Chapter Six
Strength of Concrete

General:
Strength of concrete is commonly considered its most valuable property, although in many practical cases, other characteristics, such as durability and permeability may in fact be more important. Nevertheless strength usually gives an overall picture of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. Moreover, the strength of concrete is almost invariably a vital element of structural design and is specified for compliance purposes.

Strength of concrete could be defined as the ultimate load that causes failure (or is its resistance to rupture) and its units are force units divided by area (N/mm², lb/in²).

Nature of strength of concrete:
The paramount influence of voids in concrete on its strength has been repeatedly mentioned, and it should be possible to relate this factor to the actual mechanism of failure. For this purpose, concrete is considered to be a brittle material, even though it exhibits a small amount of plastic action, as fracture under static loading takes place at a moderately low total strain; a strain of 0.001 to 0.005 at failure has been suggested as the limit of brittle behavior. High strength concrete is more brittle than normal strength concrete but there is no quantitative method of expressing the brittleness of concrete whose behavior in practice falls between the brittle and the ductile types.

Fracture and failure
Concrete specimens subjected to any state of stress can support loads of up to 40–60 per cent of ultimate without any apparent signs of distress. Below this level, any sustained load results in creep strain which is proportional to the applied stress and can be defined in terms of specific creep (i.e. creep strain per unit stress). Also the concrete is below the fatigue limit. As the load is increased above this level, soft but distinct noises of internal disruption can be heard until, at about 70–90 per cent of ultimate, small fissures or cracks appear on the surface. At this stage sustained loads result in eventual failure. Towards ultimate, cracks spread and interconnect until, at ultimate load and beyond; the specimens are increasingly disrupted and eventually fractured into a large number of separate pieces. The formation and propagation of small microscopic 2-5
cracks μm long (microcracks) have long been recognized as the causes of fracture and failure of concrete and the marked non-linearity of the stress–strain curve near and beyond ultimate.

**The stages of cracking (fracture) in concrete:**

There appear to be at least three stages in the cracking process. In describing the cracking mechanisms, it is important to differentiate between the mode of crack initiation and how this occurs at the microscopic level, and the subsequent paths of propagation and the eventual macroscopic crack pattern at the engineering level.

Although some discontinuities exist as a result of the compaction process of fresh concrete, the formation of small fissures or microcracks in concrete is due primarily to the strain and stress concentrations resulting from the incompatibility of the elastic moduli of the aggregate and paste components.

**Stage I:** Even before loading, intrinsic volume changes in concrete due to shrinkage or thermal movements can cause strain concentrations at the aggregate–paste interface. Within this stage localized cracks are initiated at the microscopic level at isolated points throughout the specimen where the tensile strain concentration is the largest. This shows that these cracks are stable and, at this load stage, do not propagate.

**Stage II:** As the applied load is increased beyond Stage I, initially stable cracks begin to propagate. There will not be a clear distinction between Stages I and II since stable crack initiation is likely to overlap crack propagation and there will be gradual transition from one stage to another. This is illustrated diagrammatically in Fig. 6.1. During Stage II the crack system multiplies and propagates but in a slow stable manner in the sense that, if loading is stopped and the stress level remains constant propagation ceases.

The extent of the stable crack propagation stage will depend markedly upon the applied state of stress, being very short for ‘brittle’ fractures under predominantly tensile stress states and longer for more ‘plastic’ fractures under predominantly compressive states of stress.

**Stage III:** This occurs when, under load, the crack system has developed to such a stage that it becomes unstable and the release of strain energy is sufficient to make the cracks self-propagate until complete disruption and failure occurs. Once Stage III is reached failure will occur whether or not the stress is increased. This stage starts at about 70–90 per cent of ultimate stress and is reflected in an overall expansion of the structure as signified by a reversal in the volume change behavior. As stated above, the load stage at which this occurs corresponds approximately to the long-term strength of concrete.
**Types of concrete strength:**

1. **Compressive strength:**
Compressive strength of specimens treated in a standard manner which includes full compaction and wet curing for a specified period give results representing the potential quality of the concrete. There are three types of loading in compression test:
   a. uniaxial loading.
   b. biaxial loading.
   c. triaxial loading.
The uniaxial loading case represents the most conservative system and yields the lowest values in compression. There are three types of failure in uniaxial compression test as shown in Fig. 6.2. They are:
   a. tension (splitting) failure.
   b. shear (sliding) failure.
   c. combined (tension and shear) failure.
The effect of steel platens of testing machine in uniaxial loading:
In compression test, tangential forces being developed between the end surfaces of the concrete specimen and the adjacent steel platens of the testing machine. These forces will cause lateral expansion in concrete. The steel platen will restrain the lateral expansion of the concrete in the parts of the specimen near its ends: the degree of restraint exercised depends on the friction actually developed. When the friction is eliminated, e.g. by applying a layer of graphite or paraffin wax to the bearing surfaces, the specimen exhibits a large lateral expansion and eventually splits along its full length.

With friction acting, i.e. under normal conditions of test, an element within the specimen is subjected to a shearing stress as well as to compression. The magnitude of the shearing stress decreases and the lateral expansion increases, with an increase in distance from the platen. As a result of the restraint, in a specimen tested to failure there is a relatively undamaged cone or pyramid of height approximately equal to $0.5d\sqrt{3}$ (where $d$ is the lateral dimension of the specimen). If the specimen is longer than about $1.7d$, a part of it will be free from the restraining effect of the platens. We can note that specimens whose length is less than $1.5d$ show a considerably higher strength than those with a greater length (see Fig. 6.3).

![Graph showing relative strength vs. height/diameter ratio](image)

2. Tensile strength:
Although concrete is not normally designed to resist direct tension, the knowledge of tensile strength is of value in estimating the load under which cracking will develop. The absence of cracking is of considerable
importance in maintaining the continuity of a concrete structure and in many cases in the prevention of corrosion of reinforcement. There are two types of test for strength in tension: direct tension test, and splitting tension test.

a. Direct tension test:
   It is the application of a pure tension force free from eccentricity, although it is very difficult but some success with the use of lazy-tong grips has been achieved. It is difficult to avoid secondary stresses such as those induced by grips or by embedded studs.

b. Splitting tension test:
   In this test, a concrete cylinder, of the type used for compression tests, is placed with its axis horizontal between the platens of a testing machine, and the load is increased until failure by indirect tension in the form of splitting along the vertical diameter takes place. However, immediately under the load, a high compressive stress would be induced and, in practice, narrow strips of a packing material, such as plywood are interposed between the cylinder and the platens. Without packing strips, the recorded strength is lower, typically by 8 per cent. ASTM C 496-90 prescribes plywood strips, 3 mm (3/8 in.) thick and 25 mm (1 in.) wide. British Standard BS 1881:117:1983 specifies a hardboard strips, 4 mm thick and 15 mm wide. With such an arrangement, the distribution of the horizontal stress will be almost uniform.

As shown in Fig. 6.4, the horizontal tensile stress will be:

\[ \sigma_t = \frac{2P}{\pi lD} \]
The strength determined in the splitting test is believed to be close to the direct tensile strength of concrete, being 5 to 12 per cent higher.

3. Flexural strength:
Flexural strength of concrete is of interest in the design of pavement slabs. However, the flexure test is not convenient for control or compliance purposes because the test specimens are heavy and are easily damaged.
In these tests, a plain (unreinforced) concrete beam is subjected to flexure using symmetrical two-point loading until failure occurs (see Fig.6.5). Because the load points are spaced at one-third of the span, the test is-called a third-point loading test (ASTM C78-02). The theoretical maximum tensile stress reached in the bottom fibre of the test beam is known as the modulus of rupture.

The modulus of rupture is calculated on the basis of ordinary elastic theory, and is thus equal to:

\[ \sigma = \frac{M c}{I} = \frac{P l}{b d^2} \]

Where
P: maximum total load on the beam.
l: span.
b: width of the beam.
d: depth of the beam.
There exists also a test for flexural strength under centre-point loading, prescribed in ASTM C 293-94. In this test, failure occurs when the tensile strength of concrete in the extreme fibre immediately under the load point is exhausted. On the other hand, under third-point loading, one-third of the length of the extreme fibre in the beam is subjected to the maximum stress, so that the critical crack may develop at any section in one-third of the beam length. Because the probability of a weak element (of any specified strength) being subjected to the critical stress is considerably greater under two-point loading than when a central load acts, the centre-point loading test gives a higher value of the modulus of rupture, but also amore variable one. In consequence the centre-point loading test is very rarely used.

Factors affecting strength of concrete:

1. Water/cement ratio:

In engineering practice, the strength of concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on two factors only: the water/cement ratio and the degree of compaction. When considering fully compacted concrete only: for mix proportioning purposes this is taken to mean that the hardened concrete contains about 1 per cent of air voids. When concrete is fully compacted, its strength is taken to be inversely proportional to the water/cement ratio. This relation was preceded by a so-called law, but really a rule, established by Duff Abrams in 1919. He found strength to be equal to:

\[
 f_c = \frac{K_1}{W} \frac{K_2}{C}
\]

the W/C represents the water/cement ratio of the mix (originally taken by volume), and \( K_1 \) and \( K_2 \), are empirical constants. The general form of the strength versus water/cement ratio curve is shown in Fig. 6.6.

It may be recalled that the water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. Thus the water/cement ratio and the degree of compaction both affect the volume of voids in concrete. Figure 6.1 shows that the range of the validity of the water/cement ratio rule is limited. At very low values of the water/cement ratio, the curve ceases to be followed when full compaction is no longer possible. Thus the increase of the water/cement ratio would improve workability and enhance the ability to decrease entrapped air.

From time to time, the water/cement ratio rule has been criticized as not being sufficiently fundamental. Nevertheless in, practice the
water/cement ratio is the largest single factor in the strength of fully compacted concrete.

2. Effective water in the mix:
The practical relations discussed so far involve the quantity of water in the mix. This needs a more careful definition. We consider as effective that water which occupies space outside the aggregate particles when the gross volume of concrete becomes stabilized, i.e. approximately at the time of setting. Hence the terms effective, free, or net water/cement ratio.

Generally, water in concrete consists of that added to the mix and that held by the aggregate at the time when it enters the mixers. A part of the latter water is absorbed within the pore structure of the aggregate while some exists as free water on the surface of the aggregate and is therefore not different from the water added direct into the mixer. Conversely, when the aggregate is not saturated and some of its pores are therefore air-filled, a part of the water added to the mix will be absorbed by the aggregate during the first half-hour or so after mixing. Under such circumstances the demarcation between absorbed and free water is a little difficult.

3. Gel/space ratio:
The influence of the water/cement ratio on strength does not truly constitute a law because the water/cement ratio rule does not include many qualifications necessary for its validity. In particular, strength at any water/cement ratio depends on:
- Degree of hydration of cement.
- Chemical and physical properties of cement.
- Temperature at which hydration takes place.
- Air content of the concrete.
- Change in the effective water/cement ratio.
- Formation of cracks due to bleeding.
- The cement content of the mix and the properties of the aggregate-cement paste interface are also relevant.

It is more correct, therefore to relate strength to the concentration of the solid products of hydration of cement in the space available for these products. Powers has determined the relation between the strength development and the gel/space ratio. This ratio is defined as the ratio of the volume of the hydrated cement paste to the sum of the volumes of the hydrated cement and of the capillary pores. (See Fig. 6.7)

![Graph showing the relationship between strength and gel/space ratio](Image)

4. Influence of aggregate/cement ratio:
There is no doubt that the aggregate/cement ratio, is only a secondary factor in the strength of concrete but it has been found that, for a constant water/cement ratio, a leaner mix leads to a higher strength (see Fig 6.8). The reasons for this behavior are not clear. In certain cases, some water may be absorbed by the aggregate: a larger amount of aggregate absorbs a greater quantity of water, the effective water/cement ratio being thus reduced. In other cases, a higher aggregate content would lead to lower shrinkage and lower bleeding, and therefore to less damage to the bond between the aggregate and the cement paste; likewise, the thermal changes caused by the heat of hydration of cement would be smaller. The
most likely explanation, however, lies in the fact that the total water content per cubic meter of concrete is lower in a leaner mix than in a rich one. As a result, in a leaner mix, the voids form a smaller fraction of the total volume of concrete, and it is these voids that have an adverse effect on strength.

Studies on the influence of aggregate content on the strength of concrete with a given quality of cement paste indicate that, when the volume of aggregate (as a percentage of the total volume) is increased from zero to 20, there is a gradual decrease in compressive strength, but between 40 and 80 per cent there is an increase. The pattern of behavior is shown in Fig 6.9. The reasons for this effect are not clear, but it is the same at
various water/cement ratios. The influence of the volume of aggregate on
tensile strength is broadly similar.

5. Influence of properties of coarse aggregate:
The properties of aggregate affect the cracking load, as distinct from
ultimate load, in compression and the flexural strength in the same
manner that the relation between the two quantities is independent of the
type of aggregate used. On the other hand, the relation between the
flexural and compressive strengths depends on the type of coarse
aggregate because (except in high strength concrete) the properties of
aggregate, especially its shape and surface texture, affect the ultimate
strength in compression very much less than the strength in tension or the
cracking load in compression. In experimental concrete, entirely smooth
course aggregate led to a lower compressive strength, typically by 10 per
cent, than when roughened.
The influence of the type of coarse aggregate on the strength of concrete
varies in magnitude and depends on the water/cement ratio of the mix.
For water/cement ratios below 0.4, the use of crushed aggregate has
resulted in strengths up to 38 per cent higher than when gravel is used.
With an increase in the water/cement ratio to 0.5, the influence of
aggregate falls off, presumably because the strength of the hydrated
cement paste itself becomes paramount and, at a water/cement ratio of
0.65, no difference in the strengths of concretes made with crushed rock
and gravel has observed.

6. Effect of age on strength:
The relation between the water/cement ratio and the strength of concrete
applies to one type of cement and one age only, and also assumes wet-
curing conditions. On the other hand, the strength versus gel/space ratio
relationship has a more general application because the amount of gel
present in the cement paste at any time is itself a function of age and type
of cement. The latter relation thus allows for the fact that different
cements require a different length of time to produce the same quantity of
gel.
In concrete practice, the strength of concrete is traditionally characterized
by the 28-day value, and some other properties of concrete are often
referred to the 28-day strength. If, for some reason, the 28-day strength is
to be estimated from the strength determined at an earlier age, say 7 days,
then the relation between the 28-day and the 7-day strengths has to be
established experimentally for the given mix. Anyway, the following
relations could be used as rough estimations only:

\[ S_{28}(MPa) = 1.4 \times S_7 + 1.0 \]
\[ S_{28} \text{ (MPa)} = 1.7 S_7 + 5.9 \]

7. Influence of temperature on strength:
The rise in the curing temperature speeds up the chemical reactions of hydration and thus affects beneficially the early strength of concrete without any ill-effects on the later strength. Higher temperature during and, following the initial contact between cement and water reduces the length of the dormant period so that the overall structure of the hydrated cement paste becomes established very early.

Although a higher temperature during placing and setting increases the very early strength, it may adversely affect the strength from about 7 days onwards. The explanation is that a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a proportion of the pores will always remain unfilled. It follows from the gel/space ratio rule that this will lead to a lower strength compared with a less porous, though slowly hydrating, cement paste in which a high gel/space ratio will eventually be reached.

The adverse effects of a high early temperature on later strength could be explained by that the rapid initial rate of hydration at higher temperatures retards the subsequent hydration and produced a non-uniform distribution of the products of hydration within the paste. The reason for this is that, at the high initial rate of hydration, there is insufficient time available for the diffusion of the products of hydration away from the cement particle and for a uniform precipitation in the interstitial space (as is the case at lower temperatures). As a result, a high concentration of the products of hydration is built up in the vicinity of the hydrating particles, and this retards the subsequent hydration and adversely affects the long-term strength. (See Fig. 6.10).
Curing of concrete:
Curing is the name given to procedures used for promoting the hydration of cement, and consists of a control of temperature and of the moisture movement from and into the concrete. In order to obtain good concrete, the placing of an appropriate mix must be followed by curing in a suitable environment during the early stages of hardening.

More specifically the object of curing is to keep concrete saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. In the case of site concrete, active curing stops nearly always before the maximum possible hydration has taken place.

It was found that, for hydration to continue the relative humidity inside concrete has to be maintained at a minimum of 80 per cent. If the relative humidity of ambient air is at least that high, there will be little movement of water between the concrete and the ambient air, and no active curing is needed to ensure continuing hydration. In practice, therefore active curing is unnecessary only in a very humid climate with a steady temperature.

It is well known that hydration of cement can take place only in water-filled capillaries. This is why loss of water by evaporation from the capillaries must be prevented. Furthermore, water lost internally by self-desiccation (due to the chemical reactions of hydration of cement) has to be replaced by water from outside, i.e. ingress of water into the concrete must be made possible. It may be recalled that hydration of a sealed specimen can proceed only if the amount of water present in the paste is at least twice that of the water already combined. Self-desiccation is thus of importance in mixes with water/cement ratios below about 0.5; for higher water/cement ratios, the rate of hydration of a sealed specimen equals that of a saturated specimen. It should not be forgotten, however, that only half the water present in the paste can be used for chemical combination; this is so even if the total amount of water present is less than the water required for chemical combination.

However, traditionally, the effects of curing are expressed in terms of the influence of curing on strength, that is on a comparison of the strength of the specimen stored in water (or in fog) with the strength of those stored under some other conditions for different periods; this is taken to demonstrate the effectiveness of curing and its beneficial effect. An example of this is shown in Fig. 6.11, obtained for concrete with a water/cement ratio of 0.50.

It must be stressed that, for a satisfactory development of strength, it is not necessary for all the cement to hydrate and the quality of concrete depends primarily on the gel/space ratio of the paste. If, however, the water-filled space in fresh concrete is greater than the volume that can be
filled by the products of hydration, greater hydration will lead to a higher strength and a lower permeability.

![Graph showing compressive strength over time](image)

**Methods of curing:**
There are two broad categories of curing whose principals will now be considered, recognizing that the actual procedures used vary widely, depending on the conditions on site and on the size, shape, and position of the concrete member. The methods may be broadly described as *wet curing* and *membrane curing*, respectively.

*A question often arises: which curing method or technique to use? For concrete with a water/cement ratio lower than about 0.5, and certainly lower than 0.4, wet curing should be used, but only if it can be applied thoroughly and continuously. If such an assurance is not possible, then membrane curing is preferable but that, too, has to be well executed.*

**1. Wet curing:**
This method is that of providing water which can be imbibed by the concrete. This requires that the surface of the concrete is continuously in contact with water for a specified length of time, starting as soon as the surface of the concrete is no longer liable to damage.

Such conditions can be achieved by:
- Continuous spraying or flooding (ponding).
- Covering the concrete with wet sand or earth, sawdust or straw.
- Covering the concrete with periodically-wetted clean hessian (burlap) or cotton mats (thick and lapped).
- Using soaking hoses on inclined or vertical surfaces. A continuous supply of water is naturally more efficient than an intermittent one, and Fig. 6.12 compares the strength development of concrete cylinders whose top surface was flooded during the first 24 hours with that of cylinders covered with wet hessian. The difference is apparent only at water/cement ratios below about 0.4 where self-desiccation results in a shortage of water within the concrete. It follows that for low water/cement ratios wet curing is highly desirable.

![Graph showing strength development](image)

As far as quality of the water used for curing is concerned, ideally it should be the same as mixing water. Sea water may lead to corrosion of reinforcement. Also, iron or organic matter may cause staining, particularly if water flows slowly over the concrete and evaporates rapidly. In some cases, discoloration is of no significance. It is essential that curing water be free from substances that attack hardened concrete. The temperature of the water should not be much lower than that of the concrete in order to avoid thermal shock or steep temperature gradients; **ACI 308-92** recommends a maximum difference of 11° C (20 °F).

2. **Membrane curing:**
This method of curing relies on the prevention of loss of water from the surface of the concrete, without the possibility of external water ingressing into it. This could be called a water-barrier method. The techniques used include:
- Covering the surface of the concrete with overlapping polyethylene sheeting, laid flat or with reinforced paper. The sheeting can be black, which is preferable in cold weather, or white, which has the advantage of reflection of solar radiation in hot weather. Paper with a white surface is also available. Sheetling can cause discoloration or mottling because of non-uniform condensation of water on the underside.

- Spray-applied curing compounds which form a membrane. The common ones are solutions of synthetic hydrocarbon resins in high-volatility solvents, sometimes including a fugitive bright-color dye. The dye makes obvious the areas not properly sprayed. A white or alumina pigment can be included to reduce the solar heat gain; this is very effective. Other resin solutions are available acrylic, vinyl or styrene butadiene and chlorinated rubber. Wax emulsions can also be used, but they result in a slippery finish which is not easy to remove, whereas the hydrocarbon resins have poor adhesion to concrete and are degraded by ultraviolet light; both these features are desirable.

A specification for liquid membrane-forming curing compounds is given in **ASTM C 309-93**, and for sheet materials in **ASTM C 171-92**.

It is obvious that the membrane must be continuous and undamaged. The timing of spraying is also critical. The curing spray should be applied after bleeding has stopped bringing water to the surface of the concrete but before the surface has dried out: the optimum time is the instant when the free water on the surface of the concrete has disappeared so that the water sheen is no longer visible. However, if bleeding has not stopped, the curing membrane should not be applied even if the surface of the concrete appears dry in consequence of a high rate of evaporation.

**Length of curing:**

The period of curing required in practice cannot be prescribed in a simple manner: the relevant factors include the severity of the drying conditions and the expected durability requirements.

It was stated earlier that curing should start at the earliest possible instant and should be continuous. Occasionally, intermittent curing is applied, and it is useful to appreciate its effect. In the case of concrete with a low water/cement ratio, continuous curing at an early age is vital as partial hydration make the capillaries discontinuous: on renewal of curing, water would not be able to enter the interior of the concrete and no further hydration would result. However, mixes with a high water/cement ratio always retain a large volume of capillaries so that curing can be effectively resumed at any time, but the earlier the better. Table 6.1 shows minimum curing periods as recommended in ENV 206:1992.
Bond between concrete and reinforcement:
Since structural concrete is, in the vast majority of cases used with steel reinforcement, the strength of bond between the two materials is of considerable importance with respect to structural behavior, including cracking due to shrinkage and early thermal effects. Bond arises primarily from:
- friction.
- adhesion between concrete and steel.
- mechanical interlocking in the case of deformed bars.

In a structure, the bond strength involves not only the properties of the concrete but also other factors. These include the geometry of the reinforcement and of the structure such as the thickness of cover to the reinforcement. The state of the surface of the steel is also a factor. The presence of rust on the surface of the steel provided the rust is well connected to the underlying steel, improves bond of plain bars and does not impair the bond of deformed reinforcement.

The critical property is the tensile strength of concrete. For this reason design formulae for bond strength usually express it as being proportional to the square root of compressive strength, As shown earlier, the tensile strength of concrete is proportional to a somewhat higher power of the compressive strength, say about 0.7; consequently, the expressions used in the various codes are not a correct representation of the indirect dependence of the bond strength on the compressive of concrete. Nevertheless, bond strength of deformed steel bars has been shown to increase with an increase in compressive strength, albeit at a decreasing rate, for concrete strengths up to about 95 MPa (14000 psi).
A rise in temperature reduces the bond strength of concrete: at 200 to 300 °C (400 to 570 °F) there may be a loss of one-half of the bond strength at room temperature.

**Quality of mixing water:**
The quality of the water plays a significant role on strength of concrete, as:
- impurities in water may interfere with the setting of the cement.
- may adversely affect the strength of the concrete.
- cause staining of its surface.
- lead to corrosion of the reinforcement.
For these reasons, the suitability of water for mixing and curing purposes should be considered. Clear distinction must be made between the quality of mixing water and the attack on hardened concrete by aggressive waters. Indeed, some waters which adversely affect hardened concrete may be harmless or even beneficial when used in mixing.
Mixing water should not contain undesirable organic substances or inorganic constituents in excessive proportions. However, no standards explicitly prescribing the quality of mixing water are available, partly because quantitative limits of harmful constituents are not known, but mainly because unnecessary restrictions could be economically damaging.
In many project specifications, the quality of water is covered by a clause saying that water should be fit for drinking. Such water very rarely contains dissolved inorganic solids in excess of 2000 parts per million (ppm), and as a rule less than 1000 ppm. For a water/cement ratio of 0.5, the latter content corresponds to a quantity of solids representing 0.05 per cent of the mass of cement, and any effect of the common solids would be small.
Conversely, some waters not fit for drinking may often be used satisfactorily in making concrete. As a rule, water with pH of 6.0 to 8.0 or possibly even 9.0 which does not taste brackish is suitable for use, but dark color or bad smell do not necessarily mean that deleterious substances are present. A simple way of determining the suitability of such water is to compare the setting time of cement and the strength of mortar cubes using the water in question with the corresponding results obtained using known 'good' water or distilled, there is no appreciable difference between the behavior of distilled and ordinary drinking water. A tolerance of about 10 per cent is usually permitted to allow for chance variation in strength.
Brackish water contains chlorides and sulfates. When chloride does not exceed 500 ppm, of SO₃ does not exceed 1000 ppm, the water is harmless. but with even higher salt contents has been used satisfactorily.
Sea water has a total salinity of about 3.5 per cent (78 per cent of the dissolved solids being NaCl and 15 per cent MgCl₂, and MgSO₄), and produces a slightly higher early strength but a lower long-term strength; the loss of strength is usually no more than 15 per cent and can therefore often be tolerated. Some tests suggest that sea water slightly accelerates the setting time of cement; others show a substantial reduction in the initial setting time but not necessarily in the final set.