintained either by putting sufficient heat into the water and aggregates, so that the concrete will contain enough heat to keep it above 50°F during the first few hours until the mass of concrete can generate sufficient heat, by hydration, to maintain itself above this necessary temperature; or alternatively, where the mass of concrete is small, as in reinforced concrete frame construction with concrete members less than 12 in. thick, it may be necessary to protect the concrete by insulation and at the same time supply heat by coke stoves, having first heated the water and aggregates before mixing.

When no precautions are taken, other than covering up the concrete at night, then concrete should not be mixed or placed until the air temperature is above 35°F and is still rising. If the temperature is not rising, or if it is falling and is below 40°F, concrete should not be mixed or placed. When concreting stops the work should be covered over with tarpaulins spread over battens to preserve an air-space above the concrete, the sides of the tarpaulins being held down to prevent cold winds blowing over the concrete surface. The coarse aggregates and sand in the stockpiles should also be covered over to ensure that they are not frozen when concreting is next started.

Rapid hardening Portland or cold weather cement (which is rapid hardening Portland to which 2 per cent calcium chloride has been added) is often used under these conditions as a safeguard against frost damage or to ensure that the shutters can be struck on time, but because rapid hardening or cold weather cement is used does not mean that the precautions outlined herein can be abandoned. High alumina cement can also be used, but it has to be restricted to small masses to prevent large temperature stresses and cracking.

Use of additives

Various additives may be used to accelerate setting and hardening so long as the concrete is warm enough at the start and is sufficiently well insulated after placing. In very cold weather the usual dose of 1 to 2 per cent of calcium chloride, or any other additive, cannot take the place of proper heating and curing. The purpose of using admixtures is to ensure that the hardening of the concrete is accelerated so that it gains the necessary strength before becoming cold. This can be done when the temperature is, say, 35 to 45°F, but when the temperature is below 40°F and still falling reliance must be placed on proper curing. Because of the misplaced confidence which may result from using additives it may be better to ban their use during freezing weather. Additives cannot be used with high alumina cement.

Air-entraining agents are often prescribed for concrete subject to freezing. The use of air-entraining agents to protect concrete against frost must not be confused with winter concreting. The purpose of winter concreting precautions is to prevent green concrete of little strength being subject to disruption by freezing, and to provide the curing conditions whereby the concrete can gain sufficient strength. The purpose of air-entraining agents is to prevent fully matured, properly cured concrete from disintegrating under the repeated attacks of freezing during the life of the concrete, although they may also be used to increase the workability during placing.

In certain structures, for example road slabs, it may be that if it is necessary to take precautions in winter for the proper construction of concrete then that concrete will, during its life, be subject to many repetitions of winter conditions and, therefore, should contain an air-entraining agent.

Heating the Concrete Materials

To ensure that concrete has a sufficiently high temperature when first placed in cold weather (below 35°F) it may be necessary to supply heat to it by heating either the water or the aggregates or both. The aim is to achieve a placed concrete with a temperature of 50 to 60°F. Appreciably higher temperatures do not give a greater protection from freezing because the heat loss is more rapid.

Heating the Water. This is the simplest and cheapest way of adding heat to the concrete mix. When night frosts are likely or when the day temperature is near freezing, then it is necessary to heat the water to about 70 to 80°F. When the temperature is colder with say 10 or 12° of frost it will be necessary to heat the water up to 160°F. Colder temperatures will require the heating of the aggregates as well so as to ensure that the placed concrete has a temperature of not less than 50°F.

The water may be heated separately by means of a calorifier using hot water or steam. Alternatively, it may be heated by passing live steam through the water tank, but care is necessary or the water may be overheated. The addition of hot water above 80°F to a mix can cause a flash set, but with the temperatures recommended, if the cement is added last to the mixer then there is little danger.

The methods adopted depend entirely upon the size of the job; for example, using a 10/7 mixer a small domestic or coke boiler may be all that is necessary to supply sufficient heat.

Heating the Aggregates. Aggregates are frequently heated by steam which is passed through the storage bins by means of a perforated pipe. Alternatively steam coils may be placed in or under the stock piles and the storage bins kept heated by hot-water coils. On small jobs sufficient aggregate for urgent work may be heated on iron sheets over coke braziers. It is difficult to heat aggregates uniformly to a controlled temperature, so that where it is necessary to heat them any adjustments necessary to achieve a concrete temperature of 50°F should be made in the heating water.

It is essential that no frozen aggregates be included in the mix, for reliance cannot be placed on the addition of hot water to the mix to defrost the aggregates. At the same time local overheating of the aggregates must be avoided, as this could lead to a rapid reaction when in contact with the cement which would tend to destroy the mortar bond. Unless large quantities of heat are necessary to compensate for low working temperatures, the coarse aggregates should be warmed only sufficiently to prevent them freezing. The sand may be heated to 90 to 100°F without causing premature hardening when mixed with the cement, but in general the heating of aggregates is expensive and is to be avoided where possible.

Curing Environment

Having produced concrete with a minimum temperature of 50°F, the problem is then to ensure a warm curing environment. The precautions necessary are dependent upon the weather, the mass of concrete and the type of construction.

The most important weather element in winter concreting is temperature, but the severity of a low temperature is greatly increased by the occurrence of high winds at the same time. For example, a cold wind blowing over concrete may reduce the temperature at the surface, edges and corners to below freezing and so cause permanent damage. Besides temperature and wind speeds, radiation losses and general topography have an effect on the rate at which concrete will cool down. An excavation can become a frost hole, subject to severe night frosts not easily cleared next day. All these factors affect the amount of heat and insulation necessary to keep the concrete warm.

Similarly the concrete mass and type of construction have an effect; a large mass of concrete may be warmed sufficiently by the heat of hydration, whilst a medium-size block may need only the addition of calcium chloride to the mixing water so as to speed up the liberation of the heat of hydration for the concrete to achieve sufficient strength later to withstand freezing temperatures.

Before any concrete is placed the forms and reinforcement must be completely cleared of any snow or ice, and in very cold weather it may be necessary to warm them by means of a steam jet. The cost of so doing may be too expensive on anything but a large job, although on very small jobs the forms may be cleared by swilling out with boiling water. Where concrete is to be placed on frozen ground, this must either be removed or covered over with a blanket of dry gravel or clinker, to form an insulation between the concrete and the frozen ground.

After placing it will be necessary to provide insulation and extra heat to the concrete. The insulation can be tarpaulins spread over the surfaces of the concrete, but in very cold weather more elaborate precautions including insulation boarding, straw boarding or insulating quilts on battens may be necessary. Wooden formwork provides some protection, the value of which can be increased by covering with tarpaulins or by forming an air space by tacking building paper over battens. Steel forms should be avoided as they readily conduct heat away from the concrete. Their insulating effect may be increased by backing with several layers of old cement bags covered over with tarpaulins to keep them dry. In some cases, for example in concrete frame construction, the proper curing environment can be achieved by hanging hessian or tarpaulins to enclose the space in which the beams, columns or slabs are to be cast, and then warming the interior by braziers or coke stoves. In general, however, complete enclosure of the construction work is too expensive, and braziers tend to increase the rate of drying of the concrete so that extra care is necessary to ensure that the concrete is kept damp.

Saturated steam from a coke-boiler may be used to heat the enclosed space. It provides an excellent but somewhat more expensive alternative to coke stoves. The curing effect is superior because the concrete is kept warm and damp at the same time. The risk of fire is eliminated and there is no danger of the concrete being dried out prematurely.

When steam curing is used it is usually necessary only in the first three days. Sufficient steam is required to heat the concrete to 50°F. It may be possible to limit the use of steam to night time. The amount of steam required can be reduced by curing the different concrete masses individually by forming separate curing chambers with tarpaulins.

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CHAPTER 5

QUALITY CONTROL

It may be a cliché but it is still true to say that concrete is the only construction material actually manufactured on the site. Other materials are merely shaped to use in site work, but concrete is produced from basic materials, and consideration must therefore be given to controlling the quality.

There are two advantages in controlling quality; it ensures that the concrete is of the required strength, and it results in uniform concrete, and uniform concrete is cheaper. There is no wastage because of poor materials, labour costs do not fluctuate widely owing to difficulties in placing, and the margin of strength required to take account of variations in the final product is reduced so that there is economy in material.

Quality control does not mean the production of high-strength concrete of low workability; it means efficient production with the quality controlled to achieve the desired properties. To produce concrete with a strength higher than necessary is wasteful of materials, and to produce concrete with wide variations in workability due to lack of proper control is wasteful of manpower.

Field control

The control of quality can be effected by control of the strength and the workability, although quality control also involves the supervision of the materials used, their proportioning, mixing and placing. Uniform concrete is achieved by a combination of correct mix design with efficient proportioning and mixing by the use of proper and correct methods of placing; in short, by good workmanship and efficient plant. The less efficient the plant used and the poorer the workmanship, the less uniform will be the concrete produced.

Many of the best practices in mixing and placing concrete are described in this book. It is in the application of this knowledge and in ensuring good workmanship and plant maintained at peak efficiency that various grades of control or supervision have to be recognized.

The various grades of control are infinite, but can be roughly classified into four main grades: excellent, good, fair and poor. Excellent control can be achieved by the work being supervised and controlled by a resident concrete engineer with, if necessary, assistants specially trained in concrete technology, together with a testing laboratory on site. The concrete engineer should control both the quality and the output, and with an efficient well-trained man this will result in the maximum output of the most uniform concrete. Good control can be achieved on a site on which an assistant engineer is resident, with periodic visits from a concrete engineer. A simple laboratory sufficient to carry out a few tests will also be necessary. Fair control can be achieved on smaller sites which are visited periodically by a concrete engineer with perhaps an assistant resident on site at the beginning of the job to help the foreman and ganger. Where sites are not visited and have no assistance from an experienced concrete engineer, except perhaps when troubles occur, then the average degree of control must not be expected to rise much above poor.

The reason for the various grades of control is the cost of a concrete engineer and assistants. Their employment is often considered economic only where either the client is willing to pay for the better quality work or the contractor is able to produce cheaper concrete. In consequence, quality control becomes associated either with large-scale production or the production of expensive work. The remainder of concrete production tends to fall into the fair or poor category.

Where no attempt is made to control quality then large variations in strength may occur, with many results being much higher than necessary and many below the specified minimum. Generally the strength for which the mix is proportioned is based on an assumption that only 1 per cent of the cubes tested will fall below the required minimum. In practice this figure is seldom realized on sites where control is poor and little attempt is made to raise the design strength to keep within this proportion — it would be uneconomic. The number of failures may be high and yet not lead to excessive "difficulties" on the site. This may be due to an assumption that it is impossible to produce concrete with a narrow range of variation; such concrete is not demanded, therefore, and when wide variations occur then they are accepted as inevitable. This attitude is often linked to the specifying of concrete by nominal mix proportions.

On the other hand the aim in concrete manufacture sometimes appears to be only the speedy production of concrete with the minimum of trouble, without due attention to the maintenance of uniform quality. This is often combined with a disinclination to change methods of production because of a fear of increasing the cost and because of ignorance of the value of quality control.

It is still possible, however, to improve the quality of the concrete by a few simple expedients. One, over which there has been much discussion, is the correct use of labour. In concrete production there are two important men, the mixer-driver and the ganger. Many arguments have been advanced for not making either a recognized concreting trade, but a well-trained mixer-driver and ganger, led by a good foreman and advised by a concrete engineer, can turn fair control into good control.

The second essential for uniform concrete is uniform materials. The quality of cement is usually good and nearly always above the minimum requirements of B.S.12, but from some works it can vary from time to time. It requires careful and consistent testing to determine any variations in quality, so that little can be done on most sites. If, however, purchasing is restricted to one works the variations due to cement will be about half those which may occur if the cement is purchased from a number of works.

Where more than one works is available to supply a site, then a study should be made of the quality of the various cements. If there is time and the job warrants it independent tests should be conducted over a period of some months; if not, then average results of standard mortar cube tests can be obtained from each works. Occasionally other factors may merit attention; for example, in a situation where the concrete would be subject to slight sulphate attack, not sufficient to warrant using sulphate resisting cement at higher cost, it would be advantageous to choose an ordinary Portland cement with a low C_3A (tri-calcium aluminate) content.

Most suppliers produce aggregates with satisfactory properties because competition usually precludes the ready sale of aggregates containing deleterious materials. But the grading of aggregates is, with some notable exceptions, most erratic. The supply of aggregates with a constant grading depends almost entirely upon the supplier and the efficiency of his plant. Coarse aggregate is often obtained in several sizes and recombined in the correct properties in batching. This ensures that the grading of the coarse aggregate is sensibly the same for each mix, but even so variations in gradings may occur because of the way in which the aggregates are separated into single sizes at the pit. In any case the $\frac{3}{8}$ to $\frac{3}{16}$ in. material and the sand grading play a more important part than the coarse aggregate. Unfortunately few suppliers are aware that the supply of aggregates, particularly sand, with a constant grading leads to simple concrete control.

If the cement/aggregate ratio is constant and the water/cement ratio is maintained constant then the workability will vary directly with the variations in the aggregate grading. Equally, if the aggregate grading is maintained constant and the workability is kept the same, then the water/cement ratio will remain constant.

The amount of water to be added to a batch of concrete to produce a required water/cement ratio depends upon the moisture content of the aggregates. This can vary between successive lorry loads by 6 per cent for the sand and 2 per cent for the coarse aggregate, and for efficient control would require continual checking during concreting; but by the time the moisture content has been determined, five to ten batches of concrete have been produced and conditions have probably changed. If the grading of the aggregates is maintained constant, however, then the control of the water is simplified. The mixer-driver is trained to recognize the workabilities required for the different mixes, and to add only sufficient water to produce that workability. A good mixer-driver can produce concrete with consistent workability, and such concrete made from aggregates with a constant grading will have a constant water/cement ratio.

This method of control leads to more uniform quality than the method of continually checking the moisture content and adjusting the water to give a constant water/cement ratio irrespective of the aggregate grading. It depends for its success upon the inspection of the concrete by the mixer-driver. To assist and train the mixer-driver and facilitate control of workability, the automatic compacting factor, the VB apparatus and the slump cone have all been used with some success.

There are one or two snags even with this method of control. Having trained a mixer-driver to produce concrete of one workability, it is sometimes difficult to persuade him to produce concrete of a different workability which may be necessary due to special conditions. Secondly, no correction is made for the difference in weight of the aggregate containing differing quantities of water, but this error is small if a correction is made for average conditions, say 4 to 6 per cent moisture in the sand and 2 to 4 per cent in the coarse aggregate. Thirdly, this method of control is unsuited to the production of a large number of different water/cement and aggregate/cement ratios such as is common in ready-mixed concrete plants; such plants are usually specially equipped with batching mechanisms which can compensate for the variation in moisture in the aggregate.

Having trained the mixer-driver to produce concrete with consistent workability it is essential that he measure out the materials with the maximum accuracy. Apart from automatically controlled continuous plants which use volume proportioning, all other plants should use weigh-batching. No difficulties are experienced with large plants with separate weighing of the cement, but in most site plants the cement is weighed in the same hopper as the remainder of the aggregates. Cement is a most difficult material; it flows steadily only when agitated with compressed air, it compacts in the storage silo and discharges in gushes. In weighing out cement the mixer-driver is usually unable to adjust the weight of cement to an accuracy greater than 20 lb, and in any case weigh-batchers on large mixers are not calibrated in less than 20 lb markings. A well-trained mixer-driver knows the danger of not adding enough cement, so that if the weight of cement is just below that required then he adds a little more and since cement discharges at a rate of about 1 cwt every 2 seconds this may result in using up to 20 lb more cement per batch.

When the cement is weighed in with the remainder of the aggregates the errors are increased. The dampness from the aggregates causes cement to build up in the weighing hopper and this leads to inaccuracy, but the main errors arise because of the use of cumulative weighing. The cement is usually weighed after the coarse aggregate and before the sand. The dial gauge on the weigh-batcher is marked off with the required cumulative weights, and any error in the coarse aggregates is corrected in weighing out the cement. If the mixer-driver weighs out too much aggregate he cuts down to the correct total on the cement; if on the other hand he does not weigh out enough aggregates then he makes up on the cement. This helps to accentuate and double the errors in water/cement ratio.

Wherever possible the cement should be weighed separately, for example in the hopper provided with most portable silos. These operate on the beam and jockey-weight principle, and are quite accurate. On many sites the cement is added by the bag; it has been mentioned already that splitting a bag produces large errors, but an even greater error occurs if the mixer-driver forgets to add a complete bag, as sometimes happens!

The adding of the water is difficult to control on most mixers because they are fitted with only one tank, whereas what is required is a large tank to discharge most of the water and an auxiliary tank from which to add small quantities to produce the required workability. The large tank would then be set to discharge about 1 or 2 gal less than the total required, and be timed to discharge during the period when the aggregates and cement were being charged in. The remainder of the water would be added after the concrete had been mixing for about a minute. Even so this method of working is suitable only for positive mixers such as a pan mixer. In operating non-tilting drum mixers the mixer-driver adjusts the mix by adding small amounts of water during the whole mixing period.

Electrical resistivity probes are available which can be fixed into a mixer to indicate the moisture content of the materials, but they need careful calibration with different sands and cements and for various aggregate/cement ratios, and their use is not yet fully developed.

Commencing Operations. On a site where the foreman and ganger are both interested in and trained to produce uniform concrete, the concrete engineer's task is simplified. More normally, however, before concreting commences, a number of things must be checked; for example, is the mixer level? Do all the controls work? Does the water-tank fill properly and discharge the correct quantity? The weigh-batcher should be checked for weighing accuracy with dead weights to its full capacity. The doors of wet hoppers and skips should be inspected to see that they open and close properly.

If aggregate has already been delivered it should be checked to ensure that it is the material required, that the right material has been ordered and delivered, and that the grading corresponds with that on which the mix was proportioned. The average moisture content of the aggregates should be determined and then about three or four trial batches should be made and the workability measured and demonstrated to the mixer-driver. It will be found that the workability of a large batch is slightly better than that of a small trial mix, and these first batches enable slight adjustments to be made to the mix if necessary.

The behaviour of these batches through the various plants — wet hopper, skip, barrow, placer — should be noted, and the way in which the concrete responds should be observed and any difficulties ironed out.

Cubes should be made from concrete sampled at different points, for example as discharged from the mixer, from the skip or barrow, and as placed in the work. When these cubes are tested they should be broken open and inspected and any differences between them noted; for example, did the samples from the mixer produce differently graded concrete because of the poor discharge characteristics of, say, a non-tilting drum mixer?

When all the equipment is working correctly and the required quality of concrete is being produced, then steps can be taken to maintain that quality by the use of simple statistical control. This is dealt with below.

Statistics and concrete quality

Whenever in engineering a large number of articles has to be produced with the same properties, it will be found convenient to determine the uniformity with which these same properties are produced by a series of tests on samples. In the simplest procedure every article is tested to ensure that it conforms to the required standard, but this may be costly and sometimes impossible. In such cases representative samples are taken and tested and the quality of the whole judged from the results.

This can be done with concrete. But if the whole of a mixed batch of concrete is made into 6 in. cubes, the result of testing all the cubes would not be a single value for the compressive strength; there would be a scattering of the results about a mean value, the greater number being concentrated within a range of perhaps ±250 p.s.i. The amount of scattering is, in itself, a measure of quality; where the sampling of the concrete is not restricted to one batch but is spread over a number, then the scatter about a mean value is greater and may be say ±500 p.s.i. depending upon a number of factors.

The variations which occur in compression test results, even when testing all the concrete from one batch, are not due to faulty workmanship but are inherent in the making and testing of concrete. They may be due to an accumulation of haphazard events in the supply and use of the concrete aggregates, and in the batching, mixing and testing conditions. The mathematical principles of statistical analysis have been applied to concrete quality control to assist in the interpretation of results. It is first necessary to understand these principles before discussing whether and in what circumstances they can be applied profitably to concrete.

Arithmetic Mean. The simplest concept is the mean or average value. If x is the observed compression strength of a concrete cube and if there are N cubes then

$$\text{the mean strength} = \frac{\Sigma x}{N} = \bar{x}$$

where Σx is the arithmetical addition of all the compression strengths of the cubes.

The mean value of a number of results gives no indication of the extent of variation of strength; for example, the average strength of two cubes of strengths 3000 and 4000 p.s.i. is the same as that of two cubes of strengths 2000 and 5000 p.s.i. but the variation in strength in the latter case is much greater.

The extent of the variation can be determined by relating the individual strengths to the mean strength and determining the variation from the mean. This is described below.

It should not be thought that the average or mean strength is a constant value. In the example suggested above of turning the whole of a batch of concrete into cubes, if the cubes were divided into two lots and then tested, the average for each lot would not be the same; the averages would be of the same order, but would become identical only if the number of cubes in each lot was very large.

Normal Distribution. Statistical observations on concrete strengths are based on what is termed a normal distribution (see Fig. 5.1 which is obtained by plotting on a histogram the results of a large number of cube strengths from the same concrete; Fig. 5.2 shows a typical histogram from results obtained on an actual job site). The results are said to follow a normal distribution if they are equally spaced about the mean value and if the largest number of cubes have a strength close to the mean value, the number falling off as the results are much greater or less than the mean value. From Fig. 5.2, it might be considered to be doubtful whether actual results lie within a normal distribution curve, but for the purpose of statistical analysis they are considered to do so.

The difference between the largest and smallest value in the results is obviously the range; for example, if the mean value of 20 cube results is 3500 p.s.i. and the lowest is 2000 p.s.i. and the highest 4000 p.s.i. the range is 2000 p.s.i.

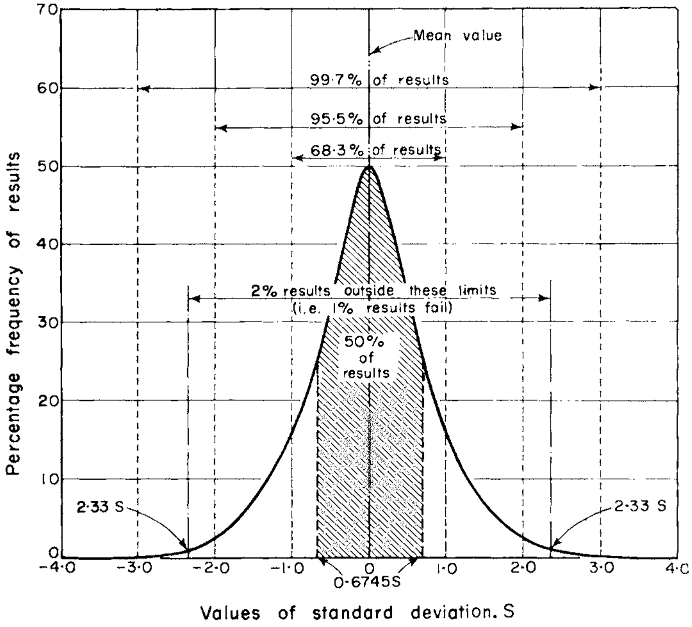

Fig. 5.1. Normal distribution of test results.

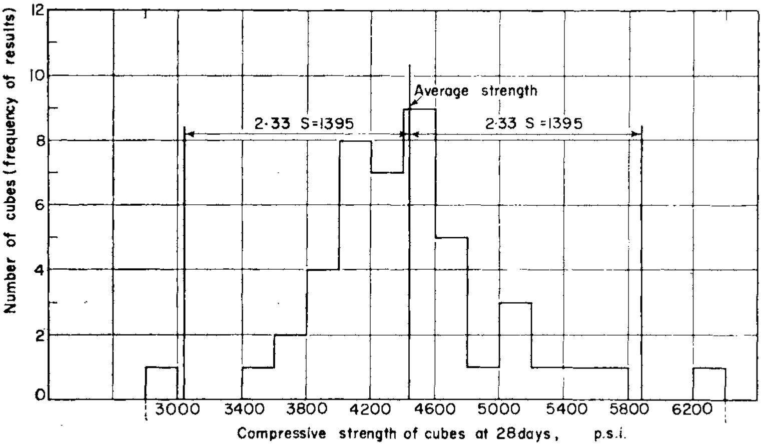

Fig. 5.2. Histogram of test results.

If there were 200 results the chances of a very low result or a very high one occurring would be correspondingly increased; with 200 cube results the lowest might be 1000 p.s.i. and the highest might be 5000 p.s.i. so that the range then becomes 4000 p.s.i. This does not mean that the concrete quality has deteriorated, but merely that the more cubes one makes and tests, all other things being equal, the greater is the likelihood of a "freak" high or low result. On the other hand it is only when large numbers of cubes are tested that statistics can be applied to the results.

Standard Deviation. If it is assumed that freak results will occur, then some criterion other than the range must be used as a check on the concrete quality. The more closely the cube results are grouped about the mean then the nearer does every cube correspond to the average value. A measure of this closeness of grouping may be used as a measure of the concrete quality.

The grouping may be determined by the standard deviation, which is a measure of the number of results which are closely grouped about the mean. The true standard deviation is given by the equation

$$\sigma = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n}}$$

This applies when the value of n is very large and there is no error due to using a small number of test results. When the number of test results is small this formula tends to underestimate the true value of the standard deviation. The standard deviations of concrete test results are usually calculated from the mean of a small number of tests. If the number of results was large then the true mean would be a slightly different value; it follows, therefore, that the sum of the squares of the deviation $(x - \bar{x})^2$ calculated about the average for a small number of results given by $\Sigma x/N$ must be less than the deviation calculated about the true mean $\Sigma x/n$ where n is very large.

It can be shown that a correction $N/(N - 1)$, known as Bessel's correction, must be applied to the standard deviation from the formula $\sqrt{[\Sigma(x - \bar{x})^2/n]}$ when the value of n is small, i.e. equal to N, so that the estimated standard deviation is determined from the formula

$$S = \sqrt{\frac{\Sigma(x - \bar{x})^2}{N} \times \frac{N}{N - 1}}$$

$$= \sqrt{\frac{\Sigma x^2 - N\bar{x}^2}{N - 1}}$$

where S = standard deviation
x = individual cube strength
$\bar{x}$ = mean strength of N cubes $= \frac{\Sigma x}{N}$

The term $\frac{\Sigma(x - \bar{x})^2}{n}$ or $\frac{\Sigma(x - \bar{x})^2}{N}$

is the variance. In the assessment or control of concrete quality it is not much used.

If the standard deviation for a series of results is known, it is possible to calculate what percentage of the results will lie within a given range. Thus if the mean strength is 3500 p.s.i. and the standard deviation is say 500 p.s.i. then within a range of 1000 p.s.i. about the mean (i.e. between 3000 and 4000 p.s.i.) there will lie about 68 per cent of all the results. Similarly, within a range of 2000 p.s.i. will lie 95 per cent of the results; this figure of 95 per cent corresponds to about twice the standard deviation; other figures are given below.

Percentage of results within the range	Probability factor
38	0·5
68	1·00
87	1·50
95	1·96
98	2·33
99·7	3·0

It is often assumed that the results of a series of tests will be satisfactory if one result in a hundred fails or falls below the required minimum so that 98 per cent of the results will be

EXAMPLE OF CALCULATION OF STANDARD DEVIATION
RESULTS OF TESTS ON 45 CONCRETE CUBES MADE FROM A NUMBER OF BATCHES OF CONCRETE

(*See also Fig.* 5.2)

Compressive Strength 28 days. p.s.i. (x)	$(x-\bar{x})$	$(x-\bar{x})^2$	Compressive Strength 28 days. p.s.i. (x)	$(x-\bar{x})$	$(x-\bar{x})^2$
4130	300	90,000	4710	280	78,400
4740	310	96,100	4810	380	144,400
4410	20	400	5180	750	562,500
4410	20	400	5190	760	577,600
2860	1570	2,464,900	4250	180	32,400
3450	980	960,400	4210	220	48,400
3660	770	592,900	4350	80	6,400
3880	550	302,500	4170	260	67,600
4170	260	67,600	4410	20	400
5100	670	448,900	4460	30	900
3790	640	409,600	4550	120	14,400
3900	530	280,900	4480	50	2,500
6260	1830	3,348,900	4720	290	84,100
5710	1280	1,638,400	4790	360	129,600
5510	1080	1,166,400	4710	280	78,400
3840	590	348,100	4550	120	14,400
3970	460	211,600	4360	70	4,900
4020	410	168,100	4080	350	122,500
4580	150	22,500	4090	340	115,600
4450	20	400	4290	140	19,600
5310	880	774,400	4090	340	115,600
4310	120	14,400	4090	340	115,600
4290	140	19,600			

$$\Sigma x = 199{,}290 \qquad \Sigma(x-\bar{x})^2 = 15{,}763{,}600$$

$$N = 45 \qquad \frac{\Sigma(x-\bar{x})^2}{N-1} = 358{,}263$$

$$\bar{x} = \frac{\Sigma x}{N} = 4430 \text{ p.s.i.}$$

$$\text{Standard Deviation } S = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N-1}} = 598 \text{ p.s.i.}$$

[NOTE: If $N = 45$ is considered to be large then $S = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N}} = 591$]

$$\text{Coefficient of Variation } V = \frac{100\,S}{\bar{x}} = 13{\cdot}3 \text{ (per cent)}$$

within the range (if one result is too low one must be too high); a figure of 2·33 S is often used, therefore, it being assumed that in every hundred cubes one will have a strength lower than

$$\text{the mean strength } - 2{\cdot}33 \times S$$

and one cube will have a strength higher than

$$\text{the mean strength } + 2{\cdot}33 \times S$$

If the minimum strength is required to be 3000 p.s.i. and a standard deviation of 600 p.s.i. is assumed, then the mean strength must be

$$3000 + 2{\cdot}33 \times 600 = 4398 \text{ p.s.i.}$$

so that the concrete would be designed for 4400 p.s.i. and 1 per cent of the cubes tested would be expected to have a strength less than 3000 p.s.i.

Coefficient of Variation. Instead of using the standard deviation to denote the way in which the results are closely (or widely) spaced about the mean value, it is possible to represent the fact by a coefficient which is calculated as a percentage of the mean strength. This figure is called the coefficient of variation V.

$$V = \frac{100\,S}{\bar{x}}$$

Where S = standard deviation $= \sqrt{\dfrac{\Sigma x^2 - N\bar{x}^2}{N - 1}}$

$\bar{x}$ = mean strength of N cubes $= \dfrac{\Sigma x}{N}$

x = individual cube strength

If the standard deviation is 500 p.s.i. and the mean strength 3000 p.s.i. the coefficient of variation = 16·6.

The use of either the standard deviation or the coefficient of variation is based on the following argument. If control was perfect so that the materials, mixing and sampling were all uniform, then every result would be the same and would correspond to the mean value. It is impossible for things to be perfect, but the more uniform they are the closer will the results correspond to the mean value and hence the lower will be the value of the standard deviation.

It follows that if the same degree of control is exercised on concrete with a mean strength of 2000 p.s.i. the standard deviation will be the same as for concrete with mean strength of 6000 p.s.i., therefore the concrete quality can be judged by the standard deviation. In fact, however, site experience shows that it is more difficult to achieve consistent results with high-strength concretes, and the standard deviation is greater than for concretes of medium or low strength.

It has been suggested that the standard deviation is proportional to the value of the mean strength; in other words that

$$\frac{\text{standard deviation}}{\text{mean strength}} = \text{constant}$$

This, of course, is the coefficient of variation. With a constant coefficient of variation the standard deviation increases with strength and is larger for high-strength concrete.

Now neither of these theories works in practice, for they do not take account of human nature; on the site, high-strength concrete receives special treatment merely because everyone is impressed with the fact that it is high-strength concrete; concrete with a strength of 3000 p.s.i. is too common to receive very much thought, while on the other hand low-strength concrete receives attention to ensure that it is placed with the maximum speed — it is often mass concrete, and the most important aspect is production.

These factors are part of concrete making and cannot be overlooked, yet they seldom receive consideration. There is some argument as to whether the standard deviation or the coefficient of variation is the correct test to apply. That in fact there is argument indicates that the answer is complex, and whilst it will eventually be resolved by more site data, at present a compromise is used.

On the basis of his experience Murdock has suggested that the standard deviation be used up to strengths of 3000 p.s.i. and the coefficient of variation be used for strengths above this figure. It is now suggested, however, that the figure of 3000 p.s.i. is too low, because the standard deviation appears to be constant up to about 4000 p.s.i. and increases above this. In the design of mixes for strengths up to about 4000 p.s.i. the standard deviation should be assumed to be constant, and for strengths above this a constant coefficient of variation should be assumed.

In the application of statistical control to the quality of concrete it should be noted that a statistical analysis cannot be applied to only half a dozen cube results, for it is based on random sampling and random data of a large number of samples.

The variations in strength may be caused by some or all of the following factors:

(1) Proportioning of the materials
(2) water/cement ratio
(3) quality of the materials
(4) efficiency of mixing
(5) age and curing of the concrete
(6) inefficient sampling of the concrete
(7) errors in making and testing the concrete.

Some of these factors have already been discussed and comments made on the difficulties which occur in proportioning materials. If, for example, cubes are made always from the first barrow-load of the mix, by the same man in the same manner and tested in the same laboratory, then the standard deviation will be less than if random samples are obtained and tested in different laboratories. The first essential, therefore, is to eliminate variations due only to the manufacture of cubes and the testing technique. But even so, if the number of cubes for any one mix is less than say 100, too much time need not be spent on statistical analysis. The standard deviation will be useful as a check but it may easily be contradicted on another job. On the other hand, attempts should be made wherever possible to collect data and to determine standard deviations and coefficients of variation for different conditions, for we still know very little about the matter; for example, it is not yet possible to say whether the assumption of normal distribution for cube test results is justified.

Concrete test cubes are regarded as the chief measure of concrete quality, but results plotted on a histogram often show marked skewness. From the published results so far available it is impossible to decide whether this skewness is due to the pecularities of the individual jobs from which the results were obtained, or whether it is a characteristic of cube strength such as to warrant a re-appraisal of the error in assuming a normal distribution. In any case tests can be made only on a small amount of the concrete produced and so can serve merely as a guide. In addition, the results are not a measure of the quality of the concrete in the constructional work but are a measure of the potential strength of the concrete at the place where it was sampled. Inadequate compaction and incomplete curing and hydration of the cement will result in only a portion of the potential being realized.

It appears from the results of ultrasonic tests on in situ concrete — when lower results are often measured in what is considered satisfactory concrete — that the whole of the potential strength of concrete is seldom attained.

The compressive strength is sensitive to water/cement ratio, and since the proportioning of both the cement and the water are the most difficult then the compressive strength is a suitable test criterion for quality control; i.e., it is not the absolute value of the compressive strength which is a measure of quality, but the relative value, the distribution of the results about the required mean.

The effectiveness of testing concrete cubes to assess the quality depends upon the fineness with which they can be used to discriminate between acceptable and unacceptable concrete; to help to achieve satisfactory discrimination a statistical approach to the problem is of value.

Values of standard deviations or coefficients of variation cannot be followed too slavishly, however, as the following examples show.

Guesses of coefficients of variation by Stanton Walker	Control
5 per cent	Attainable only in well controlled laboratory tests
10 per cent	Excellent, approaching laboratory precision
15 per cent	Good
20 per cent	Fair minus
25 per cent	Bad

Standard deviations given by Himsworth	Control
400 p.s.i.	Excellent
500 p.s.i.	Very good
600 p.s.i.	Good
800 p.s.i.	Fair
1000 p.s.i.	Poor
1200 p.s.i.	Uncontrolled

Assume that the minimum required strength below which 1 per cent of the cubes will fail is as shown in the table below. The table gives the mean strength required to achieve this minimum strength for three standards of control based on both the coefficient of variation method and the standard deviation method.

Control	Minimum Strength	Compressive strength (p.s.i.) 2000	4000	6000
Excellent	Mean strength:			
	Coefficient of variation 5%	2230	4460	6700
	Standard deviation 400 p.s.i.	2930	4930	6930
Good	Mean Strength:			
	Coefficient of variation 15%	2700	5400	8100
	Standard deviation 600 p.s.i.	3400	5400	7400
Fair	Mean strength:			
	Coefficient of variation 18%	2840	5680	8520
	Standard deviation 800 p.s.i.	3860	5860	7860

The purpose of this comparison is not to critize adversely the values of either the coefficient of variation or standard deviation suggested by Stanton Walker or Himsworth, but to show the inherent difficulties in the application of statistics to concrete mix design. The difficulties are so great in fact that mathematics of applying statistics to mix design can be avoided by making a good "guess-estimate" of the answer based on experience and inspired guesswork.

Statistical analysis can, however, be used to good purpose in showing whether the quality of the concrete is being maintained or whether it is falling off. The method is suitable only for large jobs or jobs of long duration. It is first essential for the engineer to determine whether the materials, mixing, placing and sampling of the concrete are satisfactory. This must be done by visual inspection and investigation by an engineer experienced in the manufacture and use of concrete. The results from a relatively large number of tests carried out when the work is judged to be proceeding efficiently will then enable the standard deviation or coefficient of variation to be determined.

The average strengths and the standard deviation or coefficient of variation are calculated from a number of samples for each mix and for each mixer from the formulae already given. The number of samples tested to determine these initial values for each mix and for the various mixers in use should be large; not less than 25 is suitable, although six is often used and is the minimum number (N) which is of any value. Having established basic values of standard deviation or coefficient of variation for the site, then cube test results can be used as they come to hand to determine the trend of the standard deviation or coefficient of variation. The cube test results obtained at 7 and 28 days are, in fact, useless by themselves. They have to be correlated with inspection and control observations during normal batching. It is true that the failure of a cube to reach the required minimum acts as the "ultimate deterrent", but once a required standard has been achieved the object of the cube test is to prevent any deterioration.

The standard deviation for each batch of cubes tested is plotted on a time basis and any general trend determined by inspection. In this day-to-day control a "batch" may be as low as 2 and the results still be of value.

This method of control may be refined and extended where justifiable to include the determination of the different standard deviations for the various operations such as batching, mixing and curing, and sampling and testing. Such refined analysis is required only on larger jobs and even then its value in promoting more uniform and cheaper concrete is open to doubt, although it can be argued that if the factors causing variation are identified and their relative importance estimated, an improvement in control and inspection can be achieved. In fact it may well be that a true appreciation of the most variable factors in concrete manufacture will be achieved only if the coefficient of variation or standard deviation for the cement, the batching, mixing, sampling and testing are all determined separately and not, as at present, as one overall coefficient or standard deviation.

When the standard deviation is known separately for each operation then the overall standard deviation is the square root of the sum of the square of the deviations for each cause. Thus if S_1, S_2 and S_3 are the standard deviations for cement variation, mixing and testing, then the overall standard deviation is

$$S = \surd(S_1^2 + S_2^2 + S_3^2)$$

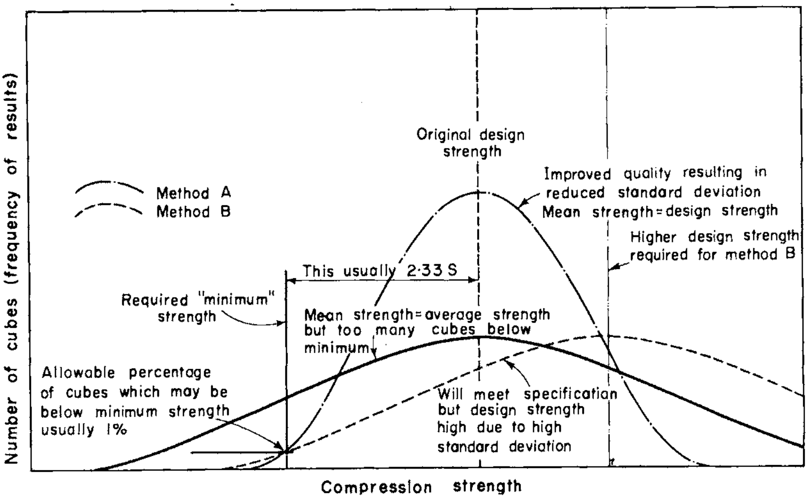

Fig. 5.3. Two methods of achieving required minimum strength.

An example of the two methods of achieving the minimum strength is shown in Fig. 5.3, in terms of standard deviation and design strength. Where the quality control is unsatisfactory more cubes than is permissible will fall below the required minimum. This may be overcome by increasing the design strength, which has the effect in Fig. 5.3 of shifting the distribution curve to the right (Method B). Increasing the design strength is achieved by using a lower water/cement ratio; to maintain the same workability the concrete must then be made richer and more expensive. If the quality is improved, however (Method A), the standard deviation is reduced and the minimum strength is achieved. Improved quality often results merely from a tightening up of site efficiency and this can lead to an increased productivity and a saving in cost.

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CHAPTER 6

RESISTANCE OF CONCRETE TO DETERIORATION

In general, concrete made from suitable materials properly placed and compacted has a high resistance to deterioration, but when badly made or produced from unsuitable materials it deteriorates rapidly. Well-made concrete often survives in a better condition than might otherwise be expected simply because of its impermeability and its ability to withstand the entry of corrosive materials. The less the surplus voids the greater is the resistance to deterioration. The surplus voids are those due to incomplete compaction or to the use of too much mixing water, in contrast to the minute air bubbles resulting from controlled air entrainment. Air entrainment increases the resistance to deterioration, but the bubbles produced are very different from the voids due to incomplete compaction.

The first essential, therefore, for concrete to resist corrosion, is that it should be well made and thoroughly compacted. It should have a low permeability and water absorption and (apart from air-entrained concrete) it should have a high density. The more complete the compaction and the lower the water/cement ratio, the greater will be the resistance to attack.

Deterioration may be caused by internal or external causes. The internal causes are unsoundness of the cement, poor quality of the aggregates, corrosion of the steel reinforcement or an adverse chemical reaction between cement and aggregates. The resistance of concrete to internal disruption does not depend directly upon the cement, but concrete made with sulphate-resisting, super-sulphated, blastfurnace or high alumina cements has a higher resistance to attack by sulphates in sea water than concrete made with ordinary Portland cement.

External causes of deterioration are adverse reactions between cement and various chemicals; for example, ordinary Portland cement concrete is attacked by organic acids present in bottling and canning factories. It is also attacked by sea water, sulphate-bearing ground waters, and frost. In addition, road slabs, pavings and waterways may suffer from abrasion or erosion.

Corrosion of reinforcement

In reinforced and prestressed work the concrete has a dual function. It has to withstand the compressive and shear forces in the structural member and also to protect the steel from corrosion. Corrosion, in reinforced concrete, causes spalling and is a major cause of deterioration, but in prestressed concrete it is more serious because it may lead to the failure of a structural member.

The protection of the steel depends upon the quality of the concrete and the amount of concrete cover. It can be shown that the rate of corrosion is proportional to the amount of cover, which in normal frame-construction may be ½ in. but in industrial areas should be increased to 1 in. Reinforced concrete in sea water should have a minimum cover of 2 in., and 3 in. is better.

Steel embedded in freshly made concrete is surrounded by an alkaline layer with a pH of about 11. The corrosion of steel at ordinary temperatures is an electrochemical process and depends upon differences in electro-potential. At a pH of 11 the electro-potential and the rate of corrosion is very small and to all intents and purposes the steel does not corrode.

With the passage of time the concrete is permeated by moisture-carrying carbon dioxide. The carbon dioxide converts the free lime in the presence of moisture to calcium carbonate, and this leads to a gradual decrease in the pH to values as low as 9. The electro-potential increases and corrosion takes place. In water the penetration of the concrete by sodium and magnesium chlorides and other soluble salts also reduces the protection of the steel resulting from the alkalinity of the concrete. Sea water acts as an electrolyte and facilitates the establishment of anodic and cathodic areas in the steel at distances which may be some feet apart; corrosion starts at the anodic areas. Sulphates in sea water react with the free lime and this helps to lower the pH.

The corrosion product formed by the expansion of the iron to iron oxide, cracks the concrete. The cracks so formed assist in the corrosion process since they allow water to penetrate the concrete more easily, promote the carbonation of any remaining free lime and supply oxygen to assist the rusting of the steel. Eventually lumps of concrete spall off, the electro-potential between the exposed and the embedded steel is increased and corrosion spreads along the bars.

Concrete is thus subject to disintegration by the corrosion of embedded steel wherever conditions favour the carbonation of the free lime, the formation of cracks in concrete and the penetration of water-carrying soluble salts. The worst situations are exposed surfaces in heavy industrial plants with a high carbon dioxide content in the atmosphere, surfaces exposed to salt and sea spray or embedded in sea water and subject to tidal and wave action, and finally exposed surfaces subject to freezing and thawing.

There is some evidence that a high percentage of soluble salts in concrete, such as would lead to efflorescence, facilitates corrosion whenever such concrete is subject to damp conditions. As the moisture penetrates the concrete the salts dissolve, yielding a low pH at a high salt concentration. This state of affairs may result from using sea water for mixing the concrete or using sea-shore sand as fine aggregate. The richness and denseness of concrete which results in low absorption and permeability retards the effect and it may not be important for such concretes, but for reinforced concrete in marine structures it is better to avoid materials which result in a high content of soluble salts in the concrete.

Cracking of reinforced concrete induced by shrinkage usually occurs at abrupt changes of section or of reinforcement. It is at such sections that future corrosion of the steel can be expected. Corrosion is more rapid when the cover is small and, therefore, relatively thin structural members suffer most. In addition, the rate of corrosion increases with an increase in the permeability of the concrete. Wet mixes, incomplete compaction, poorly made construction joints and insufficient curing, all lead to the concrete being more permeable to the penetration of moisture, air and soluble salts and hence more liable to failure by corrosion of the reinforcement.

Reaction between aggregate and cement

Attention was first drawn to the reaction between some aggregates and certain cements by Stanton in 1940, although the first structure in which a failure was later traced to this reaction was a bridge built in California in 1920. The failure of this structure was typical of the adverse reactions between cement and aggregates. What happened was that the concrete in the piers was split by extensive expansion and random cracking. Tests showed that the expansion which caused the cracking was due to the growth of a silicate gel which had resulted from a reaction between aggregate and cement with an alkali content (Na_2O) greater than 0·6 per cent. The aggregates which caused the interaction contained opaline silica and some chalcedonic silica.

The cause of expansion and disruption of concrete by the reaction of cement with aggregate lies in the formation of an alkali silicate gel which swells and so creates an expansive pressure. Expansion and disruption occur only when there is a sufficient concentration of reactive aggregate to give an amount of alkali silicate gel whose swelling more than fills any voids in the concrete, so that the reaction is dependent on the presence in the aggregate of silica in reactive form. The silica must be either in a very finely divided state, of which opaline silica gel is an extreme example, or in an unstable form such as a supercooled glass, as in volcanic types of rock. The expansion will be greater, the larger the area of aggregate exposed to the alkali. For a given percentage of reactive aggregate, the extent of the reaction increases with a decrease in the aggregate size. For expansion to occur there must be sufficient alkali available to react with the aggregate and generate enough gel to exert pressure; this happens with a cement containing more than the equivalent of 0·6 per cent Na_2O. It is possible, however, that even a cement with less than 0·6 per cent of equivalent Na_2O may in time cause trouble. To eschew these troubles it is necessary either to avoid certain aggregates or to use a cement with a low alkali content. The alkali content of British Portland cements is generally above the 0·6 per cent equivalent Na_2O limit, and thus they will react if used in combination with reactive aggregates.

The most likely sources of reactive aggregates are flints and certain types of volcanic rock. The gravels used extensively in S.E. England, for example the Thames Valley aggregates, are derived from flints. They are used without trouble, however, although, theoretically, potentially reactive. Fortunately the types of volcanic rock which contain reactive minerals are not much worked owing to the inaccessibility of the deposits, but with the advent of nuclear power stations sited in what may otherwise be inaccessible places, the possibility of using local rocks as concrete aggregates may involve the use of reactive materials. This may be a source of trouble where there is no background of site experience to indicate that the aggregates it is proposed to use are not reactive. Of the various groups of rocks only the basalt and porphry groups contain reactive rocks. In the basalt group the only rock likely to react is andesite and any deposit including this material should be tested. The porphry group contains a number of rocks known to be reactive and attention should be paid to rhyolites, felsites and trachytes. Other rock groups, such as granite, gabbro, limestone and quartzite do not contain any rocks known to be associated with reactivity.

Reaction of Chemicals in Aggregates

Apart from the reaction of opaline silica with the alkalis in the cement, certain aggregates may contain iron pyrites which oxidize and react with the free lime in Portland cement, but they are not a cause of serious trouble. Marcasite, which like pyrites may occur in certain flint gravels, can give rise to unsightly iron staining on the exposed surface of the concrete.

Resistance to various chemicals

Carbon Dioxide. The attack of carbon dioxide and sulphur dioxide gases depends upon the humidity. They are present in flue gases and in the atmosphere in many industrial undertakings such as gasworks and iron foundries. Under dry conditions the effect on concrete more than two or three weeks old is negligible, but in normal humid conditions a fairly rapid attack of Portland cement takes place. The concrete is weakened by removal of the cementing constituents. Carbon dioxide is one of the main causes of acidity in soft moorland waters.

Occasionally troubles may occur if coke stoves are used in an enclosed atmosphere for the curing of concrete during winter weather. The green concrete may be attacked on the surface, leaving it with a soft chalky skin.

Chloride. Many chloride salts have a tendency to combine with the free lime in Portland cement to form calcium chloride which is soluble and may be leached out, causing porosity of the concrete. High concentrations of calcium chloride have a destructive effect on concrete surfaces. These high concentrations occur when the de-icing of roads is carried out by using a mixture of sodium and calcium chlorides.

Chlorine. In the presence of moisture it will combine with the lime in Portland cement but it also attacks alumina in all cements. Where the products of disintegration are not removed by erosion or abrasion, however, the reaction does not penetrate the concrete more than a fraction of an inch.

Chromium Salts. Chromium salts may be added to concrete to prevent corrosion of the reinforcement, but they are poisonous and so dangerous to use that benzoate salts should be used instead.

Detergents. Many detergents are based on one of the sodium poly-phosphate group of chemicals. Slow attack of concrete is likely by these due to the formation of phosphoric acid which will attack Portland cement. High alumina cement is attacked by alkali detergents which are used in cleaning down to remove organic acids in dairies and canning factories.

Fatty Oils. Animal and vegetable fat oils, which contain fatty acids or esters of fatty acids, will attack concrete. Fatty acids react with the calcium salts and free lime in Portland cement to form calcium silicates in the concrete so that it becomes soft. The action is usually slow, but is increased rapidly if the oil or fat is warmed or if the oil is able to penetrate the concrete.

Formaldehyde. Formaldehyde is used in the manufacture of synthetic resins; aqueous solutions attack Portland cement by the oxidation of formaldehyde to formic acid, which combines with the free lime to form calcium formate which is soluble in water.

Fruit juices and Sugars. The sugar and acid in fruits slowly attack concrete.

Gypsum. Although used in the manufacture of cement, gypsum (calcium sulphate), like all sulphates, attacks set concrete.

Hydrogen Sulphide. Hydrogen sulphide is formed by the decomposition of sewage and is responsible for much of the attack of concrete in sewage systems. Hydrogen sulphide combines with free lime to form calcium sulphide which can be oxidized to calcium sulphate. Hydrogen sulphide is also oxidized directly to sulphuric acid which will attack the free lime, again forming calcium sulphate.

Inorganic Acids. All inorganic acids attack Portland cement concrete, some more severely than others. They react with the free lime to form chlorides, sulphates or nitrates. The severity of the attack depends upon conditions such as the solubility of the compound in water and the concentration and mass of the acid. The reaction is speeded up if the acid is hot.

Lactic Acid. Lactic acid is produced during the fermentation of milk, beer, silage and similar organic materials. It attacks Portland cement concrete by reacting with the free lime and forming calcium lactate, which is soluble in water. As with other materials soluble in water, damage to concrete in lactic acid occurs above the water or liquid line due to the growth of crystals in the concrete pore space. High alumina cement is attacked even more severely than Portland cement in concentrations of lactic acid greater than 1 per cent.

Lead. In the presence of moisture, the free lime in Portland cement reacts with lead. Some damage is caused to the concrete but usually the greatest damage is that caused to the lead. Where, as is often the case, lead pipes are buried in concrete, corrosion will result in complete destruction of the lead by the formation in the presence of moisture of lead oxides. Lead pipes in concrete should be protected by being wrapped.

Oils. Refined mineral oils, although able to penetrate concrete, have little effect upon it. Crude oils, particularly sulphur-crude, may have a very corrosive effect on Portland cement concrete due to the high acid content. Organic oils generally attack Portland cement concrete; their attack is dependent upon the ease with which they can penetrate the concrete, i.e. upon the viscosity of the oil and the permeability of the concrete. Those oils which turn rancid when exposed to air and develop acid products attack both Portland and high alumina cement. Many oils can be stored successfully in concrete tanks when not exposed to air and moisture. Some drying oils, for example tung and linseed oil, cause slight attack, but when painted on the surface of concrete and allowed to dry, they oxidize and harden and may be used to protect the concrete surface.

Organic Acids. Organic acids, like inorganic acids, combine with the free lime of Portland cement to form calcium salts. These organic calcium salts are not always as soluble as the inorganic salts and the attack may thus be less. But in addition the organic acids attack the alumina compounds.

Salt for De-Icing. Sodium, calcium and magnesium chloride are all used either separately or in mixtures to remove or reduce icing on roads. Although it is usually assumed that sodium chloride, for example, is not harmful to concrete, some damage may be expected on the concrete surface. The concrete may scale and form small potholes. This is probably due to crystallization in the surface of the concrete. There is little relation between durability and the type of cement used. Air entrainment reduces the amount of surface scaling, but this may be due entirely to the higher resistance of the concrete to the effect of frost.

Water. The attack of water on concrete depends upon its acidity (pH value) and the salts it contains. The effects of sulphate-bearing waters, sea-water and moorland and acid waters are described separately.

Resistance to sulphate attack

Sulphates present in soil, ground water and sea water are known to be the cause of attack on concrete. The principal sulphates are calcium sulphate (gypsum), magnesium sulphate (Epsom salts) and sodium sulphate (Glauber's salts). These react with the calcium aluminate and the free lime in Portland cement concretes.

When such concrete is in contact with sulphate solutions calcium sulphate is formed. This reacts with the aluminates to form sulpho-aluminates and sulpho-aluminate compounds, in the presence of lime, take up a larger volume and so cause expansion and disruption of the concrete.

Sodium sulphate reacts to produce hydroxide, and if there is a continuing supply of sulphates this reaction continues as long as the sodium hydroxide is continuously removed as, for example, by flowing ground water. Magnesium hydroxide is produced when magnesium sulphate reacts with the free lime, and this may be deposited as hard granules in the pores of the concrete and so hinder further penetration. The deposition of magnesium hydroxide, however, allows the calcium sulphate formed to react to form sulpho-aluminates and so causes disruption. In consequence the attack by magnesium sulphates can be more extensive than an attack by sodium and calcium sulphates which, although they produce soft mushy concrete, do not cause such extensive damage.

Reports on the durability of concrete have laid stress on the necessity for dense rich concrete based on the assumption that if the concrete was sufficiently dense and rich then the sulphate-bearing waters could not permeate it and so would not cause disintegration. This is very largely true, but although the rate of attack by sulphate-bearing waters proceeding inwards from the surface is dependent on the ease with which such water can penetrate the concrete, a low permeability is not enough. The chemical composition of the concrete must be resistant to sulphate attack. The specification of a rich dense mix is only part of the requirements for sulphate-resisting concrete, for it has been shown that the rate of disintegration is controlled by the C_3A (tri-calcium aluminate) content. Cements containing less than 6 per cent C_3A exhibit strong resistance, but when the C_3A content exceeds 12 per cent the concrete is liable to suffer from attack by sulphates no matter what the density of the concrete. In fact Miller and Manson found from an extensive laboratory investigation that when the C_3A content exceeded 9 per cent, total disintegration occurred within five years.

The rate of disintegration varies somewhat with the richness of the concrete, a more rapid attack occurring with lean mortar than with a rich mortar. On the other hand lean concrete with a cement with low C_3A content has a better resistance than rich concrete with a high C_3A content but, of course, porous concretes made with a cement with a low C_3A content will still suffer damage by sulphate attack because the water percolates through the concrete, evaporates, leaves sulphate salts behind and thus increases the salt concentration until crystals are formed. This attack by physical, as well as chemical forces, increases the damage. The damage is likely to be greater with the more soluble sodium and magnesium sulphates present in sea water than with calcium sulphate present as gypsum in various clays.

Concrete in Sulphate-bearing Soils

Many soils contain considerable quantities of sulphate and it is necessary to take precautions to protect the concrete from attack or to use concrete which has a high resistance.

It is first necessary to investigate the ground condition to determine the concentration of sulphates. The greater the amount, the more severe will be the attack, but local conditions will affect the result. A soil which has a high concentration of sulphates may not cause much damage if the sulphates are present as gypsum crystals and the concentration in the ground water is low, because it is the sulphates in solution which attack concrete. On the other hand if concrete in soil containing sulphates has an exposed surface from which water can evaporate, then if sulphate-bearing water permeates the concrete severe damage may be caused due to the concentration of sulphates caused by evaporation, even though the sulphate content of the ground water is low. Similarly the flow of the ground water through or around a concrete structure will increase the amount of damage, since the products of the chemical reactions will be removed and fresh concrete continually exposed to corrosion.

The attack of sulphates in soil and ground water is not usually associated with acid attack. The ground water from the various clays in which sulphates are present is usually neutral or even slightly alkaline. Acidic conditions may be found in sulphate-bearing ground water in marshland and peaty areas, and the corrosion is then more severe.

Concrete can be protected from sulphate attack in soils by a layer of asphalt, bitumen, pitch or rubber tar-emulsion; such materials, in fact, as are usually used to form a waterproofing membrane. Epoxy resins may also be used, but while they are highly resistant to acids and alkalis they are expensive. It is essential to ensure that the coating adheres strongly to the concrete surface, otherwise failure may occur.

To have a high resistance to sulphate attack, concrete must be dense and well compacted, while in addition the cement must be resistant to sulphate attack (i.e. have a low tri-calcium aluminate content). When the sulphate content of the ground water is low, then dense concrete made with ordinary Portland cement may be sufficiently durable; for moderately severe conditions however the cement must be sulphate-resisting, i.e. either a sulphate resisting Portland cement or a super-sulphate slag cement. For severe conditions either super-sulphate or high alumina cement must be used.

The conditions of severity are difficult to define; it is necessary to consider the worst conditions including the potential sulphate content of the ground water. Where the soil has a high content but the ground water only a low concentration of sulphates, then there is the possibility of the sulphates in the ground water increasing. In addition it should be remembered that magnesium sulphate can produce more severe corrosion than most other sulphates. The size and type of structure must also be considered; a large concrete foundation may not undergo sufficient deterioration to affect its stability or require any remedial measures, whereas a concrete pipe which has suffered the same amount of deterioration of its surfaces may have to be replaced.

Concrete in Sea Water

Concrete is one of the main materials used in sea defence works and in the construction of docks and harbours, and is subject to destructive activity both from physical pounding by the sea and from chemical attack by the salts contained in it.

The action of sea waves in causing extensive destruction of sea defence works during storms is well known. It is not always realized, however, that chemical attack may help physical destruction as well as physical destruction assisting the rate of chemical attack. Cracking leads to the penetration of sea water into the concrete; with reinforced concrete, corrosion of the reinforcement follows, and with plain concrete the depth of chemical attack is increased.

The chemical attack by sea water consists essentially of two parts; attack of the concrete which is submerged, and attack of that which is just above the water level. In concrete which is just above high water level the sea water rises by capillary attraction. No concrete has zero absorption, so that by absorption and evaporation a strong concentration of salts is formed, with eventual crystallization. The salts react with the cement, and the growth of crystals physically disrupts the concrete. In addition alternate wetting and drying causes small movements of the concrete and in cold weather alternate freezing and thawing has a disruptive effect, although in this country it is unlikely that the salt-laden moisture in the pores will freeze. It is the concrete lying between high and low water which is subject to the pounding effect of waves, to the leaching out of any reaction chemicals formed by the action of the sea water on the cement, and to the erosive action of beach sand and gravel.

Below low water level, concrete is subject only to the chemical attack with perhaps some abrasion due to sand and gravel, depending upon the coastal situation. A few feet below the sea surface the impact force of waves is very much reduced, so that physical erosion and pounding is not as great.

The chemical attack by sea water is more complex than that of simple sulphate solutions, due to the presence of other chemicals. Chlorides tend to retard any swelling of the concrete which would result from a reaction with sulphates only. In addition free lime is more soluble in sea water than plain water. The combined chemical and physical attack of sea water leads to more aggressive leaching than would take place in ground waters containing a similar concentration of sulphates.

It is the combined effects of erosion, physical pounding and chemical corrosion which cause the greatest damage, however. Where the concrete is subject to all these causes of attack it should have a high density with a minimum cement content of 5 to 6 cwt/cubic yd and be made with a cement whose C_3A content is below 6 per cent. Sulphate resisting Portland, Portland blastfurnace, super-sulphated slag or high alumina cements should be used in preference to ordinary Portland cement. Sulphate resisting or Portland blastfurnace cements are suitable for most work. Super-sulphated slag cements are suitable for mass work, because of their low heat of hydration. High alumina cement can be used with advantage in temperate climates for thin reinforced concrete sections, but the mix should not be richer than 5:1 and should not be used in mass work.

The concrete must be well compacted by efficient vibration. Reinforced concrete should have adequate cover to the steel. The aggregates used should be durable with a low moisture absorption and shrinkage. In reinforced concrete work ¾ or 1½ in. aggregates are suitable, and in mass work 2½ in. aggregate, with the water content reduced so as to ensure just sufficient workability for the concrete to be compacted with a heavy (3½ in.) vibrator. Adequate curing of all concrete exposed to sea water is essential to reduce cracking and shrinkage.

Where concrete in sea water is not subject to heavy pounding and erosion, leaner mixes can be used; aggregate/cement ratios of 10:1 have been used for mass work where the very rounded nature of the gravel permitted a relatively low water/cement ratio (0·6) but with adequate workability (VB 3 sec).

It is seldom possible to protect concrete from sea water attack by a waterproof membrane, although piles up to 100 ft long have been produced at Los Angeles since 1925. These are pressure-grouted (Wakeman *et al.*, 1958) at 100 p.s.i. with hot bitumen after drying at 250°F, in much the same manner as wood is creosoted.

Resistance to soft moorland waters

Soft moorland waters are acid with a pH as low as 3·5, and are soft with a total hardness of less than 20 p.p.m. They attack concrete by leaching out the free lime and attacking the calcium aluminates. Besides the pH and hardness, the free carbon dioxide is important. When the temporary hardness is between 10 and 20 p.p.m. attack takes place only when the free carbon dioxide is above 10 p.p.m., but with a hardness below 10 p.p.m. water will attack concrete in any case even if it has a relatively high pH of 6·5 to 7

Ordinary Portland cements suffer most. High alumina cement is not attacked in this way, but cannot be used in many structures which suffer attack; such structures are usually large concrete dams and other hydraulic structures where the hydraulic pressure induces a flow of water through the structure, and the leaching action of the acid water is thus accentuated.

Concrete pipes and culverts may also suffer corrosion by moorland waters but the attack is often less than might otherwise be expected, for the surface becomes coated with a thin deposit of peat slime. This may reduce the carrying capacity but it helps to protect the concrete. When concrete pipes are first put into service carrying soft waters there is an initial alkali pick-up by the water in the first few months when free lime is leached from the surface. Concrete for pipes and aqueducts should be a rich dense mix with a low water/cement ratio. Mortar as rich as 1:1 to 2:1 (aggregate/cement ratio by weight) with a water/cement ratio of 0·35 has been used *in situ* to provide a new lining to corroded iron and steel pipes. The proper curing of such linings and of all concrete pipes is essential to prevent shrinkage cracks. Adequate curing can be achieved by painting the exposed concrete surface when it is 6 to 8 hours old with a cut-back bituminous paint. This has the advantage of eliminating the initial alkali pick-up and protecting the concrete surface from attack until it is quite old — 5 to 10 years at least, even with acid waters. Where the leaching attack of soft water is severe, the aggregate may be exposed and then removed by erosion. This exposes fresh unattacked surfaces to corrosion, which then continues. In an aqueduct this roughening of the surface reduces the flow capacity, the Hazen-Williams flow coefficient dropping from 130—140 to say 70—80.

Resistance to sewage

Concrete is not normally affected by domestic sewage, which is alkaline and is usually in a fresh condition. Trade wastes may be highly acid or alkaline and cause severe attack. Sewage may decompose and become septic, and with the help of sulphide-reducing bacteria mineral sulphates are reduced to hydrogen sulphide. Such sewage will attack concrete. Fresh sewage does not produce sulphides in appreciable amounts until it has been stored for two or three days, but once sulphide-forming bacteria are present they can rapidly decompose fresh sewage and produce sulphides in a few hours. Furthermore, increases in temperature produced either by hot weather or by the addition of hot trade wastes can promote the production of hydrogen sulphide.

Hydrogen sulphide combines with free lime to form calcium sulphide, which can then be oxidized to calcium sulphate. In addition it is oxidized directly to sulphuric acid which will attack the free lime to form calcium sulphate. Portland cement concrete which has been attacked exhibits a yellowish-white flaky coating on the concrete. The concrete surface is attacked by intermittent crumbling, and often becomes soft and putty-like. This deterioration is most marked at or near the sewage water line. Concrete entirely immersed or completely exposed to the air is usually free from attack.

High alumina cement has a higher resistance than Portland cements, but is not the complete answer in that it can be partially corroded. Moreover, high alumina cement in sewers may, during hot weather, be subject to temperatures above 85°F; when combined with the high humidity this causes reversion in the cement with a reduction of its strength and resistance to corrosion.

To prevent the corrosion of concrete by sewage, the best precaution appears to be to avoid the formation of septic sewage. If sulphate-reducing bacteria are present their activities should be minimized by ensuring adequate ventilation and, if necessary, by chemical treatment of the sewage.

Resistance to freezing

The resistance of concrete to frost is probably more important on the Continent, in Russia, Canada and the United States than in this country. Indeed in some of these countries it is not possible to build in the winter without taking special precautions. In this country, on the other hand, the frost resistance of concrete is important mostly in road construction where from time to time in cold winters some damage occurs. This is usually restricted to surface scaling and spalling at joints, but occasionally concrete slabs are disintegrated.

When water freezes it expands; if restrained, this expansion can cause a high internal pressure sufficient to disrupt even the strongest concrete. Since, however, concrete can successfully withstand repeated freezing and thawing it follows that either the water in the concrete is not necessarily frozen even when there is ice on the surface, or else the ice in the concrete was able to expand due to all the voids in the concrete not being filled with water.

For a concrete to be resistant to frost it should have a low water content, so that it is never fully saturated. It should have a low absorption and low permeability so that it will not readily take up water. In addition the cement paste should have a high permeability, so that on freezing of the water high pressures are not generated within its pores. This last requirement is incompatible with a low overall permeability, but if the concrete contains small entrained air bubbles then the distance any water is forced to migrate to the first free void space (or air bubble) will compensate for the low permeability of a rich mortar. The concrete should have a relatively high cement content at a low water/cement ratio so that as much water as possible is used up combining with the cement during hydration and sufficient strength is achieved to resist stresses set up during freezing conditions. In general the water/cement ratio should not exceed 0·60, and for road slabs should be restricted to 0·50.

These requirements may appear contradictory, but they are made clearer when we consider how concrete is subject to disintegration by freezing.

Freezing of Green Concrete

The simplest explanation of the damage caused by frost is that it is due to the growth of ice crystals in the voids in the concrete. In a concrete road slab, for example, when any layer reaches a sufficiently low temperature the water in the larger pores, where it is free from surface tension, will begin to freeze. The water gives up its latent heat, and tends to maintain a constant temperature at the point of ice formation by the transfer of heat between the cool surface and the point where freezing takes place. The mechanism is as follows.

Ice crystals, which are formed in the water-filled voids, will by the creation of a suction draw unfrozen water from the surrounding small pores. In this way the ice crystals continue to grow. In any case the force exerted by the ice lens will be perpendicular to the cold surface, so that if the concrete is of low strength a plane of weakness parallel to the surface will form as ice lenses grow. The growing crystals of ice draw water first from the largest voids and then from the smaller ones. As less water becomes available the growth of ice is reduced. The release of latent heat from the freezing of the water is then not sufficient to maintain constant the temperature at the point of ice formation, and in consequence the temperature will once more begin to fall. This reduction in temperature of the concrete progresses inwards from the surface, but since the voids in the immediate vicinity of the ice crystals are devoid of water, freezing will not again take place until the low-temperature front arrives at voids sufficiently far away from the previous ice lenses as to contain sufficient water to allow the growth of further ice. The result is that the concrete will contain a series of planes of weakness parallel to the surface, which can result in the scaling of the concrete surface.

If the concrete is subject to subsequent cycles of freezing and thawing, ice will again form at the same levels as before because the pores in the concrete will have been dilated by the previous ice growth, the voids will be larger, and the freezing point of the water in them will be higher than in the surrounding concrete. Damage to the concrete is caused not so much by the increase in volume of the water in the voids on freezing as by the subsequent growth of ice crystals and by the concentration of ice into lenses.

Physics of Saturated Concrete

The entrainment of air increases the resistance of concrete to damage from freezing, but to understand how this occurs it is first necessary to consider the structure of the cement paste. The hydration of cement produces a porous gel which envelopes the unhydrated cement particles. If this gel, together with the aggregates, completely filled the available space, the only pores remaining would be the very small ones in the gel itself. When, as is usually the case, the gel does not fill the space completely, then the paste is intersected by a system of capillary pores. During hydration these capillaries, at first full of water, are partially emptied as a result of the hydration process, and they do not readily refill with water even when the concrete is cured under water. In addition, when a cement mortar is dried, it shrinks, and as a result the cement paste can reabsorb only about 95 per cent of the original volume of water that it held. This is important because it contributes towards the frost resistance of concrete. When dried concrete is completely saturated by first removing the air from it under vacuum, then instead of being able to withstand say 100 or more cycles of freezing and thawing it will disintegrate completely in less than 5 cycles. The completely saturated concrete is not able to withstand the pressures that are developed when the water in it freezes. Since apparently saturated concrete does not ordinarily fail completely on first freezing, this means that it was not fully saturated and there is enough unsaturated space in the concrete to accommodate the expansion that accompanies freezing.

Concrete is able to withstand many cycles of freezing and thawing before disintegration if its water content is initially below about 90 per cent saturation, and below 80 per cent it is rarely damaged. Saturation affects the temperature below freezing at which ice can exist in concrete. When concrete is nearly or completely saturated, the freezing point is only slightly below 32°F. As the saturation is reduced the water is held by the finer capillaries and the temperature at which it will freeze becomes progressively lower, because the surface tension in these small capillaries holds the water in a state of stress and reduces its freezing point.

Mechanism of Disintegration

When concrete is subject to freezing and thawing it may show little change in weight and appearance but suffer large losses in strength and resilience; alternatively it may slowly crumble and spall on the surface but show little loss in strength, or it may show a combination of both crumbling and loss of strength.

Under some conditions concrete may be damaged by freezing even when the degree of saturation of the specimen as a whole is below the 90 per cent critical value that would cause disintegration.

Consider a road slab whose surface has been saturated with rain and which is then exposed to frost. The water freezes, thus sealing the surface of the slab. Ice forms on the outside first because the freezing point of the water inside the concrete is lower than 32°F. Next the water in the large spaces of the concrete near the surface will freeze, whilst water unfrozen in the smaller capillaries will be displaced towards the less saturated interior by the expansion of the frozen water. If the water were free to move without resistance, no hydraulic pressure whatever would develop. But the water is required to move through a fine porous cement gel, so that a pore water pressure is set up. If the freezing is sufficiently rapid then it is possible for the pore pressure to become so high as to exceed the strength of the cement mortar, and so cause spalling.

On the other hand with slowly repeated freezing and thawing in water, concrete will absorb water and on freezing at the surface more water will be pushed inside the concrete. As the thickness of the saturated region increases, the resistance to displacement of water out of it toward the region of lower water content increases. When the saturated region becomes sufficiently thick the hydraulic pressure becomes greater than the strength of the material and causes disintegration or spalling of the surface.

If concrete is uniform in structure and not wholly saturated at the start of freezing, no crumbling or spalling will result until a certain amount of water has been absorbed, sufficient to saturate the surface region to the critical depth. The pore pressure generated will depend upon the permeability, the rate of freezing, and the amount of water in the concrete at the freezing surface. It follows that the lower the permeability then the higher will be the pore pressure generated, so that a rich concrete will contain higher pore pressures than a lean one. But this is offset by the low absorption of rich concrete. Lean concrete absorbs water much more rapidly, whereas rich concrete does not become fully saturated, even after prolonged soaking.

Under natural conditions of exposure, concrete is subject to alternate wetting and drying as well as freezing and thawing. The periods of drying are usually long relative to the periods of wetting so that dense, impermeable concrete is less saturated than lean concrete which absorbs water quickly. In addition, where a lower permeability is due to a rich mix, such concrete will have a high degree of desiccation due to hydration of the cement, as already described. In freezing and thawing tests the advantage of a rich concrete in having a low rate of absorption is not always demonstrated. Since frost damage is more easily caused when the concrete is highly saturated, then the greatest amount of damage may be expected when a wet autumn is followed by a sharp spell of frost, or where early winter is very wet and is followed by freezing weather, so that the pore pressures generated in the unfrozen water by the expansion during the formation of ice crystals force the unfrozen water into the small voids.

It follows, therefore, that the greater the number of the air voids the less will be the damage due to freezing, and the closer they are together the lower will be the pore pressure.

The strength of concrete is affected by the amount of air voids present, every 1 per cent of air reducing the strength by 5 per cent. It is essential to ensure that concrete has adequate strength, and the amount of air voids must therefore be limited.

For a limited amount of air the maximum resistance to freezing is obtained if the average size of the air bubbles is small, so that there are a large number of them closely spaced. This can only be achieved by incorporating an additive which will entrain a controlled amount of air (usually 5 to 7 per cent) and produce a large number of equally spaced small air bubbles in the concrete.

It is possible for air-entrained concrete to have a frost resistance no greater than non-air-entrained concrete. This is because some air-entraining agents increase the air content by entraining only a few large air bubbles.

Resistance to erosion and abrasion

In the United States the problem of erosion was investigated in connexion with the deterioration of spillways of the Boulder and Grand Coulee dams. From the investigations it was concluded that well made and properly compacted concrete is essential for maximum resistance to erosion. Poorly compacted concrete or concrete with a rough surface deteriorated rapidly. Provided concrete is well made and properly placed its resistance to erosion depends more upon the design of the structure than upon the concrete; in other words if the hydraulic characteristics of the structure are poor, so that abrupt changes of velocity or direction of flow occur, producing cavitation, then high erosion will be induced.

Where, as sometimes occurs in spillways, water at high velocity carries suspended gravel, sand or silt, then erosion of the concrete surface can be expected. The resistance of concrete to such erosion is linked to its resistance to abrasion, in that imperfect work or poor materials produce a layer of friable material on the surface which is particularly susceptible to erosion or abrasion. This friable material consists mainly of cement laitance and fine sand, which is rapidly abraded; afterwards the rate of abrasion is usually constant. Where the coarse aggregate is a hard material such as flint gravel or granite, the rate of abrasion is related directly to the quality of the matrix surrounding the coarse aggregate. As the quality of this matrix is improved the resistance is increased. Where the coarse aggregate is a weak material, such as weakly cemented sandstone, then this material, and not the mortar, will control the rate of abrasion.

Resistance to fire

The resistance of concrete to fire depends upon the materials with which it is made, its condition, and the shape and size of the structural element subjected to the fire. The most important of these factors is the shape and size of the concrete member. The fire resistance of a beam increases rapidly with increase in size and mass, but is less if it is an I section with a thin bottom flange or a T section with a thin stem.

No concrete structure can withstand indefinitely the effects of fire, but the larger and more massive the structure the greater is the resistance. Fire resistance, however, is chiefly of concern to the structural engineer dealing with relatively thin reinforced or prestressed concrete members. In such construction, besides the shape and size of the structural element, the amount of cover over the steel or prestressing wires and the protection afforded by a plaster coating are of more importance than the materials, age and condition of the concrete.

Certain aggregates, however, have a better resistance to fire than others, while resistance to high temperatures can be achieved by using high alumina cement and refractory aggregates.

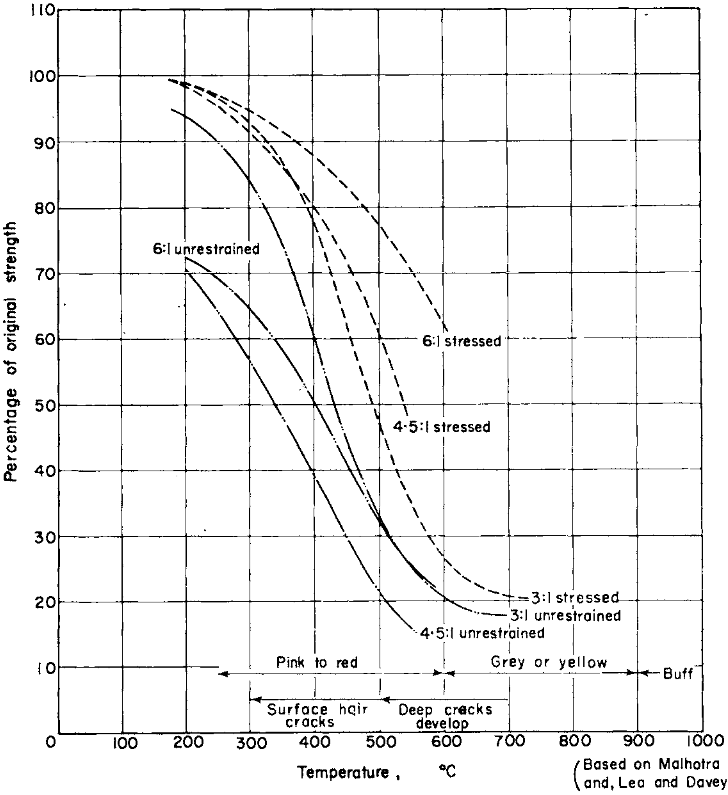
Aggregates with a high resistance to fire are dolerites, basalts, limestone and nearly all the manufactured and lightweight aggregates, such as blastfurnace slag, foamed slag, sintered clay and shale aggregates, vermiculite, and broken brick if free from quartz. Manufactured aggregates such as slag and sintered clays are unaffected by temperatures up to 1000°C, which is less than that to which they were heated during manufacture. Limestone calcines at about 700°C and is liable to disintegrate upon subsequent exposure to air. Flints and coarsely crystalline rocks such as granites and gabbros are less resistant to fire because the quartz they contain causes spalling. Even with these materials, however, fire tests have shown that explosive spalling of concrete made with flint gravel is unlikely to occur when the structural member has no part less than 2 in. thick. If, however, the temperature is high enough, cracking and spalling will occur, even on massive structures, depending upon the time over which the high fire is effective.

It is most important to be able to assess the strength remaining in a concrete structure after a fire. If the fire has been extensive, lasting for more than an hour or two, then the concrete will have ceased to be a structural material for its temperature will have reached 1000°C; this will be indicated by extensive spalling with the main reinforcing steel left bare and showing signs of scaling. The remaining concrete will show varying amounts of crumbling, scaling and cracking. Usually the only satisfactory solution in such a case is demolition and re-construction.

In a less extensive fire, brought under control within an hour or so, much of the structure may remain sound. The residual strength depends upon the temperature reached in the concrete and the form of construction. Tests at the Fire Research Station have shown that with a surface temperature of 700°C the following temperatures were reached at various depths.

Distance from face (in.)	Temperature after 15 min exposure (°C)	Temperature after 30 min exposure (°C)
$\frac{1}{2}$	380	510
1	180	320
2	70	110

Sandstone and flint aggregate concretes show different colours depending upon the temperature (see Fig. 6.1). From this it may be seen that if the temperature reaches 500 to 600°C, then the residual strength of that concrete is less than half of the initial strength. Although granite and other igneous rocks do not show these colour changes, they still occur in concretes containing such rocks but made with a normal quartz sand. When the temperature reaches 573°C quartz changes its chemical structure with a rapid increase in volume, and this leads to spalling. Thus spalling of the concrete covering the



(Based on Malhotra and, Lea and Davey)

Fig. 6.1. Residual strength of concretes subject to high temperatures.

reinforcement, accompanied by a pinkish colour, is an indication that the concrete probably has only half its strength, although in beam and slab construction the compression concrete, if remote from the fire, may not be much affected.

Fire, of course, affects steel reinforcement, but the effect is much less for mild steel, although a temperature of 800 to 1000°C may lower the yield point by about 25 per cent. The effect on prestressed concrete is more serious. At 200°C a prestressed member will show some loss of prestress, although the ultimate strength may still be a high proportion of its original value. Temperatures of 200°C in the wires may be reached by conduction of heat from adjacent members subject to the fire. There is a marked reduction in bond between concrete and steel at 300°C, whilst at 400°C it can be assumed that the prestressing wires have lost nearly all their prestress. They will have been annealed so that they are the equivalent of mild steel bars. At this temperature, however, the concrete may show very little colour change and not much cracking.

Heat-resistant Concrete

Concrete resistant to heat up to 1000°C is used in the construction of boiler and oven foundations, and is produced by using high alumina cement with various aggregates. Crushed brick aggregate or crushed fire brick is often used. The mix proportion by volume is 1:2:2 to 1:2:4, depending upon the size of the coarse aggregate, which is usually limited to $\frac{3}{4}$ in.

Ordinary Portland cement and normal aggregates can be used for temperatures up to 150°C where precautions are taken to dry out and heat up the concrete gradually and where the changes in temperature occur slowly. Such concrete has been used with success for longitudinal pits underneath brick tunnel kilns.

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CHAPTER 7

SURFACE TREATMENT OF CONCRETE

THE surface treatment of concrete consists of treating structural concrete by certain techniques to expose the aggregate, or of facing it with precast or *in situ* facing concrete.

There has been a rapid development in the use of precast facing slabs, which are now used as a cladding material and for in-filling panels. They may be applied to the building during general construction and used as permanent formwork. A wide range of textures and colours may be achieved by the use of suitable aggregates. A similar wide range of finishes may be obtained in structural concrete by the subsequent exposure of the aggregate.

Surface treatment of *in situ* concrete

A number of surface finishes can be achieved with *in situ* concrete, not all of which are of equal value and not all of which are expensive, but whatever treatment is adopted its quality is always controlled by the quality of construction. The simplest treatment — but that requiring the greatest care — is the surface finish as left by the formwork. The second type is obtained by exposing the aggregate by tooling, such as bush-hammering or chiselling. A third type of finish is achieved by using a surface retarder and washing down the exposed surfaces after the shutters have been struck.

Finish Left by Formwork

This type of finish includes that left by rough-sawn timbers, the smooth finish of plywood-lined shutters, or the special finishes achieved by lining the formwork with absorptive wall-board or textured rubber.

At one time sawn timber formwork was the only material available and its use was a necessity of making the best of an otherwise difficult material. However, striking effects have been achieved with it, although care is necessary in the detailing and construction; but then care is necessary to produce any satisfactory surface finish.

To obtain a good finish, correct design of the formwork is important. The formwork affects the patterns which appear on the concrete surface; for example, all the junctions of boards butted together show up as slightly protruding lines of concrete, and the board marks of a making-up piece show if the rest of the formwork consists of smooth plywood-lined shutters.

The formwork must be mortar-tight to prevent bleeding, with the consequent uncontrolled loss of mortar resulting in honeycombing. The various components of the formwork must be properly secured together to prevent uncontrolled movement, as the movement of shutter-boards produces surfaces which accentuate the size and type of the boards used. If not properly braced, shutter boards may bulge and allow the escape of mortar between adjacent boards. The movement of boards and the junction of boards butted together may be used to produce a regular and controlled pattern which fits in with the architectural treatment, but this requires care and selection in the use and fixing of the shutter-boards. The age and number of uses to which the boards have been put affect the finished surface, because old shutters tend to be rougher than new ones and produce a very different surface finish.

The joints between shutter-boards are important; they should be staggered, and alternate joints should line up with one another. The direction of the joints should be maintained to avoid the haphazard juxtaposition of horizontal and vertical boards.

All construction joints should be rigidly controlled, and where the surface finish is important their position should be specified before construction commences; otherwise difficulties may arise which might result in the forming of a construction joint in such a position as to mar the surface finish.

A smooth finish is now usual because of the use of plywood shutters in place of sawn timber. Such a surface is desirable for the subsequent exposure of the aggregate by tooling or other methods. For most general work the standardization of formwork and the use of unit or modular formwork often built up of plywood-lined frames has led to simplicity, to an increase in the number of uses, and also an improvement in the surface finish of the concrete.

Plywood is available in various thicknesses, varying from 3-ply, about $\frac{1}{8}$ in. thick to multi-ply, about $\frac{3}{4}$ in. thick; 3-ply may be used as a lining to a sawn timber shutter, but it is usual to use plywood about $\frac{1}{2}$ in. thick made up into stud panels which bolt together. Care is necessary in using plywood to ensure that it can be stripped easily; difficulty in stripping results in the plywood being damaged, it being more liable to damage than wrought timber. It is, of course, impossible to produce a smooth surface with damaged plywood.

The use of other methods of shutter lining has not gained much ground, although various materials including p.v.c. sheeting, textured rubber, wall boarding and etched timber sheets have all been used from time to time to produce certain desired surface effects (see Plates 9 and 10).

Exposed Aggregate Finish

Even when all precautions have been observed an untreated concrete face as left from the formwork may have a dull and dead appearance, due to the grey cement film on the surface. To improve the appearance the surface may be treated to expose the aggregate either by washing off the cement or by tooling the surface. This exposes the structure of the concrete, emphasizing its nature as a cemented stone aggregate.

Objections have been raised to tooling, it being alleged that it diminishes the resistance to weathering. But the resistance of a concrete depends upon the quality of the materials and the completeness of the compaction, and not merely on the surface skin.

The removal of the superficial cement film to expose the aggregate emphasizes any deficiencies in the concrete due to bad composition, inadequate compaction or faulty shuttering. The exposure of the aggregate is thus indirectly an effective incentive to good workmanship.

Tooled Surfaces. The most common form of tooled surface

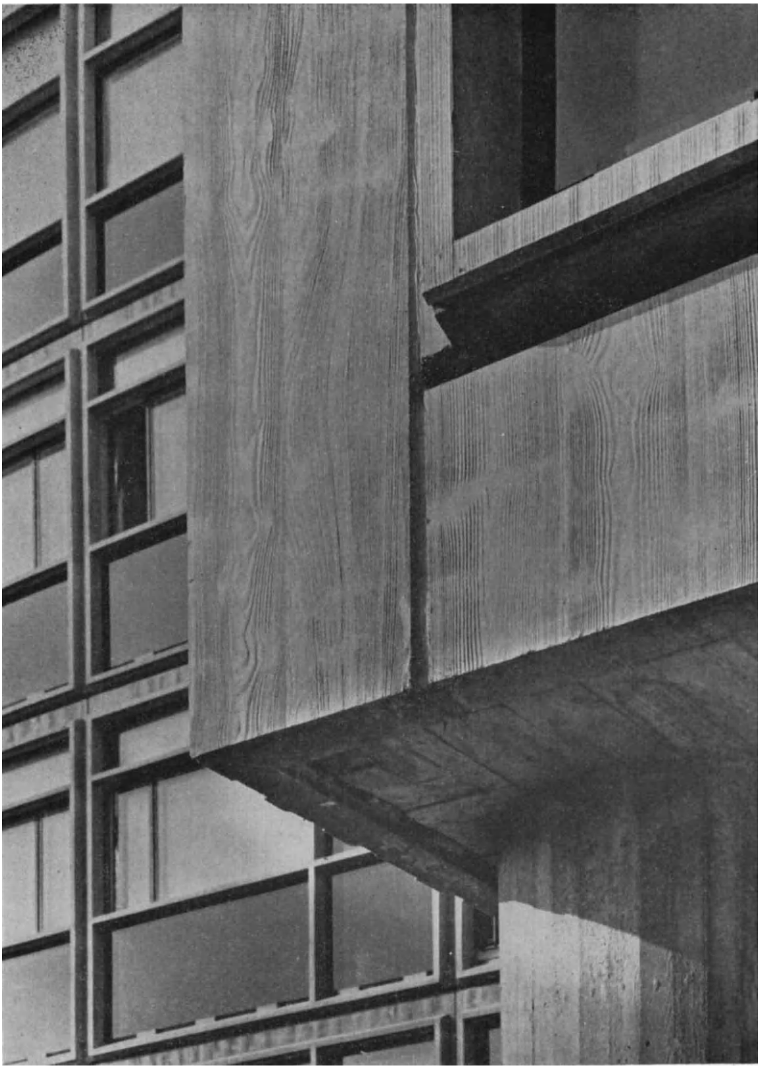

Plate 9. Texture achieved by casting against sand-blasted pine.

is produced by bush-hammering. The concrete is hammered with a light pneumatic or electric jack-hammer so as to remove the film of cement mortar and expose the aggregate. Various

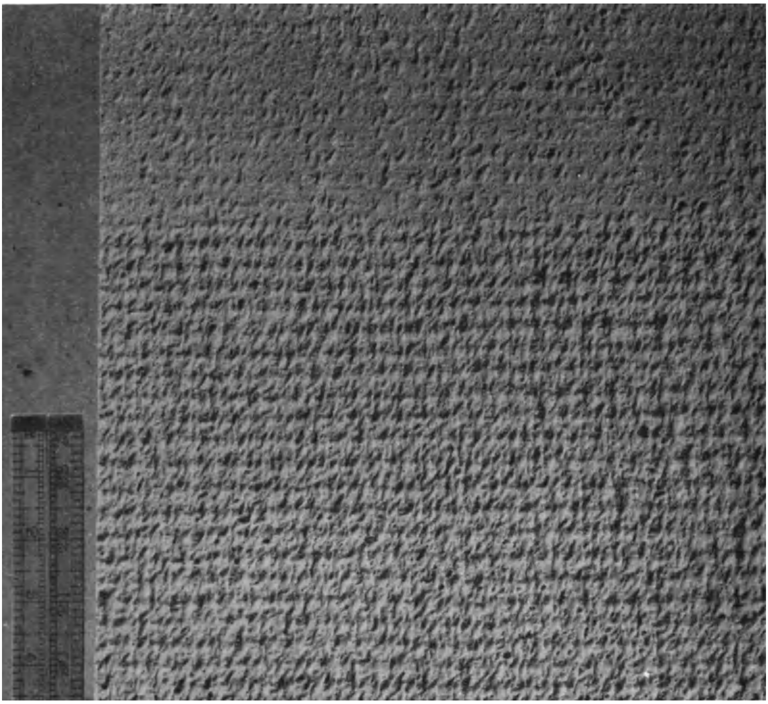

Plate 10. Texture resulting from casting against crepe rubber.

kinds of surface can be produced by using different tools such as a chisel, star drill, steel comb or disc (see Plates 11 and 12).

Sparrow-pecking is another kind of surface finish, produced by using a pointed hammer.

Bush-hammering may be used for reinforced concrete faces, but good surface effects are difficult to achieve as even repeated bush-hammering with a coarse hammer does little more than flake off the cement film and split a few coarse aggregate particles. More pronounced effects can be achieved by power chiselling, often performed by an irregular tooling in two directions.

Reinforced concrete may be chiselled as long as the steel is covered by about $1\frac{1}{2}$ in. of concrete after chiselling, i.e. by $2–2\frac{1}{2}$ in. initially, but power chiselling should be restricted to

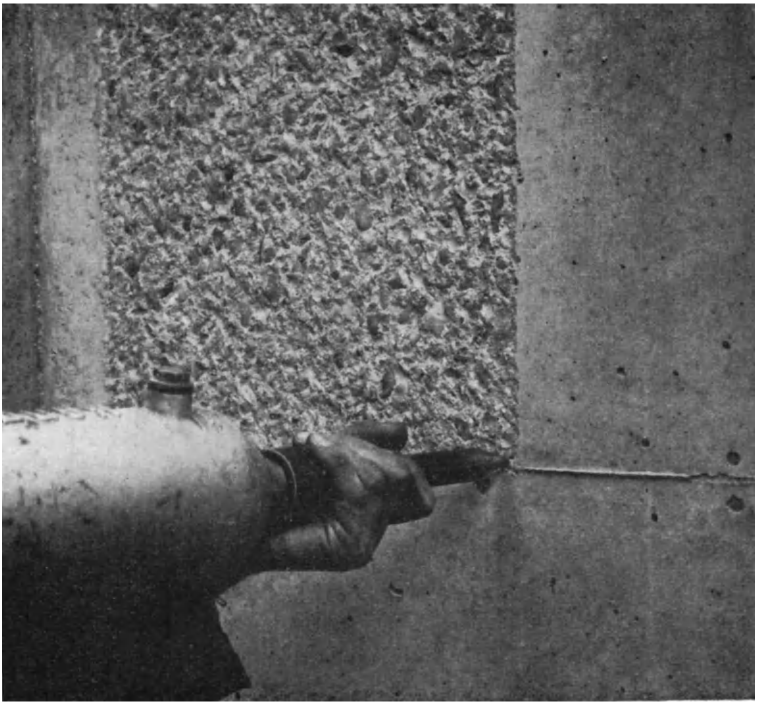

Plate 11. Exposed aggregate produced by mechanical tooling.

massive plain concrete and only manual chiselling used for reinforced concrete. The cost of such work is relatively high, and so its use is restricted. To obtain the best effects it is necessary to split the coarse aggregate, and generally speaking a chiselled surface is more attractive if large coarse aggregate has been used. It is essential that the aggregate be resistant to weather and frost, and care must be taken to ensure that the chiselling spalls and breaks off the surface concrete and does not produce fine hair-cracks in the remaining concrete.

Bush-hammering or chiselling should not be carried out up to the edge of a sharp arris or corner, otherwise spalling of the concrete at the edge may occur. The margin may be quite narrow, and should be lightly tooled to remove some of the cement cover to the aggregate.

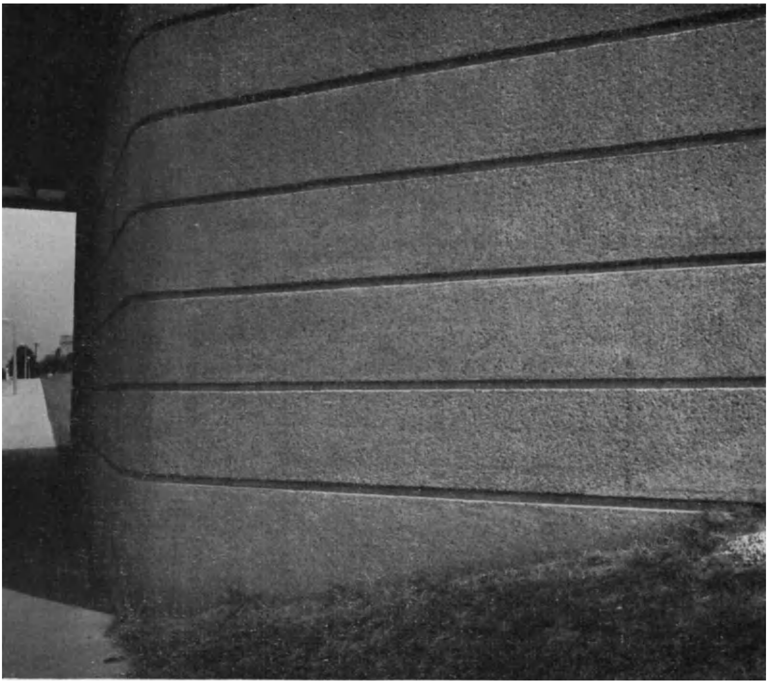

Plate 12. Surface texture produced by light tooling.

Exposed concrete surfaces are sometimes tooled too early. This makes the work easier, but it results in crushing of the concrete and in tearing out the larger aggregate particles. The older the concrete, the more pleasing the effects of tooling; a minimum age is about four weeks, and six or eight weeks is preferable. Where concrete is bushed hammered, in the preparation of a waterproof joint (see Plate 13) this is usually carried out at 7 days.

Scrubbed and Sand-Blasted Surface. The aggregates can be exposed and the composition of the concrete accentuated if the cement-mortar film on the surface is removed by scrubbing or sand-blasting. The simplest method is to use a surface retarding agent painted on the shutters, strip the shutters after 6 to 8 hours, and scrub the concrete surface with wire brushes

Plate 13. Surface bush hammered around starter bars and P.V.C. water bar to ensure first-class construction joint.

or scrape with a saw blade (see Plate 14). The scrubbed surface is then washed down to clean the exposed aggregate.

Scrubbing and washing down is restricted to single-storey work due to the difficulties of maintaining the already completed work free from contamination as the structure is erected. Care is necessary on all arrises to avoid a poor finish. The arris is either left untreated or is avoided by the use of rounded corners.

The most pleasing surface is achieved by using single-size

Plate 14. Texture produced by scraping with saw blade.

large aggregate of uniform colour — in fact by the use of gap-graded concrete (see Plate 15). This type of exposed surface has been used in this country, whilst on the Continent a similar material, termed "natural concrete", has been produced by using pre-packed concrete grouted with a high-strength mortar.

Sand-blasting has been used to some extent on pre-cast work (see plate 16) and it has also been used with great architectural effect to produce abstract and pictorial designs on otherwise plain walls. Because of the site difficulties with sand-blasting — in particular the dangers of silicosis — return shot-blasting has been tried in which the surface is blasted with shot of a particular size, the shot and the eroded material being automatically returned to the machine by a vacuum line.

Etching with acid has also been used, but this process is restricted to precast work and the same effect can be largely attained by using a surface retarder and spraying the exposed surface with water.

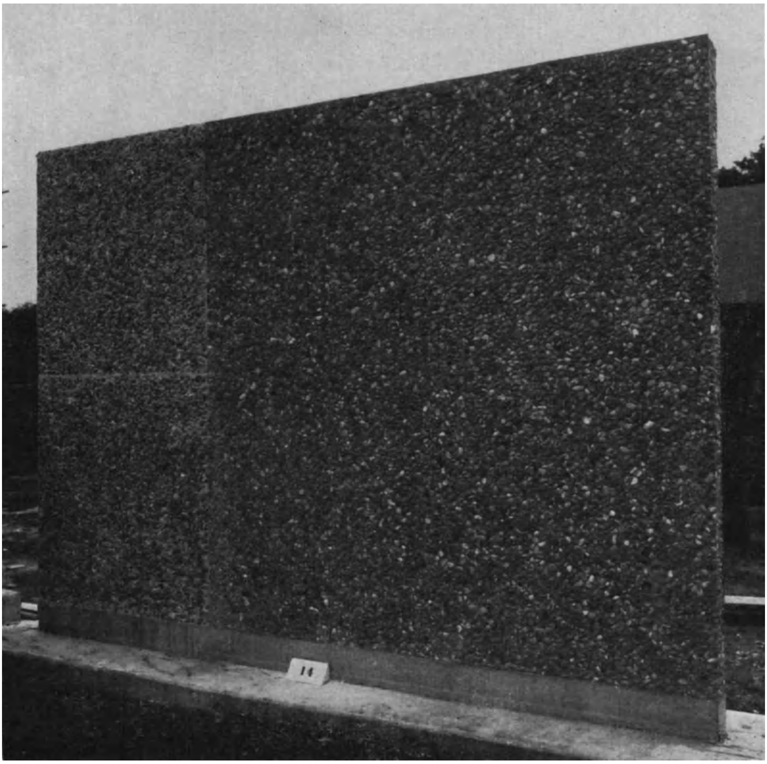

Plate 15. Panel of exposed gap graded aggregate (white cement used on left)

Requirement for Surface-Treated Concrete

Treatment such as tooling will not hide poor construction and honeycombing; no satisfactory finish can be obtained unless the concrete is well compacted, uniform both in texture and colour, and free from segregation, bleeding, and defective construction joints.

The aggregates must be obtained from the same pit or quarry throughout the work, because it is important to maintain constant the colour and grading of the fine and coarse aggregates as well as the aggregate/cement and water/cement ratios otherwise different batches will show up as different colours.

The cement content must be maintained constant and should not be less than 500 lb per cubic yd of concrete; the strength should

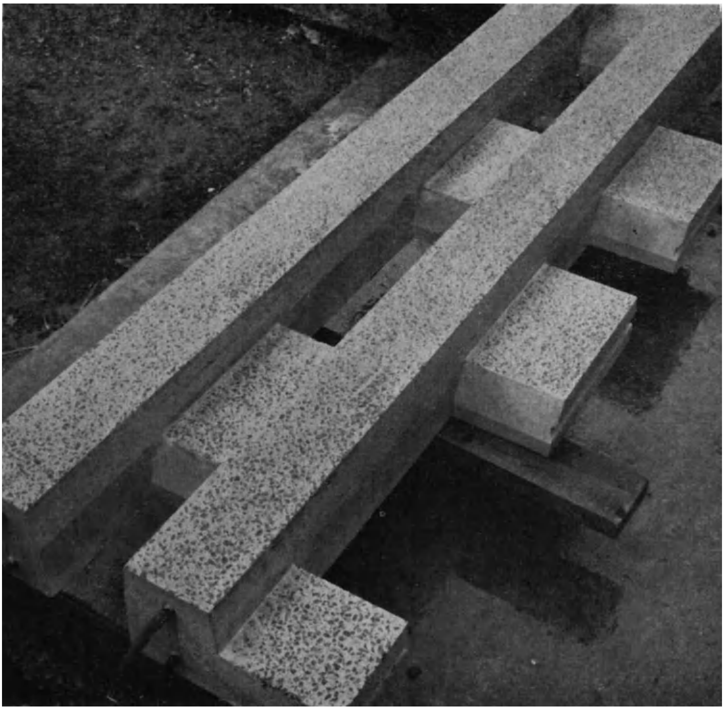

Plate 16. Pre-cast unit aggregate exposed by shot blasting.

not be less than 3000 p.s.i. If the normal concrete is of this or better quality then special facing concrete is not required, provided there is sufficient water to give a plastic consistence during compaction. Such concrete will usually fulfil the requirements for impermeability, weathering and uniform appearance of surface concrete. If the normal concrete is of lower strength then a surfacing concrete may be necessary, but a surfacing concrete with a high cement content or low water/cement ratio should not be used, for the difference in cement content between the facing and the ordinary concrete results in differential shrinkage and the facing concrete spalls off. Facing concrete should not be used in reinforced concrete structures. It may be used in plain concrete construction, but should not be less than 1 ft thick. The differences between the water/cement ratios and the aggregate/cement ratios of the mass and the facing concrete should be small.

The grading of the aggregate for surface concrete depends on whether the exposed surface will subsequently receive any treatment. If the surface is to be tooled, the coarse aggregate used should be at least 1½ in. except in the case of parapets where a finer aggregate is required. Tooled surfaces always appear more pleasant and varied if the exposed aggregate is coarse.

If it is intended to expose the surface aggregate by removing the mortar surrounding it, then the aggregate should be single-sized. A continuously graded aggregate results in a less pleasing texture than a single-sized gap-graded aggregate. Although a gap-graded material may prove a little more difficult to place, its use permits the combination of a highly efficient structural material with a pleasing surface.

Specially selected aggregates may help to enhance the appearance, but if coloured coarse aggregates are used, coloured or white sands must be used as well. Crushed aggregate should be avoided in facing concrete as it is more difficult to compact and requires a larger proportion of fines and a higher water content than rounded gravel.

Care must be exercised in choosing aggregates to ensure that they do not include material likely to cause staining as, for example, pyrites or marcasite which cause iron staining, or soft chalk which can cause a streaky white deposit. Sufficient fine sand passing a No. 52 sieve is necessary in the mix because a deficiency may cause streaks on the concrete surface due to the wet concrete giving up water which gathers on the shuttering, trickles down and washes out the cement from the concrete below. Planing and oiling of the shuttering makes this worse. The content of fine aggregate passing a No. 7 sieve should amount to between 6 and 8 per cent of the total quantity of aggregate, so that the combined amount of cement and fine aggregate should represent 20 per cent of the total dry mix. When special colour effects are desired, experiments should be carried out using the aggregate and methods of surface treatment proposed.

Colour effects may be obtained by the use of pigments. The mixing of dry pigments with cement requires such care as can be achieved only by using a cement blending plant — insufficient mixing results in a patchy appearance. Coloured cements should be used in preference to mixing pigments in on the site. If the exposed surface is to receive subsequent treatment it is best to avoid the use of coloured cements and pigments and to rely on coarse and fine aggregate for colour effects.

Mixing and Placing. Adequate mixing is essential; it is impossible to obtain a uniform consistence in a concrete that has not been properly mixed. Should segregation occur during the transport of the concrete from the mixer to the site, the concrete should be mixed again before placing. To reduce segregation the mixer should be as near as possible to the site of the structure. Concrete should not be allowed to fall freely, to slide down a chute or be conveyed on a belt; all cause segregation. Whenever possible the concrete should be placed by means of a tremie pipe.

The quantity of mixing water should be kept as low as is compatible with good workability. Facing concrete should not be mixed too dry, however; the concrete must be plastic and should flow when being vibrated.

Precast facing concrete

With the introduction since the war of a style of architecture which calls for large areas of flat surface, many facing materials have been developed, one of the most important of which is the precast concrete facing slab. Such slabs have been used as cladding to framed structures, particularly flats and office blocks. They can be manufactured in a variety of colours, with various aggregates and different textures; the texture and colour are generally obtained by exposing the aggregate, although a number of slabs have been produced with smooth surfaces produced by grinding.

Various treatments of the surface are available. The slab may be etched with acid or scraped with a tool whilst still green to give a fine texture. A coarser texture is produced by using fine aggregates subsequently exposed by removing the surrounding mortar, either by spraying the green concrete with water

Plate 17. Exposed aggregate facing slabs.

or brushing with a stiff brush. Coarse textures are produced by using large aggregate $\frac{3}{4}$ to $1\frac{1}{2}$ in. or $1\frac{1}{2}$ to 3 in. The large aggregate may be embedded in the precast slab and later exposed by removing the surface cement, or it may be laid on a bed of sand in the casting mould and covered with a layer of mortar and backing concrete; in the latter case, when the concrete has hardened the sand is brushed off the face, thus exposing the aggregate; the depth of sand and size of aggregate determine the depth of exposure and the ruggedness of the texture. Alternatively the aggregate can be embedded in mortar and later exposed by spraying with water; in such a case the surface

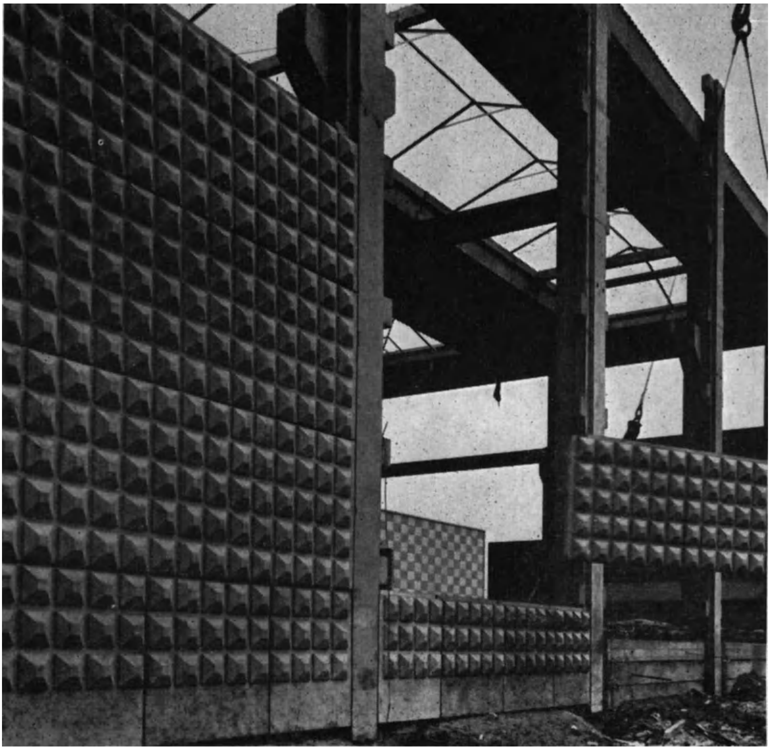

Plate 18. Profiled precast facing slabs.

must be painted over with a retarding agent to prevent the cement setting.

The Production of Precast Facing Slabs

Precast facing slabs of which examples are shown in Plates 17 and 18 are nearly always produced in factories. The techniques employed are different from those of site concrete work, and their production is as specialized as all precast concrete work. The precast slab is made up of three main elements: the special aggregates for the surface finish, the mortar in which these aggregates are embedded, and the backing concrete. The facing aggregates depend entirely upon the texture and surface required. The mix for the mortar is also controlled by the appearance required but in addition it must be resistant to weathering and have sufficient strength. Mixes of from 1:1½ to 1:3 are usual for this mortar. Mortar weaker than 1:3 may not be strong enough to prevent some of the large aggregates being dislodged either during erection or when in service, whilst mortar stronger than 1:1½ suffers from excessive shrinkage.

The backing concrete is usually made up of ½ or ¾ in. aggregate designed to have a strength of 5000 to 6000 p.s.i. at 28 days. Whenever possible the cement/aggregate ratios of the backing concrete and the facing concrete (facing mortar + the special aggregate) should be about the same; the nett result of this is that the facing mortar is richer and consequently stronger the larger the facing aggregate, which is exactly what is required. Reinforcement is usually embedded in the backing concrete to give the precast slab sufficient strength for handling and erection. Small slabs are reinforced with a steel mesh which in thin slabs may be galvanized to prevent rusting. Large slabs are usually panelled out to reduce the dead weight; the reinforcement is then incorporated in the thickened sections with a minimum cover of 1 in.

The backing concrete is placed in the mould immediately after the facing concrete has been placed and before it has set, to ensure that the two bond together. To assist in this bonding the back surface of the facing concrete should be rough and not trowelled smooth before the backing concrete is placed.

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CHAPTER 8

SPECIAL CONCRETES

Gap-graded concrete

GAP-GRADED concrete is concrete in which a single-size coarse aggregate is mixed with fine sand and cement. On the Continent it has been termed skeleton concrete, it being visualized as a concrete formed from the skeleton of large stones touching one another with the voids in between filled with cement mortar.

It is a structural concrete which combines the advantages of a lean concrete of low shrinkage with that of high strength and impermeability. But it may also be used as a facing material in which the cement mortar is removed by brushing and washing down the surface 6 to 8 hours after casting to produce so-called natural concrete. The skeleton structure of gap-graded concrete is advantageous for such surface treatment because it facilitates the early striking of shuttering, particularly on retaining walls and other exposed vertical surfaces.

The aggregate is proportioned to produce the maximum density of concrete by using certain gradings of aggregate so that the amount of large material used is a maximum. If one visualizes a box filled with the largest aggregate which can be used or which is available (in practice this is usually 3, $1\frac{1}{2}$ or $\frac{3}{4}$ in.) and the aggregate is compacted so that the voids are a minimum, then the amount of space left between the aggregate particles will depend upon their shape and size. Even for large aggregates this space is usually quite small, generally about one-eighth of the aggregate particle, i.e. $\frac{3}{8}$ in. for 3 in. aggregate, $\frac{3}{16}$ in. for $1\frac{1}{2}$ in. aggregate, etc.

To fill the spaces left by the large aggregate a much smaller material is required. If continuously graded material is used then the next smaller material — for example $\frac{3}{4}$–$\frac{3}{16}$ in. for $1\frac{1}{2}$ in. aggregate and $\frac{3}{16}$ in.–No. 7 for $\frac{3}{4}$ in. aggregate — will be too large to fill the voids, and will cause particle interference; in other words the use of a continuous grading will prevent the large aggregates compacting to their maximum density. Particle interference in concrete occurs as follows. The compaction of concrete results first in complete subsidence of the loose concrete and then its liquefaction and de-aeration. During this second phase the smaller particles attempt to penetrate the voids between the larger ones. If the smaller particles are too large to fit into the voids existing when the larger particles are in direct contact, then the larger particles are forced apart and there is particle interference.

A gap is left, therefore, in the grading of the aggregates, and a smaller material used. In practice this gap is greater than is theoretically required, and a fine sand is used with a single-size 1½ or ¾ in. aggregate. The advantage of using a fine sand is that it increases the total specific surface of the aggregates and hence the water-holding properties, so permitting the use of a reasonable water/cement ratio and resulting in better workability. If the theoretical size of material was used to fill the voids left by the large aggregate, then although a low water/cement ratio could be achieved, a harsh mix would result. In practice it is not possible to obtain single-size sands of the sizes required, so there has to be a compromise which results in the use of a fine sand with a narrow size range. As with all "concreting" sand, however, not more than 5 per cent should pass a No. 100 sieve.

The sand has to filter between the voids in the coarse aggregate, and a simple test to measure whether it is suitable is to pack an 18 in. diameter ⅜ in. sieve with the coarse aggregate that is to be used and determine whether the proposed sand filters through. If it does then it should be satisfactory.

Because there is some particle interference in the sand size, more sand must be used than is theoretically necessary. The filling of concrete into moulds of finite size also requires more mortar and hence more sand. If the theoretical sand content was 23 per cent then it would be necessary to increase it to 26 to 27 per cent to take care of these factors. Twenty-six per cent of sand is about the minimum quantity usually used. Even so the sand content of a gap-graded concrete may be

10 per cent less than that of a concrete made with continuously graded aggregate.

It is sometimes necessary to use aggregates which are deficient in one or more sizes so that a gap exists in the continuous grading, but such material should not be referred to as being gap-graded. A concrete produced with such a material possesses few of the advantages of a gap-graded concrete as herein described, whilst it may suffer from a number of disadvantages; it may tend to be harsh due to the existence of the gap in the grading, whilst due to the continuous grading of most of the aggregate more sand will be required. There may also be trouble due to bleeding and segregation.

The Characteristics of Gap-Graded Concrete

The characteristics of gap-graded concrete can be considered under two headings: those of the green concrete and those of the set concrete.

Green Concrete. When first mixed, gap-graded concrete has the appearance of an amorphous mass of stones which it is hard to believe is suitable for concrete construction. A properly designed mix appears dry. Because of the use of single-size aggregate the danger of segregation occurring during compaction are greatly reduced. There is, however, some possibility of segregation occurring during handling, because there is not a large enough volume of cement mortar to bind the whole together and, in consequence the cement mortar can become segregated from the large material.

In compacting gap-graded concrete there is an immediate collapse of the material which is more consistent and rapid than with continuously graded concrete, but this immediate collapse must be distinguished from complete compaction. The amount of vibration necessary to compact the concrete fully is greater than would be required to compact a similar mix with continuously graded aggregate. Excess mortar facilitates compaction, so that in general gap-graded concrete — which contains little mortar — requires more compaction. In addition the large-size material requires a greater energy input to bring it into the same state of vibration as the smaller particles, again requiring more vibration. Laboratory tests

(Shacklock, 1959) appear to indicate little difference between concrete from continuous and gap-graded aggregates, but the sand content in laboratory tests usually has to be higher than that used in site work and this makes it difficult to measure workability in the laboratory.

Because of the skeleton nature of the concrete in which the stones theoretically rest against one another, 1 cubic yd of concrete is occupied by 1 cubic yd of aggregate when fully compacted.

The control of the aggregate gradings is more important than with continuously graded concrete, as slight changes in the sand can lead to a loss of workability or to segregation. The amount of water added is critical; if it is not enough then complete compaction cannot be attained; on the other hand, if too much water is added then segregation results because the concrete is far too wet.

This sensitivity to water content can be an advantage or disadvantage, depending upon the control exercised over the sand grading and upon the quality control on the site. If the sand grading is controlled within narrow limits and the site control is good, then concrete of uniform quality is obtained very easily because small changes in water content produce large changes in workability and hence the control of the workability controls the concrete quality within narrow limits. On the other hand if the site control is only fair or even poor and the sand grading varies, then distinct and evident failures can be expected.

The particle shape of the aggregate also affects the workability and consistence, and the substitution of a flaky large aggregate for a rounded one results in a decrease in strength if the workability is maintained constant.

When a gap-graded concrete is properly designed, well mixed and compacted into such structures as retaining walls, a self-supporting structure is achieved such that with heights of about 8 ft the face shutters can be removed some two hours after completion of the vibration. This can lead to economy due to the more rapid re-use of the shuttering, and it is advantageous when it is required to expose the aggregate to obtain a special finish, for then early stripping means that it is easy to remove the mortar covering the aggregate. But care is needed in removing the mortar to prevent washing out aggregate from the lower lifts of the wall.

In comparison with concrete from continuously graded aggregates, gap-graded concrete is somewhat under-sanded. It is, therefore, difficult, if not impossible, to pump. Pumpable concrete has to be cohesive so that it can be pushed along the pipe easily, and generally requires up to 40 per cent sand. The action of pumping tends to produce a central core of leaner concrete in the pipeline, but with gap-graded concrete this results in blockage of the pipe. This is not surprising when it is considered that a gap-graded concrete is proportioned to make it mechanically stable when compacted. If the sand content is increased then it could be pumped, but then it ceases to have any advantages over continuously graded concrete.

Gap-graded concrete is usually placed by skip, and in thin sections is a little more difficult to place than continuously graded concretes.

Set Concrete. From theoretical considerations the characteristics of set and hardened gap-graded concrete are maximum density and minimum shrinkage. Because it is impossible to achieve the theoretical limits of gap grading, however, the voids to be filled are slightly greater than the theoretical minimum, and for reasons already outlined the amount of cement mortar used is seldom less than 26 per cent. In practice, therefore, gap-graded concrete is not free from drying shrinkage or from movements due to moisture changes in the cement paste, and the difference between it and a well designed continuously graded cement is not very great, but shrinkage and moisture movement is a little less.

Freezing and thawing tests have indicated that gap-graded concrete has a lower resistance to frost than continuously graded concrete. Such tests have yet to be confirmed by site trials, but where resistance to freezing is important then air-entrained concrete should be used.

Lightweight concrete

Structural concrete made with crushed rock or gravel aggregates has a density of about 140 to 150 lb/cubic ft. Where a high strength is not required a less dense material can be used if it is required to take advantage of the increased thermal insulation which results from a lightweight concrete. Lightweight concrete can be produced by using an aggregate which is itself of low density (for example a lightweight expanded clay), or by foaming the cement mortar mixture so as to incorporate a large volume of air. It can also be produced by using only coarse aggregate and cement, i.e. by omitting the fine aggregate from an otherwise conventional concrete, or by a combination of one or more of these methods.

Lightweight concrete varies in density from 20 to 120 lb/cubic ft as indicated in the following table.

Aggregate	Density (lb/ft^3) for different concretes		
	Structural	Load-bearing	Insulating
Sintered clays and shales	95 to 120	90 to 110	
No fines (gravel aggregate)		100 to 120	
No fines (lightweight aggregate)		60 to 100	
Foamed slag		60 to 100	
Cellular or foamed concrete		80 to 100	20 to 80
Vermiculite concrete			20 to 60

The density depends upon the type, the specific gravity and grading of the aggregates, the mix proportions, and the amount and method of compaction. Many lightweight concretes are not fully compacted although they are rodded to ensure that they fill the mould or shutters. The lightest concretes are suitable only as insulation materials, (e.g. a vermiculite roof screed), but when the density is above about 75 lb/cubic ft the concrete is usually suitable for load-bearing structures.

The chief advantages in using lightweight concrete are the reduced density, and hence the reduced dead load of structural members, and the increased insulation. The reduction in density is accompanied by an increase in the thermal insulation which is valuable for building work whilst, in addition, lightweight insulating concretes can be easily cut and nailed for fixing building fittings. Lightweight concretes, particularly the foamed concretes, are subject to high drying shrinkage and moisture movement. No-fines concrete suffers less from drying shrinkage because the aggregate particles are mostly in direct contact with each other although not compacted. Careful curing is essential to reduce both drying shrinkage and moisture movement.

The strength of lightweight concrete varies with the density — the lower the density, the lower the strength (see Fig. 8.1). For any particular aggregate or type of concrete there is a narrow range of densities which correspond to any particular strength, and similarly for any density there is a narrow range of strength. Different ranges of strength and density are obtained by using the different kinds of lightweight concrete, and in consequence lightweight concrete may be divided roughly into three groups:

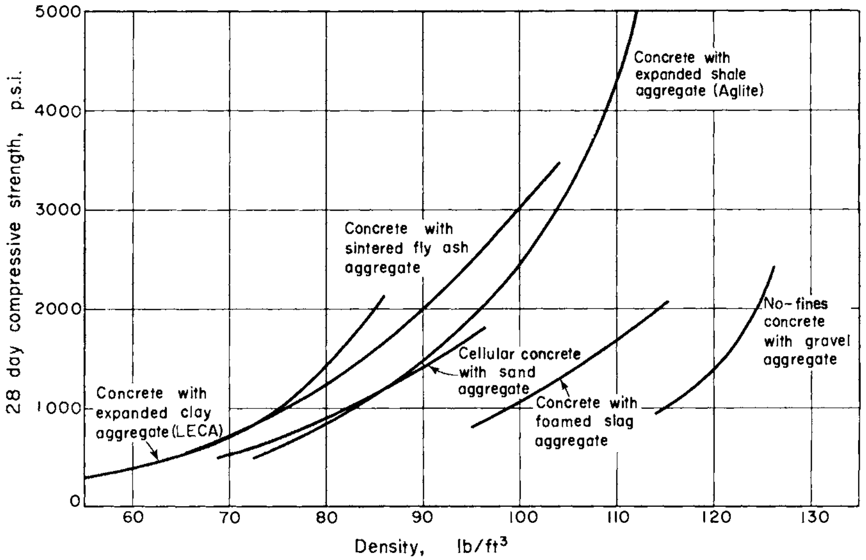

Fig. 8.1. Relationship of strength and density for various lightweight concretes.

structural concrete, load-bearing concrete and insulation concrete. These groups are classified by the compressive strength and corresponding density.

	Strength at 28 days (p.s.i.)	Density (lb/cubic ft)
Structural concrete	3000–6000	95–120
Load-bearing concrete	500–2000	75–105
Insulation concrete	—	down to 20

Structural Lightweight Concrete

Structural lightweight concrete is similar to normal concrete except that a lightweight aggregate is substituted for gravel or crushed rock. The compressive strength may be as high as 6000 p.s.i. and the density in the range 95 to 120 lb/cubic ft.

The density and strength depend upon the type of aggregate and the aggregate/cement ratio. For a particular aggregate the strength is roughly proportional to the density. A density of 95 lb/cubic ft corresponds to a compressive strength of 2000 p.s.i. and a density of 115 lb/cubic ft to 6000 p.s.i. but for any required density there is only a certain narrow range of strength which can be achieved. Increased strength can be obtained by replacing the fine lightweight aggregate by sand, but this increases the weight. To achieve a given compressive strength the use of sand results in a leaner mix.

The lightweight aggregates used to produce structural concrete are the various expanded shales and clays and sintered fly ash. The properties of these lightweight aggregates have already been described in Chapter 3. Lightweight structural concrete is usually a little more harsh than normal. The aggregates also have a much higher water absorption, so it is necessary to see that they are wetted before being mixed or the concrete will tend to dry and become unworkable during or after mixing.

The usual precautions as regards placing are necessary, although being light in weight the larger aggregate has less tendency to segregate. Placing and compacting is a little more difficult and more labour is required to obtain a good finish.

If the surface of a floor slab is left rough it provides an excellent key for a granolithic finish.

The various physical properties of structural lightweight concrete will depend upon the aggregates used, but for structural lightweight concrete using expanded shale the modulus of elasticity is lower than that of normal gravel concrete. The initial modulus of elasticity may be determined (Evans and Hardwick, 1960) from the equation

$$E_c = \left(0 \cdot 7 + \frac{f_c}{3000}\right) \times 10^6 \text{ p.s.i.}$$

where f_c = compression strength (p.s.i.).

These values are about 60 per cent of those for gravel concrete, but values ranging from 50 to 80 per cent have been measured. The tensile strength is higher than for normal concrete of the same compressive strength. The flexural strengths of lightweight and normal concrete do not differ greatly at early ages, being about 450 p.s.i. for a compressive strength of 3000 p.s.i. At later ages the flexural strength of normal concrete exceeds that of lightweight concrete.

The deferred strains are greater than for ordinary concrete, and for a stress of 1000 p.s.i. values may be up to 60 per cent greater than for gravel concrete, the creep coefficient m_c being about 0·40 (Shideler, 1957) compared with 1·07 for gravel concrete. There is an increase in shrinkage with concrete made with sintered clay aggregates. The immediate deflexion of a concrete beam is 10 to 25 per cent greater than that of a corresponding gravel concrete beam.

Poisson's ratio determined statically is about the same for lightweight and gravel concretes, 0·16 to 0·20. Determined dynamically it has a slightly higher value of 0·20 to 0·23. The resistance of lightweight concrete to deterioration is not known with accuracy. Structural lightweight concrete has its greatest application in floor slab and beam construction where its behaviour is satisfactory. The rusting of reinforcement may be the most serious cause of deterioration, but it is unlikely that lightweight concrete would be used in situations demanding a high resistance to attack. In any case the normal considerations described in Chapter 6 apply, so that in general the use of a lightweight aggregate will have less influence than the concrete cover over the reinforcement and the conditions of exposure of the structural member.

Load-Bearing Lightweight Concrete

Load-bearing lightweight concrete has a compressive strength at 28 days of 500 to 2000 p.s.i. with a density of 75 to 100 lb/cubic ft. It is used for the load-bearing walls of houses and flats usually of two or three storeys, although flats have been constructed at Stuttgart in which the top thirteen storeys were of no-fines concrete. The advantage of load-bearing lightweight concrete is that it is an insulating and damp resistant material so long as its density is kept low.

It can be made from lightweight aggregates such as the sintered clays and shales and foamed slag, but for house and flat construction the most popular material is no-fines concrete. No-fines is usually made from gravel aggregates using only the $\frac{3}{4}$ to $\frac{3}{8}$ in. coarse material. Load-bearing lightweight concrete using lightweight aggregates is proportioned, mixed and placed in much the same manner as normal concrete. The harsh nature of sintered clay aggregates may result in poor workability when used in lean mixes with an aggregate/cement ratio of 8:1, but this can be overcome by entraining air in the concrete, and up to 25 per cent has been used. Such a quantity reduces the compressive strength, but strengths within the range of 500 to 1000 p.s.i. can still be attained (Nelson and Frei, 1958). Air-entrainment is not required in the richer mixes, such as are used for structural lightweight concrete.

Concrete blocks for load-bearing walls are manufactured from foamed concrete with densities of 70 to 90 lb/cubic ft. They are manufactured in factories producing precast concrete products, and are often cured in high-pressure steam to increase the early strength and reduce the drying shrinkage. They can be readily sawn and nails can be driven in without plugging, which effects a saving in building costs.

No-Fines Concrete. No-fines concrete is made from cement and coarse aggregate. The aggregate is usually $\frac{3}{4}$ to $\frac{3}{8}$ in. material, though $\frac{1}{2}$ in. single-size material may also be used. Crushed rock, gravel, blastfurnace slag and clinker have all been used successfully, and "lightweight" no-fines concretes for load-bearing walls have been made with lightweight aggregates such as foamed slag and sintered clay.

Due to the absence of fines the finished concrete has a cellular structure of low strength. The compressive strength lies between 1000 p.s.i. for a 10:1 mix by volume and 2000 p.s.i. at 28 days for a 5:1 mix by volume. The strength continues to increase after 28 days in much the same manner as for normal concrete. Crushed rock aggregate usually gives slightly higher strengths and blastfurnace slag lower strengths than the above, which are typical for gravel aggregates. The strength is proportional to the density; a 10:1 mix by volume has a density of 115 lb/cubic ft, and a 6:1 mix has a density of 125 lb/cubic ft.

Whilst the permeability of no-fines concrete is high it forms a good barrier to moisture penetration because of the elimination of capillary absorption; at the same time its cellular structure provides a good thermal insulation and unlike other lightweight concretes it does not suffer from excessive shrinkage.

Mix Proportioning. Mix proportioning is based on the required strength. The relation between strength and density is given in Fig. 8.1, and the relation between strength and water/cement ratio in Fig. 8.2. The proportions are governed more by the necessity to achieve a cellular structure and coat each stone with cement grout than by a high strength requirement. From the required density the volume proportions and water/cement ratio are determined. A trial mix is made with the aggregate it is proposed to use, to assess what adjustments, if any, are required to the mix proportions to produce the required strength with the necessary workability, and at the same time to avoid bleeding which results from too much water in relation to the cement.

If the workability is too low the mix may be increased in richness or the water/cement ratio increased. Alternatively if the workability is too high and bleeding occurs then the water/cement ratio may be reduced or the mix made leaner.

Mixing and Placing. The water must be added to the mixer just before the aggregate and the cement, as otherwise the cement cakes on the aggregate and the sides of the mixer.

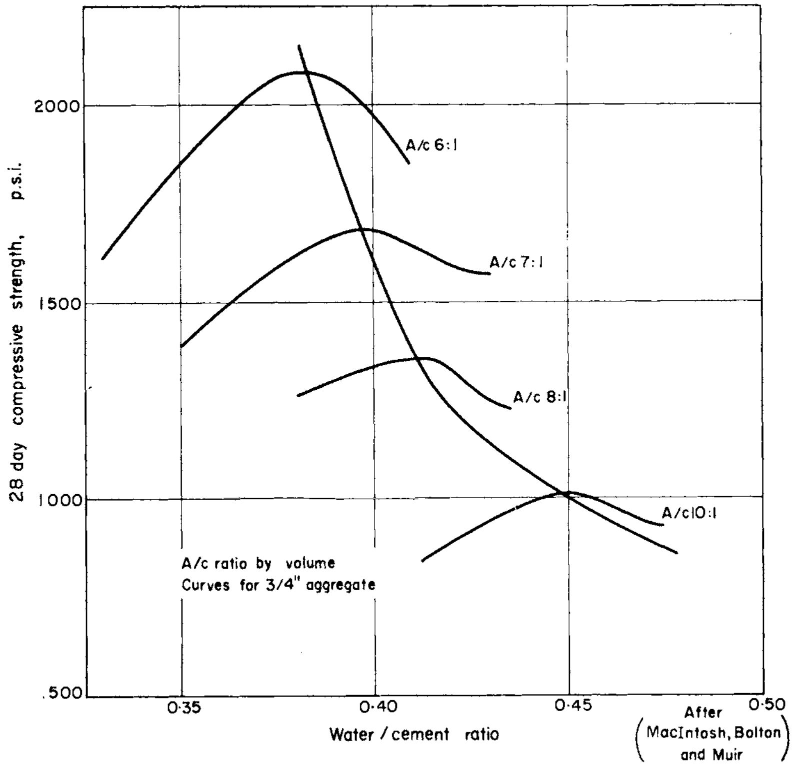

Fig. 8.2. Relationship of compressive strength w/c and a/c for no-fines concrete.

Assuming that weight-batching is being used the mix proportions must be converted from volume to weight by first determining the rodded bulk density of the aggregate to be used.

Most mixers are suitable, and a mixing time between 1 and 2 minutes will generally be adequate.

No-fines concrete does not segregate, and placing is comparatively simple. It can be dropped considerable heights without detriment. In house and flat construction the concrete can be placed one storey high in one lift, and compaction is usually unnecessary; it is essential that the concrete be lightly rodded, however, to ensure that it fills the space between the shutters. Where continuous pours are made, up to two storeys in height, the concrete should be deposited uniformly without the formation of construction joints, because the bond between new and old work is usually poor. The formation of conical heaps of concrete should be avoided since they may be disturbed, some time later, perhaps after the initial set, when the next lift of concrete is placed.

The nailing and cutting into no-fines concrete is difficult, so holes and chases in the concrete should be boxed out before concreting is begun.

Curing. It is essential that no-fines be properly cured. It should be prevented from drying out rapidly, as can occur on exposure to hot sun or dry winds. Rapid drying out will prevent the hydration of the cement and possibly cause disintegration of the concrete.

When used as a walling material adequate curing is more difficult than with slabs and floors, although the shutters prevent drying to some extent for at least the first 24 hours. Concreting during winter conditions is easy, since the material is not so subject to frost damage. In severe weather, however, it may be necessary to take the precaution of heating the water and aggregate, although the addition of calcium chloride may often be sufficient.

Insulation Concrete

This is a material used purely for its insulating properties as, for example, in the construction of slabs and screeds to flat roofs. It can be produced in a wide range of densities and its properties may be varied to suit specific requirements.

It can be produced by using the very lightweight aggregates such as vermiculite, or by entraining 60 per cent or more air into a cement mortar to produce cellular or foamed concrete. The material has little strength, 50 to 60 p.s.i., and a low density, 20 lb/cubic ft. As with the other lightweight concretes the density increases with increasing strength. The conductivity is lowest at low densities, and a density of 20 lb/cubic ft corresponds to a thermal conductivity of 0·5 B.t.u/ft^{2}hr in.°F.

The drying shrinkage and moisture movements are large, and a material with a density of 20 lb/cubic ft will have a drying shrinkage of 0·50 per cent (compared with 0·05 per cent for

100 lb/cubic ft lightweight concrete with a strength of 2000 p.s.i. (see Fig. 8.3).

The lowest density material (20 lb/cubic ft) compares well with traditional insulating materials, and has been used for cold-storage insulation and underlays to floors. Although its strength is low it is sufficient to support light traffic if protected from wear by a cement mortar rendering, so that it can be used as roof screeds. Foamed concrete made by mixing a preformed foam with cement grout has been used for insulating hot water and steam pipes, particularly for the distribution pipes of district heating schemes. Lightweight building blocks with densities of 20 to 40 lb/cubic ft are common. They are usually cured by steam heating or autoclaving under heat and pressure to reduce drying shrinkage and give a high early strength so as to cut down the breakages due to handling.

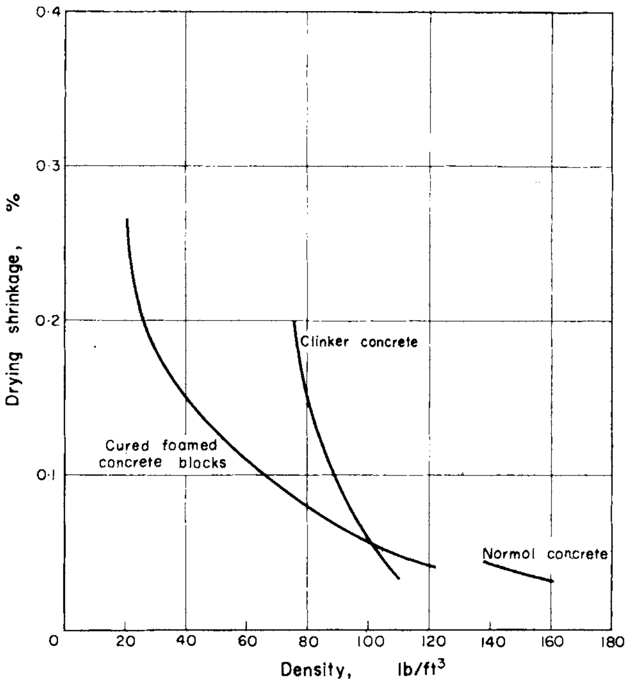

Fig. 8.3. Drying shrinkage for various concretes.

Precast blocks and walling panels are usually plastered internally and rendered externally. It is important to ensure that the foamed concrete has achieved moisture equilibrium before plastering if freedom is required from shrinkage cracks in the plaster.

Cellular or Foamed Concrete. The introduction of an air-entraining agent into concrete reduces its density. When the air content is high (in excess of 25 per cent) the properties of the concrete are completely changed from those of normal or of air-entrained concrete containing only 6 per cent air.

Cellular or foamed concrete is made from Portland cement, sand, water and a foaming or gas-forming agent. The chief methods are by adding:

(a) a chemical, for example 0·2 per cent (by weight of cement) of aluminium powder, which reacts with the alkalis in the cement to form a gas;
(b) a pre-formed stable foam, which is mixed with the remainder of the materials;
(c) a foaming agent which entrains a large quantity of air when stirred at high speed with the sand before the other materials are added. This method produces the heavier types of aerated mortar (80 to 90 lb/cubic ft).

Instead of sand, other aggregates may be used, such as fly ash, foamed slag and expanded shale. Lime may also be added to produce a fatty mix which is more easily aerated to give low densities. The lowest densities, down to 20 lb/cubic ft, result from aerating a cement-lime mixture or a neat cement and water mixture. Densities of 40 to 60 lb/cubic ft are achieved with cement–lime mixes to which fly ash or very fine sand has been added, whilst densities of 80 to 100 lb/cubic ft are produced by using sand–cement mixes in proportions of up to 4:1 by weight. Coarse aggregates are not used for foamed concrete.

The foamed concretes of higher densities (80 to 100 lb/cubic ft) fall into the load-bearing concrete class with strengths up to 2000 p.s.i. especially where the concrete has been cured in steam at high pressures. This method of curing is only used for precast products.

The water/cement ratio has an indirect effect on the strength; at any one density there is a narrow range of water/cement ratios within which the bubble structure of the concrete is stable; within this range the water/cement ratio does not affect the strength, but as the density varies so does the range of water/cement ratios. The strength is directly proportional to the density. The thermal conductivity is roughly proportional to density, as has already been mentioned. In the heavier forms of aerated concrete, lower thermal conductivity can be achieved by using fly ash instead of sand in the mix before aeration.

A major difficulty with all lightweight concrete is the high drying shrinkage — up to 0·5 per cent — and high volume change with change in moisture content. These large movements produce shrinkage cracks which have been sufficiently serious to hinder the use of lightweight concretes. Drying shrinkage and moisture movement are both considerably reduced if the concrete is steam cured under high pressures. There is also some improvement if the concrete is dried by hot air, and one or other of these processes is used by most concrete block manufacturers.

The total absorption of water by precast foamed concrete blocks is relatively high, although the permeability is relatively low probably due to the presence of a large number of non-interconnected pores. The frost resistance is high for the same reason.

As the special curing methods used to reduce shrinkage cannot be used for *in situ* work, foamed concrete produced on the site is restricted to use as an insulation material. As a roof screed it is usually laid at a density of about 25 lb/cubic ft to a fall of 1 in 8. A rendering of ordinary cement mortar is laid over the foamed concrete, especially where it is covered with bituminous roofing felt or where traffic on the roof will be greater than normal. It is not so necessary where two or three coats of hot asphalt are used as the waterproofing membrane.

The Manufacture of Cellular or Foamed Concrete. Apart from the special use of expanding cements, which are discussed elsewhere (see page 66), cellular or foamed concrete is not usually manufactured on the site by adding a chemical to react with the cement. The process needs considerable technical skill in its operation; for example, the temperature must be carefully controlled to ensure that the air bubbles do not coalesce to form a laminated structure. Fine aluminium powder is the most usual material added, but hydrogen peroxide and bleaching powder may be used to generate gas.

The production of a cellular concrete by using a preformed foam is simpler. The foam is produced in the same way as in a foam fire extinguisher, being much the same material. A foam-producing apparatus is used from which, by means of a foaming agent, water and compressed air, a controlled quantity of foam can be delivered to either a pan or paddle mixer and there mixed with a cement mortar, already mixed to a plastic state. The mixing-in of the foam produces the lightweight foamed concrete. If only a normal tilting or non-tilting drum mixer is available, the foam and the necessary amount of water should be mixed first before the cement and sand are added.

The third method of producing foamed concrete is to mix a mixture of foaming agent, water, sand and cement at high speed. Where a paddle or pan mixer is used it may be necessary to assist the foaming by aerating with compressed air and by adding wetting agents. The mixing time to produce the necessary density may be 5 or 6 minutes. A high-speed rotary mixer, however, enables a foamed concrete to be produced in less time. The foaming agent and water are first mixed to form a foam, before the sand and then the cement are added. The heavier types of aerated concrete are produced by this method.

Concrete for atomic radiation shielding

Concrete is used to form shields against atomic radiation resulting from nuclear fission and the use of γ-rays. An atom is built up of three main primary particles: protons, neutrons and electrons. Atoms of different elements are characterized by combinations of different numbers of these particles. Protons and neutrons are particles which are grouped together in the central core of an atom known as the nucleus. Some nuclei are not stable but are continuously disintegrating. This is known as radioactivity, and in the disintegration process particles are emitted:

α-particles: charged helium nuclei
β-particles: fast-moving electrons emitted as a neutron decays into a proton
γ-rays: very-high-frequency electromagnetic radiations; they have many properties similar to moving particles but are also wave-like radiations similar to light and X-rays.

These particles and rays are lethal; when γ-rays interact with animal tissue, the atoms in the tissue cells are ionized and the cells die. For this reason it is necessary to surround sources of radioactivity with a shield to protect the operators and reduce the intensity of the particles and γ-rays emerging to a tolerable level.

α- and β-particles may be stopped completely by shielding, but γ-rays are only attenuated and their intensity reduced. The attenuation of γ-rays depends almost directly upon the mass through which the rays have to penetrate, and the relative values of two substances in affording protection against these rays is in proportion to the densities of the materials; thus 6 in. of steel of specific gravity 7·8 is equivalent to 6 × 7·8/2·3 in. of concrete of specific gravity 2·3. The attenuation of γ-rays from an atomic reactor thus merely requires a given mass of material.

In fission reactors, in addition to the fission products, fast neutrons are emitted. These may be slowed down by collision with atoms until their energies are reduced to values comparable with the thermal energy of vibration of the atoms with which they collide; these low-energy neutrons are termed thermal neutrons. They are rapidly slowed down by collision with nuclei of the same weight, and since they are of low atomic weight the ideal material would be hydrogen.

The capture of thermal neutrons releases γ-rays and produces heat in the mass. If concrete alone were used to capture thermal neutrons the heat produced might lead to cracking, so it is usual to insert a thermal shield prior to the concrete to reduce the intensity of thermal neutrons entering the concrete. This thermal shield may be some inches of steel. There will still be some heat generated in the concrete, but it will not be as much.

The requirements for concrete for radiation shielding are, therefore, that it shall have a large hydrogen content to capture fast neutrons, that it shall be able to resist the thermal stresses induced by thermal neutron capture, and that it shall have sufficient mass to attenuate the γ-rays. In addition the concrete must be able to withstand the heat radiated from the atomic pile during its operation. The optimum density and composition for shielding concrete are influenced by the type and intensity of radiation, by the complexity of the placing conditions, the number of pipes, tubes and other embedded items and the amount of reinforcement, together with the limitations on the shield dimensions due to restrictions of space.

Hydrogen is, of course, contained in the water mixed with the concrete, but the heat generated in the reactor and in the concrete shield will tend to dry out the concrete. The equilibrium moisture content of shielding concrete under operating conditions is not known, but if the water content is below 4 per cent the neutron shielding efficiency is impaired. It is on the safe side, however, to assume that the concrete dries out, and that the only water remaining in the concrete is that chemically combined with the cement at a water/cement ratio of 0·22 to 0·25.

The density of concrete can be increased by using aggregates with high specific gravity, and various materials such as barytes, magnetite, limonite and steel shot have all been used. The characteristics of these are considered below. The density decreases as the concrete dries; that used in calculations is usually the dry density determined by curing the concrete in water for 28 days and then drying it to constant weight at 100°C.

The percentage of hydrogen in dry concrete is usually quite low, being about 0·5 per cent, so that most of the slowing down of fast neutrons is done by elements of medium atomic weight and not by hydrogen. The chemical composition of the concrete is thus important in calculating the shielding effects. Typical chemical analyses for various concretes are given on p. 305.

Concrete for a biological shield should have no straight-through construction joints in the line of the radiations. It

Aggregate/cement ratio (by weight)	Aggregate		
	Flint gravel 5:1 or 6:1	Magnetite 11:1	Barytes 8·5:1
Silica	26	4	6
Aluminium	7	0·5	1
Iron	4	55	—
Calcium	8	4	4
Magnesium	2	1	—
Sulphur	0·1	—	11·5
Sodium	1·5	—	—
Oxygen	50	33	36
Hydrogen	0·4	0·3	1
Barium	—	—	40

should have a uniformly high density; where normal aggregates are used this is about 150 lb/cubic ft, but with heavy aggregates densities should be in excess of 220 lb/cubic ft. The depth of penetration of γ-rays and fast neutrons is directly proportional to the density.

The properties of radiation concretes are similar to those of normal concretes when compared on a volume basis to take into account the higher specific gravities of heavy aggregates. With strong aggregates such as magnetite, high strengths of the order of 6000–7000 p.s.i. can be obtained with a water/cement ratio of 0·5. The workability is usually much lower with heavy aggregates, and although a well-designed mix will respond to vibration the effective radius of any vibrator is reduced by about half due to the mass of the aggregate particles.

Heavy Aggregates

The following heavy aggregates have been used for radiation shielding concrete.

Iron punchings and steel shot. These materials are satisfactory but are difficult to obtain in suitable sizes; in addition they are expensive. Owing to their high density (specific gravity 7·8) they are liable to segregate during placing and compaction. Densities of up to 350 lb/cubic ft have been achieved with steel shot.

Barytes. Barium sulphate ($BaSO_4$), marketed as barytes, has been used to produce concrete with densities in excess of 220 lb/cubic ft. It has a specific gravity of 4·3 to 4·6, although the finer material may have a specific gravity as low as 4·0, probably due to the presence of impurities of lower specific gravity. Its hardness (Mohr's scale) varies from 2·5 to 3·5, but it is prone to degradation and this causes dusting of the aggregate and breakdown of the particles during mixing. Concrete with a wet density of about 224 lb/cubic ft can be produced with aggregate/cement ratios of about 8·5:1 by weight.

Limonite. Limonite is a complex hydrated iron oxide of specific gravity 3·6 to 4·0 and a hardness (Mohr's scale) of 5 to 5·6. Although it has the advantage of containing chemically combined water usually in excess of 10 per cent, in most deposits in this country it contains a high percentage of impurities. Limonite occurs in earthy masses and its physical characteristics make it unsuitable as a concrete aggregate.

Haematite. This oxide of iron (Fe_2O_3) has a specific gravity of 4·2 to 5·3 and a hardness of 5·5 to 6·5. The metallic iron content is 70 per cent. It occurs in irregular masses and is a main source of iron ore.

Magnetite. This material is a ferrous-ferric oxide of iron with a specific gravity of 5·1 and a hardness of 5·5 to 6·5. Its iron content is 72 per cent. It does not occur in commercial quantities in this country, but is imported from Sweden where it occurs in large masses of high-grade ore. Its specific gravity in this somewhat impure form varies from 4·1 to 4·6. It may contain up to 20 per cent impurities which are usually quartz, felspar and ferro-magnesium. These materials crush more easily than magnetite with a consequent increase in impurities in the finer gradings. As imported the material needs re-crushing to produce a satisfactory grading, and this may result in up to 10 per cent extra material having to be processed. The crusher dust can be used as fine aggregate.

Additives

The capture of a neutron may produce a new isotope which is unstable and might, therefore, release secondary radiations. It may then be necessary to make special provisions to ensure that the secondary radiation is in the form of α- and β-particles rather than γ-rays so that such secondary radiation can be easily shielded and to ensure that there is no long-term build-up of secondary radiation. These requirements may be accomplished by the incorporation of cadmium, boron or lithium into the concrete.

Neutron capture by boron results in the release of secondary α-particles but cadmium, although it has a high capacity for neutron capture, results in γ-rays as a secondary reaction. Boron and lithium both help to reduce the possibility of long-term build-up of secondary radiation by producing stable or short-life isotopes as secondary radiation resulting from the capture of neutrons. The use of these materials in the shielding concrete makes it possible to obtain access to the thermal column of small 50 kW reactors after they have been shut down.

These additives have a deleterious effect upon the strength and delay the setting of the concrete, and can therefore be used only in small quantities.

Colemanite. Calcium borate ($Ca_2B_6O_{11}.5H_2O$) can be added as a fine aggregate and can be obtained in various grades. It has a specific gravity 2·2 to 2·4 and a hardness (Mohr's scale) of 4 to 4·5. It is insoluble in water. It contains 21 per cent of chemically combined water, which increases its usefulness as a fast neutron shield. Commercial colemanite may contain impurities, primarily gypsum and limestone, and it is necessary to carry out trial mixes with the material it is proposed to use to determine its effect upon the concrete.

Borocalcite. This is a calcium borate, similar to colemanite except that it is slightly more soluble in water. It is available as a refined product, borocalcite grit, made by fusing boric acid with other materials such as lime, silica and alumina. This is ground to grades ranging from a medium sand to a fine powder.

About 0·2 to 1 per cent of boron compounds have been used, principally in association with barytes, but the limited improvement in attenuation of γ-rays makes it difficult to justify their use in view of the delay caused to the setting of the concrete and the reduction in final strength. Where it is necessary to use boron it may be better to apply it as a mortar to the inside of the concrete.

Other materials, such as graphite, cadmium aluminium sheets and boral sheets (sheets of boron carbide and aluminium) may be used in special circumstances, but they have no direct effect on the concrete.

Dry-lean concrete

The construction of airfield runways consists of a wearing surface which is a dense, high-strength material either of paving quality concrete or of bituminous construction, overlying a weaker sub-base material. The stresses from aircraft wheels are transmitted from the paving surface to the soil via the sub-base. This may be of stabilized soil where the conditions are suitable, but due to the heavier impact and loading resulting from higher tyre pressures a material of greater strength is often necessary.

Lean concrete is a suitable sub-base material; it behaves somewhat like stabilized soil and has the same freedom from moisture and temperature movements. Like stabilized soil it can be compacted by rolling. If, however, it has a strength above 1500 p.s.i. it acts like normal concrete and troublesome shrinkage cracks may occur; it will also expand with heat, and may cause buckling of the overlying paving surface. Lean concrete properly made is not a weak concrete, but a strong stabilized soil.

The aggregate may be all-in ballast or 1½ in. gravel and sand. It is mixed in a central batching and mixing plant using normal tilting or non-tilting drum mixers. The mixing time can be reduced to nearly 30 sec, since the quantity of water added, which usually controls the mixing time, is generally very small.

If the grading of the aggregates is nearly constant then by keeping them saturated, by hosing down from time to time, it is often unnecessary to add any further water to the mix.

The mixed concrete is distributed by 5 cubic yd tipper lorries. It is spread on the site and rolled, first by a light roller and then by a heavy 10 ton roller. The mixing of the cement into the ballast causes little change in either the colour or the other properties of the ballast; it reacts like shingle and has to be rolled with a light roller first, as a heavy roller merely pushes up a wave of material in front of itself.

The strength of lean concrete depends largely upon the density to which it is compacted (see Fig. 8.4). If the wet bulk density is above 140 lb/cubic ft then the strength is roughly proportional to the water/cement ratio (see Fig. 8.5), although the aggregate/cement ratio also has an effect. The aggregate/cement ratio varies from about 18:1 to 12:1. The water/cement ratio is adjusted so that the cube strength lies between 750–1500 p.s.i.; this ensures that the material has sufficient strength but behaves as a stabilized soil and not as a weak concrete.

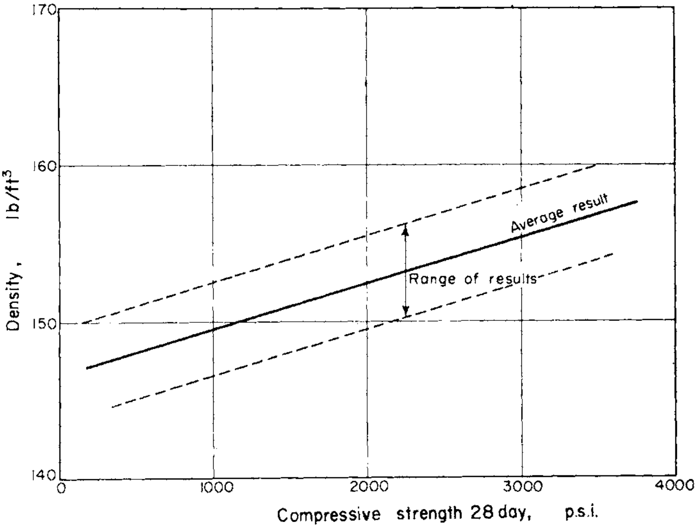

Fig. 8.4. Effect of compaction on dry lean concrete.

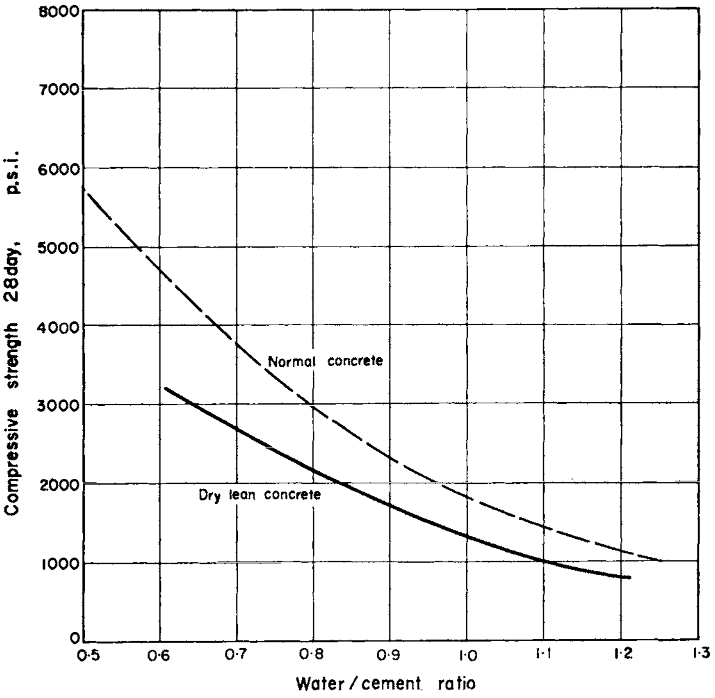

Fig. 8.5. Approximate relationship of strength and water/cement ratio for dry lean concrete.

Pre-packed or grouted concrete

Concrete is normally made by mixing all the materials in a mixer and then placing and compacting the plastic concrete in situ. Concrete may be constructed, however, by first placing the coarse aggregate and then grouting this with a cement and sand grout. This is termed pre-packed or grouted concrete and has been used with success on a number of different types of work, in particular for roads and airfield pavements and for underwater concreting. Grouted concrete has also been used where difficulties of construction or special requirements have necessitated large masses of concrete being laid monolithically, without construction joints.

Pre-packed concrete is in essence a gap-graded concrete in which the coarse, single-sized aggregate is packed between the concrete shutters and the voids then filled with a cement-sand mortar.

The essential requirement with this work is that the grout should fill all the voids and develop full bond with the aggregate. The aggregate must be clean and not coated with dust, dirt or rock flour. It is necessary to use a single-size coarse aggregate, usually $1\frac{1}{2}$ in. material, together with a workability agent in the grout to ensure that it flows properly. In addition about 1 per cent of aluminium powder is often added to cause slight expansion in the grout just before setting, together with a fly ash which has a low carbon content.

A grout for injection should be sufficiently stable to prevent segregation or bleeding. If bleeding takes place it should be not more than 0·5 per cent by volume of the grout. The grout should have sufficient fluidity to be capable of being pumped 400 to 500 ft and be able to penetrate uniformly and fully into the voids in the aggregate.

Grout can be made from nearly all the cements in common use, including high alumina and super-sulphated cements.

Suitable grout can be produced in normal mixers if a workability agent is added, either alone or with fly ash. The maximum size of sand is about $\frac{1}{16}$ in., the sand/cement ratio being 2:1. Alternatively grout may be prepared in a high-speed mechanical mixer without using additives to produce so-called colloidal grout. This enables sand with a maximum size of $\frac{3}{16}$ in. to be used in proportions of up to 4:1.

A colloidal grout consists of a cement and sand grout in which the cement and sand particles are so efficiently wetted by the high-speed mixing that a stable grout is produced which is sufficiently fluid to travel uniformly through the voids of the aggregate. The fluidity of a grout and its ability to prevent bleeding of water or the deposition of sand particles is dependent upon the grading and particle shape of the sand and the degree to which the cement particles are dispersed and wetted. This wetting can be achieved by mixing in a special colloidal mixer. Cement can also be fairly efficiently wetted by using a combined dispersing and wetting agent in a normal mixer.

Type of Aggregate. Aggregate suitable for grouted construction is similar to that used in gap-graded concrete except that a minimum size must be used; this is normally 1½ in. The maximum size of aggregate should be the largest which can be handled and placed within the formwork and between the reinforcement. In mass work the voids can be reduced by using two sizes of aggregate, in which case the larger should be about eight times the size of the smaller, as in gap-graded concrete. The large aggregate is arranged in single layers and blinded over with the smaller stone. The voids in the aggregate should be a minimum consistent with the ability of the grout to penetrate fully, so that particle shape is important; flat and elongated particles are unsatisfactory.

The aggregates should be clean, with no adhering dust or film of dirt which will reduce the bond with the grout and result in reduced strength. Depositing the aggregate through water removes dust films but tends to reduce the control over the placing. In underwater construction this is inevitable, but otherwise it is better to place the aggregates in the dry, and if necessary flood with water afterwards to remove any dust. Flooding with water is, in any case, advocated as it leads to better wetting of the aggregates and more thorough penetration of the voids by the grout. If the quantity of water pumped into the voids is measured then the required volume of grout will be exactly determined. When the coarse aggregate is bought by the cubic yard it should be remembered that a cubic yard of aggregate, either mixed or single-size, is required for every cubic yard of concrete.

Grouting. Grouting by gravity penetration is limited to a depth of 12 in. for aggregate smaller than 1½ in. For mass work and underwater concreting the grout is introduced at the bottom of the aggregate and moves upwards in the mass. Grout has a specific gravity greater than water, so that it pushes the water up.

Grouting is carried out in mass work by building 2 in. diameter pipes into the pre-packed aggregate at about 4 ft centres. For small masses of say 250 cubic yd the whole of the mass is grouted in one continuous operation, all grout pipes being used at once. In large masses of 10,000 cubic yd or more the work is carried out in sections. The grout is injected in one section until it is several feet above adjoining sections; it is then stopped and work carried out in an adjoining section; by this method the process is easier to control. Construction joints are avoided by continuing grouting on any one section before the previous grout has stiffened. By using a suitable admixture the set can be delayed up to 12 to 15 hours, which usually allows ample time between successive groutings at any one point.

Grouting Equipment. Grouting equipment consists essentially of a grout mixer, an agitation tank, a grout pump with delivery manifold, and grout pipes. Other equipment may be necessary such as batching equipment, a scalping screen for the sand where it is not pre-screened to the required size before delivery, together with duplicate pumps and mixers to ensure that continuity of grouting is maintained.

A grout mixer is usually a double-drum colloidal mixer consisting of two mixing drums together with a hopper tank. The first mixer drum produces a cement/water slurry, which is transferred to the second drum where the sand is added to produce a cement/sand grout. In the first drum there is a disc which rotates at up to 2000 rev/min in close proximity to a stator. Water and cement passes at high speed through this narrow gap, and this helps to wet the cement particles more completely.

The second drum is a high-speed rotating paddle mixer which mixes the sand and the cement/water slurry. The first batch of cement is mixed in the first drum and then discharged into the second one. Whilst the sand is being added to the cement slurry in the second drum the next cement batch is discharged into the first. Double-drum mixers are available in various sizes, the most usual dealing with 1 or 2 cwt of cement per batch. The total batching and mixing time per batch is about 1½ minutes, but depends upon the sand/cement ratio.

Single-drum mixers may be used where the capacity of a double-drum mixer is not required. The output is half that of the double-drum mixer.

Where a large capacity is required it is usual both in this country and on the Continent to use a number of colloidal mixers in tandem, but in the U.S.A. large colloidal mixers of 2 cubic yd capacity have been used.

The mixer discharges its batch into an agitator, in which the cement and sand grout is kept continuously mixed. The grout is drawn from the agitator and fed to a pump. Positive displacement, horizontal double-acting force pumps are used, with a delivery pressure of up to 300 p.s.i. being usual. The pump delivers to a manifold from which the grout is fed to the individual grout pipes.

On large jobs involving a long pumping main it is usual to arrange a ring main with delivery back to the agitator, with tappings for the 2 in. grout pipes. This ensures that the grout is kept continuously in circulation. This is important to prevent blockage, especially where the work is grouted in sections.

Properties of Pre-Packed Concrete. In general, pre-packed concrete exhibits the same relation between strength and water/cement ratio as does normal concrete. The addition of workability agents and materials such as aluminium powder and fly ash, however, affects the relation. As with all concretes containing fly ash the strength at early ages is reduced, but the strength at ages of 6 months to a year are as great if not greater than that of normal concrete with the same ratio of water to cement + fly ash.

Pre-packed concrete has a low drying shrinkage, which may be less than half that of normal concrete due to the point-to-point contact of the aggregate before grouting.

It may be used with advantage where good bond to old concrete is required. The contact between the pre-packed aggregate and the old concrete, together with the fact that the cement grout possesses greater fluidity than is normal with conventional cement mortar, ensures a high bond strength between old and new concrete, but the surface of the old concrete must first be properly cleaned to remove laitance or friable material.

Freezing and thawing tests on pre-packed concrete have indicated a higher durability than conventional concrete, but this may be due in some measure to the entrainment of gas bubbles in the concrete due to the inclusion of an expanding agent (aluminium powder) in the grout.

Vacuum concrete

Vacuum concrete is concrete from which excess water is removed by a vacuum when the concrete has been placed in position. Such concrete has the advantage that it can be made more workable by using more water; placing is then easier, and if the vacuum pressure is applied while the concrete is vibrated then compaction is assisted. By removing excess water under vacuum, a lower water/cement ratio and higher strength can be achieved, although this is limited by the range of concretes which can be treated by the vacuum process.

The process depends upon the creation of a vacuum at one or more surfaces of the concrete. This is done by lining the shutters with a filtering material or by applying filter pads to the concrete surfaces, and creating a vacuum behind the filter pads. The vacuum generates a pressure difference between the atmospheric pressure and the vacuum pressure, which acts as a compacting force and squeezes the concrete together and so induces a hydrostatic pressure in the water.

The water migrates to the surface of the concrete and is drawn off through the filter pads. As the concrete consolidates, more and more of the atmospheric pressure is taken by intergranular pressure between the aggregate particles, while at the same time the pore pressure in the water reduces; thus less water is drawn off, and little further consolidation takes place.

After processing, the fine and coarse aggregates are in closer contact than before. This results in a pseudo-solidification with an apparent strength in the green concrete which enables it to be self-supporting to a considerable degree before it sets and hardens. Much of the excess water is removed in the first hour, but because it is the consolidation of the concrete which controls the rate of water extraction, complete extraction of the excess water can take place only after a considerable time — longer in fact than is required for the concrete to set. All the concrete is subject to the static compaction force of atmospheric pressure, but it is from the concrete close to the vacuum pads that most of the water is extracted. The effective depth of penetration is about 6 in. so that the process is more suited to flat slabs and beams than to mass concrete.

The Equipment and Process. The equipment consists of vacuum pads, a vacuum pump which can produce a vacuum not less than 25 in. of mercury, and suction lines from the pump to the pads connected through an air–water separator tank.

Vacuum pads may be built into the shutters of columns or the side shutters of beams, or may be applied as pads to the surface of slabs or retaining walls. They are made of a sheet of fine linen, backed by wire gauze and a perforated or moulded steel plate fitted with an airtight cover. The cover is sealed in contact with the concrete by a strip of rubber. The linen sheet is in contact with the concrete, and rigidity is provided by the perforated steel plate and cover. The backing cover may be of rubber to form flexible pads for the treatment of slabs and floors, or it may be of timber or steel and designed to form part of the shutters. From the back of the cover a pipeline runs to the air–water separator and from there to the vacuum pump. The vacuum pads should be square and not rectangular, since the capacity of a pad depends upon its circumference and not its area. In treating an area the number of individual pads should be as small as possible to reduce the leakage which occurs at the joints. Furthermore, sealing rings are liable to damage, and the fewer there are the better.

To reduce friction loss in the vacuum lines the connecting pipes should be 1 in. diameter armoured hose. The use of small-diameter pipes leads to icing troubles where they are connected to larger hose, and leaks can occur which are troublesome but which are not easily noticed on the vacuum gauge.

Difficulties can occur if the vacuum process is used in winter. Water in the pipelines freezes when the air temperature drops below about 40°F, and icing troubles in the vacuum lines cause some loss of vacuum to the shutters. These troubles can be avoided if before placing the concrete is warmed to about 60°F in the manner described under Winter Concreting. Unless such heating is required in any case, the need for it may preclude the use of the vacuum process in cold weather.

The Effect on the Concrete. The effect of the vacuum process in reducing the water content and compacting the concrete extends only four to six inches in depth from the face of the concrete treated. When made with Portland cement this processed concrete has an increased strength, and there is an increase in the rate of gain of strength at early ages. The water/cement ratio is reduced by about 0·15 or 0·20, although it cannot be reduced below 0·3 to 0·4.

The resistance of the concrete surface to abrasion or erosion is increased. The properties of the coarse aggregate affect this resistance, and to produce concrete with a high resistance to abrasion it is necessary to use first-class materials with a well proportioned mix. The vacuum process will not make resistant concrete out of poor materials, but it will effect an improvement. The increased resistance to abrasion and erosion may well be due to the increase in the density. There is also an improvement in the frost resistance, and this may be due to the same cause. The vacuum process would not be used to produce frost-resistant concrete, however, as this is more easily produced using air entrainment.

The absorption of the concrete is reduced, and because of the reduction in water content the shrinkage is also reduced. The permeability, however, is increased, notwithstanding the lower water content and the higher density, probably due to the formation of capillaries as the excess water is drawn towards the vacuum pads.

For thin slabs using Portland cement it is possible to design the mix to take advantage of the reduction in the water/cement ratio by 0·15 from say 0·65 to 0·50, and so produce a more workable concrete. In concrete thicker than 4 to 6 in. for single-side treatment and 8 to 12 in. for double-side treatment, a core of concrete with the original water/cement ratio will remain. The process is not economic, however, if it is used merely to facilitate the placing or more workable concrete; this can be more easily and cheaply achieved by redesigning the mix or using a suitable workability agent.

Finely ground cements, or concretes containing fine-ground powdered admixtures such as diatomaceous earth, bentonite or lime, are difficult to treat because such materials increase the suction pressure necessary to effect removal of the water.

High alumina cement shows no advantage from the vacuum process, as this cement produces a high early strength with the water/cement ratios normally used.

Application. Vacuum concrete has its main applications in concrete members such as beams, columns, slabs, and precast concrete products. It is of little value for mass concrete although it has been used with advantage to produce a toughened skin on the spillway channels of some large dams and to increase the resistance to erosion. It has also been used to form the water-retaining reinforced concrete membrane to the upstream face of a rock-filled dam; here the slope was 1 in 1·3, and the vacuum process enabled concrete to be placed by making it self-supporting so that it did not slump or flow, whilst at the same time it produced a dense concrete with few shrinkage cracks.

The vacuum process cannot be used with intricately shaped precast units because it cannot be applied to units containing small recesses or projections.

In wall or column construction, the application of the vacuum process to the concrete while it is still being vibrated will result in a concrete which is self-supporting, so that the shuttering can be stripped soon after the vacuum processing is complete. In heavy construction involving large hydrostatic pressures on the shuttering, the pressure can be reduced by installing vacuum pads. By removing the excess water and converting the hydrostatic pressure to inter-granular pressure, the load on the formwork is considerably reduced.

The surface of floors or slabs may be walked upon immediately after treatment, and where required can be almost immediately trowel finished without waiting for the concrete to attain its final set.

Ready-mixed concrete

Since the war there has been a major development in the use of concrete mixed in a central batching plant, and purchased ready-mixed. The supply of such concrete has been most highly developed in the U.S.A. where over 1200 operators are reputed to produce over 80 per cent of that country's concrete. Ready-mixed concrete was little known in this country at the end of the war, but since then its use has expanded rapidly and most major industrial areas are served by commercial suppliers. There has been some reaction against its use and some supervising engineers have required more stringent testing and the preparation of test cubes from every batch, but such a procedure is justified only in the case of disreputable suppliers. The contractor using ready-mixed concrete is as much in the hands of the supplier as is the supervising engineer, but since he is likely to suffer serious loss if work is condemned he usually attaches his own stringent conditions to the supply of such concrete, and deals only with reputable suppliers.

The supplier of ready-mixed concrete usually sells concrete with specified properties or of guaranteed mix proportions. He also undertakes to deliver the quantities necessary as and when required.

The concrete is mixed in a central batching plant located close to areas of demand and where supplies of aggregates can be easily arranged. In most plants the batching and mixing is of the highest quality, with an efficiency achieved only by paying attention to the important matters of correct batching and proper charging and mixing of the materials. The plant incorporates at least two weigh-hoppers, so that with four separate sizes of aggregate not more than two are weighed together. The cement and water are weighed separately, and a correction is made for moisture in the sand. It is not possible to control the mixing by reference to workability as described under Quality Control, because of the large number of different mixes which are normally supplied.

In some plants the batching and mixing can be carried out by punch-card operation or by push-button controls, but in most plants reliance is placed on the operator. After thorough mixing, the concrete is discharged into an agitator truck for transporting to the site. The haulage distance is usually limited to 10 miles or about half hour's travelling time. With the use of rotating-drum truck-mixers, the haul time and distance can be increased.

In some countries (for example Sweden) there has not been the same insistence on truck-mixers, and open lorries are used. If a truck-mixer fitted with a separate water tank is used, the haulage can be increased by delaying the time when the measured quantity of water is added until the truck is near the site.

It has been suggested that the use of ready-mixed concrete entails the disadvantage that it is not possible to stop the flow of concrete to the site when there is a delay or mechanical breakdown. In practice, however, this is of only insignificant proportions, since it is not usually difficult to divert the concrete to another part of the site; moreover with ready-mixed concrete the mechanical equipment required on the site is restricted to placing and compacting machinery, so that breakdowns are less frequent.

The use of ready-mixed concrete in this country is associated with the use of agitator and mixer-trucks. There are two types, the horizontal drum truck-mixer and the inclined drum agitator type. The capacity of each varies from 1½ to about 4½ cubic yd of concrete.

Horizontal Drum Truck-Mixer

This has an end-opening revolving drum, with blades attached, and the drum revolves on a horizontal axis. These mixers have given satisfactory service for a number of years. The design of the mixer blades is suitable for mixing the concrete properly, although some trucks are used more as agitators than mixers. To empty the drum, the direction of rotation is reversed; this causes the helical blades to push the mix to the open end, where a movable chute feeds to the point of placement.

Most trucks carry two water tanks, one for supplying water to the mixer (if this is not done at the batching plant) and one for washing out the drum after discharging. The drum is not always washed out after discharging, and for short hauls of half hour's duration there seems little advantage in washing out.

The materials are batched dry at the central plant and then charged into the truck-mixer. When the truck nears the site, the driver adds the measured quantity of water and the materials are mixed.

The Inclined Drum Agitator-Truck

This has a revolving drum, with blades attached, but the drum is inclined; agitation and discharge both take place with the drum rotating in the same direction. The helical blades take the concrete to the high discharge end and allow it to return under gravity. The mix is thus carried to the discharge door without reversing. The charging hopper is integral with the discharge door and remains open, thus allowing visual inspection and sampling during mixing. The high point of discharge of this type gives a wide range of deposition, by the various chutes and extensions provided, with all but low-slump mixes. The agitator truck is charged with mixed concrete at the central plant, and from there the lorry proceeds to the site with its drum slowly rotating, so that the mixing is particularly complete and thorough. An allowance has to be made, however, for the amount of water used up during the travelling time, because there is a loss of workability in the concrete from the time it leaves the plant until it arrives on the site.

Specification for Ready-Mixed Concrete

Ready-mixed concrete is produced in two general types of specification.

(1) The purchaser designs the mix and assumes responsibility for the strength and quality of the concrete. The manufacturer produces concrete to the required proportions.

(2) The purchaser fixes the minimum required strength and also the required workability. This may be done directly by specifying slump or compacting factor, or by implication when the concrete is specified to be suitable to go through a pneumatic placer without segregation. The manufacturer is free to produce the concrete as economically as possible.

With the first specification the quality control required is similar to that which has to be exercised on any site supplied from a central batching and mixing plant. The accuracy of weigh-batching, combined with accurate moisture determination and control of the aggregate production, enables the manufacturer to produce concrete with little variation in quality.

The control problem to the purchaser in the second specification is limited to taking samples and testing, since the onus is on the manufacturer to produce concrete of the required quality.

Ready-mixed concrete may be used with advantage on small jobs where the frequent moving of the mixer and the setting-up of a small mixer on different parts of the site may result in wastage as high as 7½ per cent. The elimination of such wastage of materials, the elimination of the cost of moving a mixer, and the reduction in congestion on the site, may more than compensate for the extra cost of ready-mixed concrete. The relative value of the saving increases as labour costs increase, and the continued rise of such costs combined with the shortage of first-class labour should make for an increased use of ready-mixed concrete. High labour costs are said to be one of the main reasons for its rapid growth in the U.S.A. On large sites, ready-mixed concrete may be used before or while the central batching plant is being erected. This enables the site concrete and concrete for foundations to be placed before the batching plant is ready, and hence may enable the overall contract time to be reduced.

Ready-mixed concrete may have some advantages in winter concreting due to the absence of water tanks and pipelines which might freeze, but if calcium chloride is added to the mix it reduces the setting time as well as increasing the rate of hardening. This is important if an agitator truck has a long haul or a long standing time before discharge.

Some difficulties occasionally occur due to the properties of the concrete changing between the time of mixing and the time of discharge. After mixing there is some loss of workability which is rapid within the first ten minutes but is less thereafter, but it still affects the resulting workability at least half an hour after mixing. The loss of workability between that measured at the mixing plant and at the point of discharge may be 1 to 1½ in. of slump for haulage times up to half an hour.

There is some evidence that hot cement affects the result and can cause difficulties at the batching plant when concrete of constant workability is required.

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