Contents

Length Comparator with specimen in place

8

CHAPTER

- Elastic Properties of Concrete
- Creep
- Microscopic Rheological Approach
- Shrinkage

Elasticity, Creep and Shrinkage

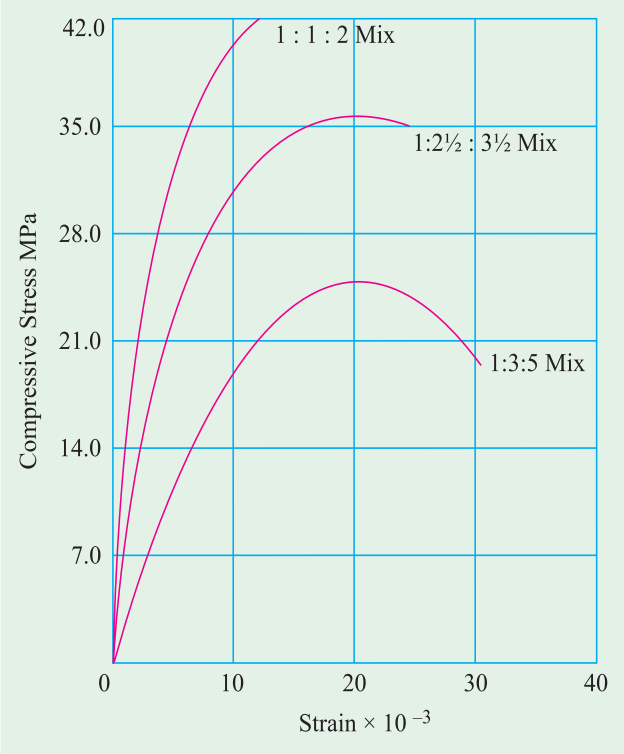
Elastic Properties of Concrete

In the theory of reinforced concrete, it is assumed that concrete is elastic, isotropic, homogenous and that it conforms to Hooke's law. Actually none of these assumptions are strictly true and concrete is not a prefectly elastic material. Concrete deforms when load is applied but this deformation does not follow any simple set rule. The deformation depends upon the magnitude of the load, the rate at which the load is applied and the elapsed time after which the observation is made. In other words, the rheological behaviour of concrete i.e., the response of concrete to applied load is quite complex.

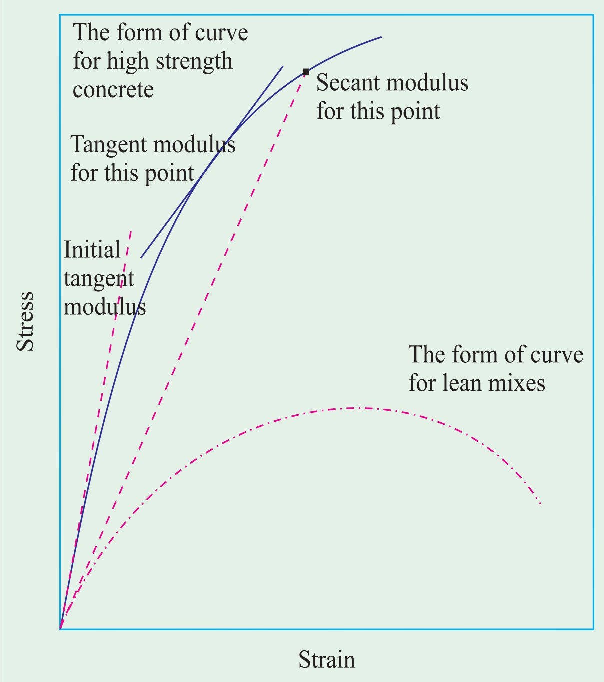
The knowledge of rheological properties of concrete is necessary to calculate deflection of structures, and design of concrete members with respect to their section, quantity of steel and stress analysis. When reinforced concrete is designed by elastic theory it is assumed that a perfect bond exists between concrete and steel. The stress in steel is "m" times the stress in concrete where "m" is the ratio *between modulus of elasticity of steel and concrete, known as modular ratio. The accuracy of design will naturally be dependent upon the value of the modulus of elasticity of concrete, because the modulus of elasticity of steel is more or less a definite quantity.*

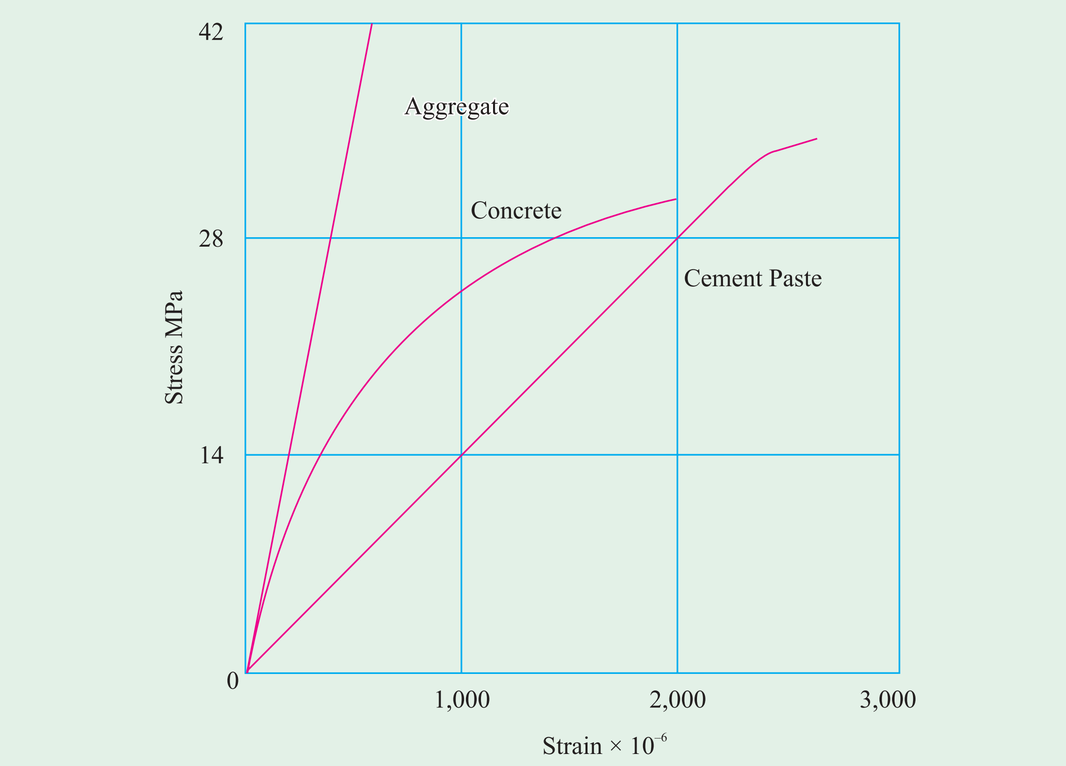
It is to be further noted that concrete exhibits very peculiar rheological behaviour because of its being a heterogeneous, multi-phase material whose behaviour is influenced by the elastic properties and morphology of gel structures. The modulus of elasticity of concrete being so important and at the same time so complicated, we shall see this aspect in little more detail.

The modulus of elasticity is determined by subjecting a cube or cylinder specimen to uniaxial compression and measuring the deformations by means of dial gauges fixed between certain gauge length. Dial gauge reading divided by gauge length will give the strain and load applied divided by area of cross-section will give the stress. A series of readings are taken and the stress-strain relationship is established.



The modulus of elasticity can also be determined by subjecting a concrete beam to bending and then using the formulae for deflection and substituting other parameters. The modulus of elasticity so found out from actual loading is called static modulus of elasticity. It is seen that even under short term loading concrete does not behave as an elastic material. However, up to about 10-15% of the ultimate strength of concrete, the stress-strain graph is not very much curved and hence can give more accurate value. For higher stresses the stress-strain relationship will be greatly curved and as such it will be inaccurate. Figure 8.1 shows stress-strain relationship for various concrete mixes.





In view of the peculiar and complex behaviour of stress-strain relationship, the modulus of elasticity of concrete is defined in somewhat arbitrary manner. The modulus of elasticity of concrete is designated in various ways and they have been illustrated on the stress-strain curve in Figure 8.2. The term Young's modulus of elasticity can strictly be applied only to the straight part of stress-strain curve. In the case of concrete, since no part of the graph is straight, the modulus of elasticity is found out with reference to the tangent drawn to the curve at the origin. The modulus found from this tangent is referred as initial tangent modulus. This gives satisfactory results only at low stress value. For higher stress value it gives a misleading picture.

Tangent can also be drawn at any other point on the stress-strain curve. The modulus of elasticity calculated with reference to this tangent is then called tangent modulus. The tangent modulus also does not give a realistic value of modulus of elasticity for the stress level much above or much below the point at which the tangent is drawn. The value of modulus of elasticity will be satisfactory only for stress level in the vicinity of the point considered.

A line can be drawn connecting a specified point on the stress-strain curve to the origin of the curve. If the modulus of elasticity is calculated with reference to the slope of this line, the modulus of elasticity is referred as secant modulus. If the modulus of elasticity is found out with reference to the chord drawn between two specified points on the stress-strain curve then such value of the modulus of elasticity is known as chord modulus.

The modulus of elasticity most commonly used in practice is secant modulus. There is no standard method of determining the secant modulus. Sometime it is measured at stresses ranging from 3 to 14 MPa and sometime the secant is drawn to point representing a stress level of 15, 25, 33, or 50 per cent of ultimate strength. Since the value of secant modulus decreases with increase in stress, the stress at which the secant modulus has been found out should always be stated.

Modulus of elasticity may be measured in tension, compression or shear. The modulus in tension is usually equal to the modulus in compression.

It is interesting to note that the stress-strain relationship of aggregate alone shows a fairly good straight line. Similarly, stress-strain relationship of cement paste alone also shows a fairly good straight line. But the stress-strain relationship of concrete which is combination of aggregate and paste together shows a curved relationship. Perhaps this is due to the development of micro cracks at the interface of the aggregate and paste. Because of the failure of bond at the interface increases at a faster rate than that of the applied stress, the stress-strain curve continues to bend faster than increase of stress. Figure 8.3 shows the stress-strain relationship for cement paste, aggregate and concrete.

Relation between Modulus of Elasticity and Strength

Figure 8.4 shows the strain in concrete of different strengths plotted against the stress-strain ratio. At the same stress-strength ratio, stronger concrete has higher strain. On the contrary, stronger the concrete higher the modulus of elasticity. This can be explained that stronger the concrete the stronger is the gel and hence less is the strain for a given load. Because of lower strain, higher is the modulus of elasticity. The Table 8.1 gives the values of modulus of elasticity for various strengths of concrete.

Modulus of elasticity of concrete increases approximately with the square root of the strength. The IS 456 of 2000 gives the Modulus of elasticity as $E_C = 5000\sqrt{f_{ck}}$

where E_C *is the short term static modulus of elasticity in* N/mm^2.

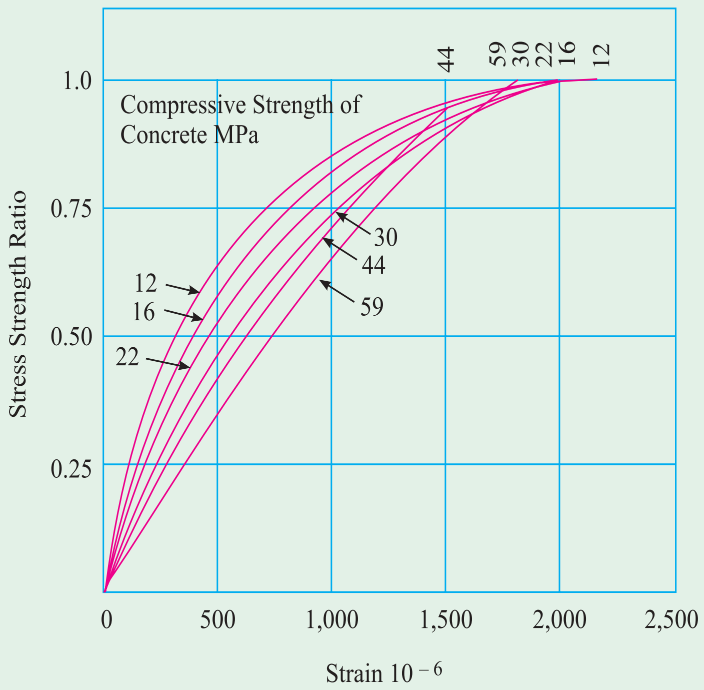


Table 8.1. Modulus of Elasticity of Concrete of Different strengths

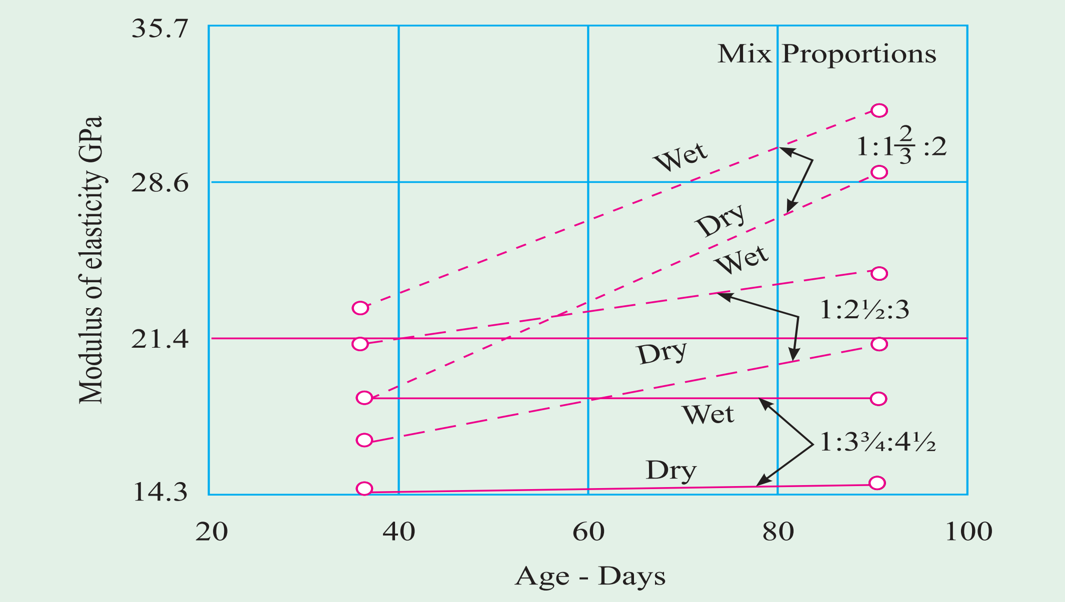
Average compressive strength of works cubes MPa	Modulus of Elasticity GPa
21	21.4
28	28.5
35	32.1
42	35.7
56	42.9
70	46.4

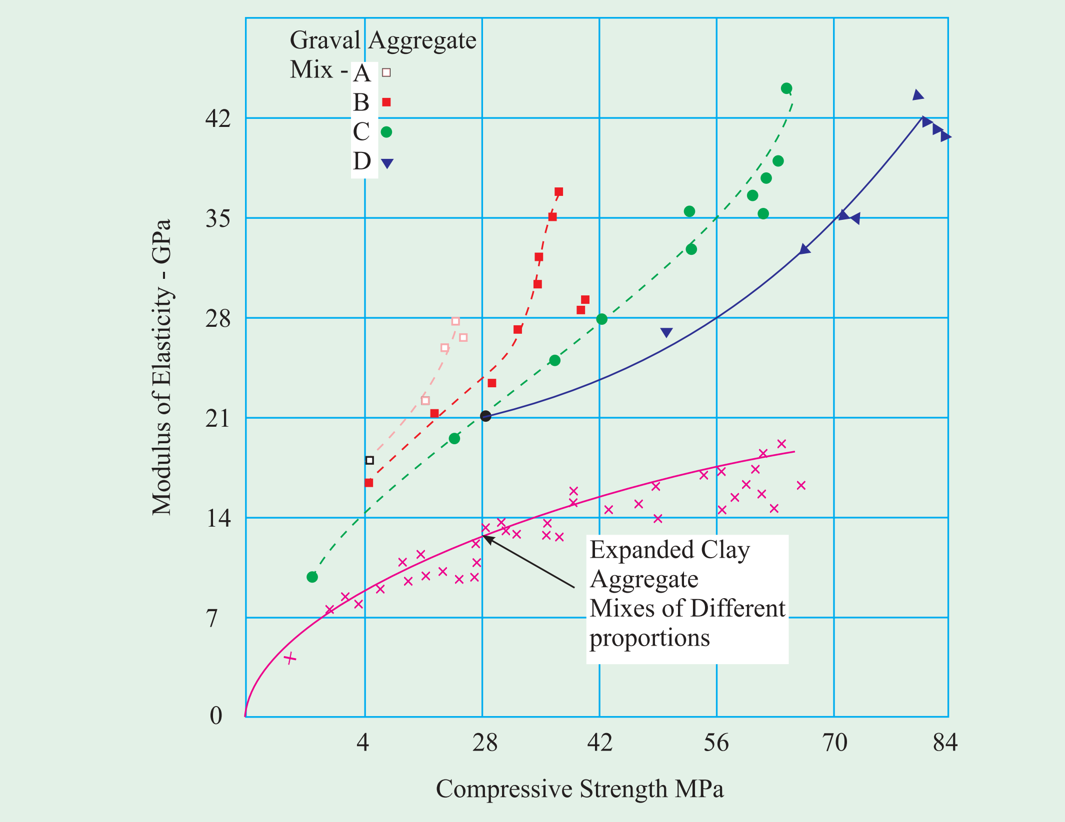
Actual measured values may differ by ± 20 per cent from the values obtained from the above expression.

Factors Affecting Modulus of Elasticity

As explained earlier, one of the important factors affecting the modulus of elasticity of concrete is the strength of concrete. This can be represented in many ways such as the relationship between ratio of mix or water/cement ratio. The modulus of elasticity also depends upon the state of wetness of concrete when other conditions being the same. Wet concrete will show higher modulus of elasticity than dry concrete. This is in contrast to the strength property that dry concrete has higher strength than wet concrete. The possible reason is that wet concrete being saturated with water, experiences less strain for a given stress and, therefore, gives higher modulus of elasticity, whereas dry concrete shows higher strain for given stress on account of less gel water and inter-crystal adsorbed water. Figure 8.5 shows the influence of moisture content on the modulus of elasticity.

Figure 8.5 also shows the relationship between the modulus of elasticity, mix proportions and age of concrete. It can be seen that richer mixes show higher modulus of elasticity. Similarly older the concrete which again is supposed to have become stronger shows higher





modulus of elasticity, thereby confirming that the stronger the concrete higher is the modulus of elasticity.

The quality and quantity of aggregate will have a significant effect on the modulus of elasticity. It is to be remembered that the strength of aggregate will not have significant effect on the strength of concrete, whereas, the modulus of elasticity of aggregate influences the modulus of elasticity of concrete. Figure 8.6 shows the modulus of elasticity of concrete with gravel aggregates and expanded clay aggregates. It has been seen that if the modulus of elasticity of aggregate is E_a and that of the paste E_p then the modulus of elasticity of concrete E is found out to be

$$\frac{1}{E}=\frac{V_p}{E_p}+\frac{V_a}{E_a}$$

where V_p and V_a are volume of paste and aggregate respectively in the concrete.

The modulus of elasticity of light weight concrete is usually between 40 to 80 per cent of the modulus of elasticity of ordinary concrete of the same strength. Since there is little difference between the modulus of elasticities of paste and light weight aggregate the mix proportions will have very little effect on the modulus of elasticity of light weight concrete.[8.1]

The relation between the modulus of elasticity and strength is not much effected by temperature upto about 230°C since both the properties vary with temperature in approximately the same manner. Steam-curved concrete shows a slightly lower modulus than water-curved concrete of the same strength.

Experiments have shown that the modulus in tension does not appear to differ much from modulus in compression. As the experimental set-up presents some difficulties, only limited work has been done to determine the modulus of elasticity in tension.

Since the principal use of reinforced concrete is in flexural members, considerable amount of work has been conducted to find out the modulus of elasticity in flexure on specimens of beam. The approach was to load the beam, measure deflection caused by known loads and to calculate the modulus of elasticity from well-known beam deflection formulae. It has been seen that the stress-strain curves in flexure agreed well with the stress-strain curve obtained in companion cylinders concentrically loaded in compression.

Dynamic Modulus of Elasticity

It has been explained earlier that the stress-strain relationship of concrete exhibits complexity particularly due to the peculiar behaviour of gel structure and the manner in which the water is held in hardened concrete. The value of E is found out by actual loading of concrete i.e., the static modulus of elasticity does not truly represent the elastic behaviour of concrete due to the phenomenon of creep. The elastic modulus of elasticity will get affected more seriously at higher stresses when the effect of creep is more pronounced.

Attempts have been made to find out the modulus of elasticity from the data obtained by non-destructive testing of concrete. The modulus of elasticity can be determined by subjecting the concrete member to longitudinal vibration at their natural frequency. This method involves the determination of either resonant frequency through a specimen of concrete or pulse velocity travelling through the concrete. (More detail on this aspect is given under the chapter ('Testing of concrete'). By making use of the above parameters modulus of elasticity can be calculated from the following relationship.

$$E_d = Kn^2L^2\rho$$

where E_d *is the dynamic modulus of elasticity;* K *is a constant,* n *is the resonant frequency;* L *is the length of specimen; and* ρ *is the density of concrete.*

If L *is measured in millimetres and* ρ *in kg/m*^{3}

then $$E_d = 4 \times 10^{-15} n^2L^2\rho \text{ GPa}$$

The value of E found out in this method by the velocity of sound or frequency of sound is referred as dynamic modulus of elasticity, in contrast to the value of E found out by actual loading of the specimen and from stress-strain relationship which is known as static modulus of elasticity.

The value of dynamic modulus of elasticity computed from ultrasonic pulse velocity method is somewhat higher than those determined by static method. This is because the modulus of elasticity as determined by dynamic modulus is unaffected by creep. The creep also does not

Ultra Sonic Pulse Velocity Equipment is used for finding dynamic modulus of elasticity.

significantly effect the initial tangent modulus in the static method. Therefore, the value of dynamic modulus and the value of initial tangent modulus are found to be more or less agree with each other. Approximate relationship between the two modulai expressed in GN/m^2 is given by

$$E_c = 1.25\, E_d - 19$$

where E_c *and* E_d *are the static and dynamic modulus of elasticity.*

The relationship does not apply to light weight concrete or for very rich concrete with cement content more than 500 kg/m^3. For light weight concrete the relationship can be as follows

$$E_c = 1.04\, E_d - 4.1$$

Poisson's Ratio

Sometimes in design and analysis of structures, the knowledge of poisson's ratio is required. Poisson's ratio is the ratio between lateral strain to the longitudinal strain. It is generally denoted by the letter μ. *For normal concrete the value of poisson's ratio lies in the range of 0.15 to 0.20 when actually determined from strain measurements.*

As an alternative method, poisson's ratio can be determined from ultrasonic pulse velocity method and by finding out the fundamental resonant frequency of longitudinal vibration of concrete beam. The poisson's ratio μ *can be calculated from the following equation.*

$$\left(\frac{V^2}{2nL}\right)^2 = \frac{1-\mu}{(1+\mu)(1-2\mu)}$$

where V *is the pulse velocity (mm/s),*

n *is the resonant frequency (Hz) and L is the length of the beam (in mm). The value of the poisson's ratio found out dynamically is little higher than the value of static method. The value ranges from 0.2 to 0.24.*

Dynamic modulus of elasticity can also be found out from the following equation.

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

where V *is the pulse velocity*

ρ *is the density and*

μ *is the Poisson's ratio*

Creep

Creep can be defined as "the time-dependent" part of the strain resulting from stress. We have discussed earlier that the stress-strain relationship of concrete is not a straight line relationship but a curved one. The degree of curvature of the stress-strain relationship depends upon many factors amongst which the intensity of stress and time for which the load is acting are of significant interest. Therefore, it clearly shows that the relation between stress and strain for concrete is a function of time. The gradual increase in strain, without increase in stress, with the time is due to creep. From this explanation creep can also be defined as the increase in strain under sustained stress.

All materials undergo creep under some conditions of loading to a greater or smaller extent. But concrete creeps significantly at all stresses and for a long time. Furthermore, creep of concrete is approximately linear function of stress upto 30 to 40 per cent of its strength. The order of magnitude of creep of concrete is much greater than that of other crystalline material except for metals in the final stage of yielding prior to failure. Therefore, creep in concrete is considered to be an isolated rheological phenomenon and this is associated with the gel structure of cement paste. Cement paste plays a dominant role in the deformation of concrete. The aggregates, depending upon the type and proportions modify the deformation characteristics to a greater or lesser extent. Therefore, it is logical initially to examine the structure of cement paste and how it influences creep behaviour and then to consider how the presence of aggregate modifies the creep behaviour.

Cement paste essentially consists of unhydrated cement grains surrounded by the product of hydration mostly in the form of gel. These gels are interpenetrated by gel pores and interspersed by capillary cavities. The process of hydration generates more and more of gel and subsequently there will be reduction of unhydrated cement and capillary cavities. In young concrete, gel pores are filled with gel water and capillary cavities may or may not be filled with water. The movement of water held in gel and paste structure takes place under the influence of internal and external water vapour pressure. The movement of water may also take place due to the sustained load on concrete.

The formation of gel and the state of existence of water are the significant factors on the deformative characteristics of concrete. The gel provides the rigidity both by the formation of chemical bonds and by the surface force of attraction while the water can be existing in three categories namely combined water, gel water and capillary water.

It is interesting to find how such a conglomeration of very fine colloidal particles with enclosed water-filled viods behave under the action of external forces. One of the explanations given to the mechanics of creeps is based on the theory that the colloidal particles slide against each other to re-adjust their position displacing the water held in gel pores and capillary cavities. This flow of gel and the consequent displacement of water is responsible for complex deformation behaviour and creep of concrete.

Creep takes place only under stress. Under sustained stress, with time, the gel, the adsorbed water layer, the water held in the gel pores and capillary pores yields, flows and readjust themselves, which behaviour is termed as creep in concrete.

Rheological Representation of Creep

Analysis of the mechanical behaviour of a material like hardened cement paste which exhibits both elastic and inelastic components of deformation under load, can be expressed in rheological terms. The rheological approach illustrates the mechanical behaviour of an ideal elastic, viscous and plastic components.

Macroscopic Rheological Approach

At the macroscopic level, the structure of cement paste can be represented as a continuous solid phase containing saturated voids having a wide ranges of sizes. Figure 8.7 (*a*) shows macroscopic representation of deformational behaviour of hardened cement paste. This model can show the time-dependent volume changes, as long as the isotropic stresses are applied through the solid phase and the drainage of the liquid can take place.[8.2]

The corresponding rheological model consists of a spring device representing the elastic mass around a central viscous dash-pot representing the confined liquid. Refer Figure 8.7 (*b*). With the help of this model it is possible to have an idea about the deformational behaviour of cement paste.

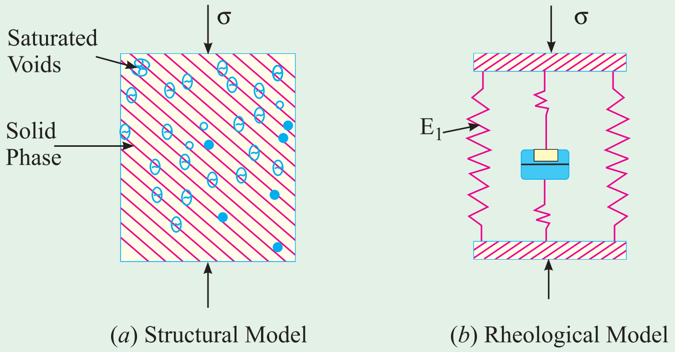
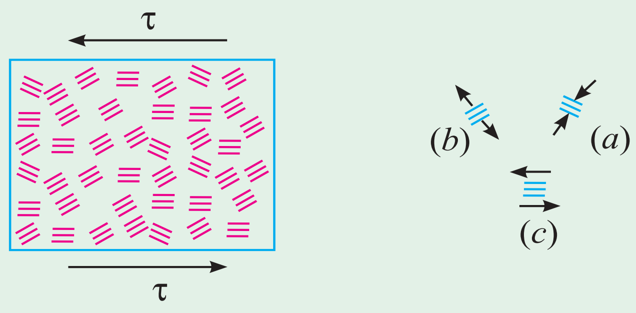


Fig. 8.7. Macroscopic representation of the deformational behaviour of hardened cement paste.

Microscopic Rheological Approach

At the microscopic level, the structure of cement of gel can be represented as an anisotropic crystal clusters randomly oriented in a solid matrix (Figure 8.8). The application of a macroscopic shear stress to the anisotropic system results in an irrecoverable volumetric contraction of the spaces in some of the clusters [Figure 8.8 (a)] and a separation in other clusters [Figure 8.8 (b)]. Only. a fraction of the elements is subjected to pure shear [Figure 8.8 (c)]. On removal of the load there is a visco-elastic recovery, but due to some deviatory stress component, certain local irrecoverable volume changes will remain. Figure 8.9 shows the further submicroscopic models.



They represented metastable crystalline gel consisting of two sheet like crystals separated by a layer of water. Three basically different mechanisms of deformation are possible. They are compressive stresses normal to contact layer [Figure 8.9 (a)] tensile stresses normal to the contact layer [Figure 8.9 (b)] sheer stresses parallel to the contant layer [Figure 8.9 (c)]

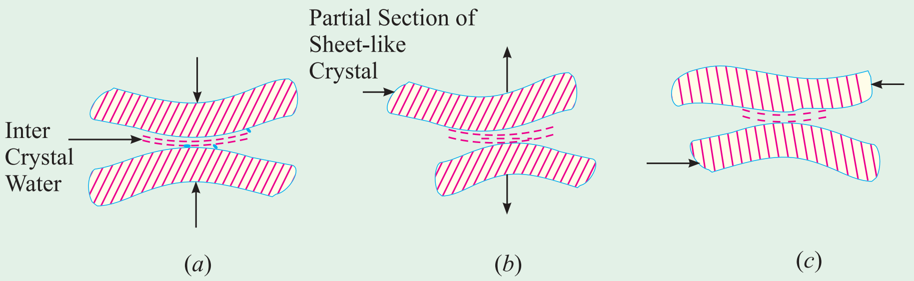


Fig. 8.9. Sub-microscopic models representing the three basic intercrystal mechanical states.

In mechanism (a), the liquid is compressed and squeezed out laterally. This is accompanied by a reduction of the intercrystalline space. The rate of liquid movement is slow and will decrease with narrowing of space which tends towards a limit equal to a monomolecular compressed water layer (about 3 Å). This squeezing away of liquid against strong frictional forces is the principal cause of the time dependent, irrecoverable changes in the cement gel.

In mechanism (b), visco-elastic elongation may be expected, at a faster rate than in the case of compression. This elongation is restrained, however, by the solid matrix and delayed, although complete recovery may be expected long after unloading.

In mechanism (c), the shear stress results in the water layers.[8.3]

Under the complex systems of applied loading, below the elastic limit of the material, various combinations of these basic mechanisms of deformation may be expected. On the basis of the available experimental evidence, it may be assumed that the long term deformation mechanism in cement gel is that involving narrowing of the intercrystalline spaces. This is reflected in the slow and decreasing rate of time-dependent of deformation, as well as in the irrecoverable component of the deformations which increase with loading time.

The time dependent deformation behaviour of loaded and unloaded hardened cement paste shows a distinct similarity between creep (and its recovery) and shrinkage (and swelling). All these processes are governed by movement or migration of the various types of water held. It can be further explained as follows:

Application of uniaxial compression which is the most usual type of loading, results in as instantaneous elastic response of both solid and liquid systems. The external load is distributed between these two phases. Under sustained load, the compressed liquid begins to diffuse and migrate from high to lower stressed areas. Under uniform pressure, migration takes place outwards from the body. This mechanism is accompanied by a transfer of load from the liquid phase to the surrounding solid, so that stress acting on the solid matrix increases gradually, resulting in an increased elastic deformation.

There is reason to believe that, after several days under sustained load, the pressure on the capillary water gradually disappears, being transferred to the surrounding gel. Similarly, the pressure on the gel pore water disappears after some weeks. The pressure on the inter and intracrystalline adsorbed water continues to act during the entire period of loading, although the magnitude decreases gradually. It can be said that the ultimate deformation of the hardened cement paste, in fact, is the elastic response of its solid matrix, which behaves as if the spaces within it (which are filled with unstable gel) were quite empty.

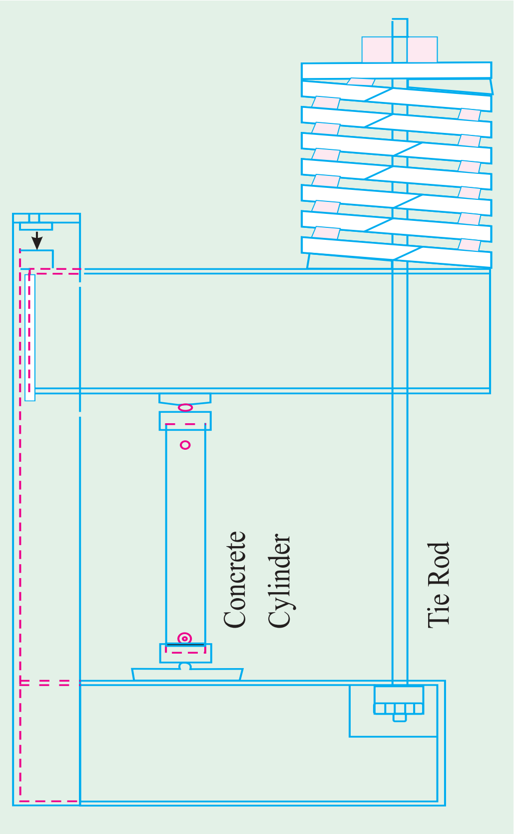
Hydration under Sustained Load

Under sustained load the cement paste continues to undergo creep deformation. If the member is subjected to a drying condition this member will also undergo continuous shrinkage. The migration of liquid from the gel pore due to creep may promote the shrinkage to small extent. It can be viewed that the creep, the shrinkage and the slip deformations at the discontinuities cause deformations and micro cracks. It should be remembered that the process of hydration is also simultaneously progressing due to which more gel is formed which will naturally heal-up the microcracks produced by the creep and shrinkage. This healing up micro cracks by the delayed hydration process is also responsible for increasing the irrecoverable component of the deformation.

Increased rigidity and strength development with age are additional contribution of hydration to time dependent deformation. Moreover, it is likely that, with continuing hydration the growth of the solid phase at the expense of the liquid phase gradually changes the parameter governing the extent and rate of the total creep.

Concrete structures in practice are subjected to loading and drying. At the same time certain amount of delayed hydration also takes place. Under such a complex situation, the structure creeps, undergoes drying shrinkage, experiences micro cracks and also due to progressive hydration, heals up the micro cracks that are formed due to any reason.

Measurement of Creep



Creep is usually determined by measuring the change with time in the strain of specimen subjected to constant stress and stored under appropriate condition. A typical testing device is shown in Figure 8.10. The spring ensures that the load is sensibly constant in spite of the fact that the specimen contracts with time. Under such conditions, creep continues for a very long time, but the rate of creep decreases with time.

Under compressive stress, the creep measurement is associated with shrinkage of concrete. It is necessary to keep companion unloaded specimens to eliminate the effect of shrinkage and other autogenous volume change. While this correction is qualitatively correct and yields usable results, some research workers maintained that shrinkage and creep are not independent and are of the opinion that the two effects are not additive as assumed in the test.

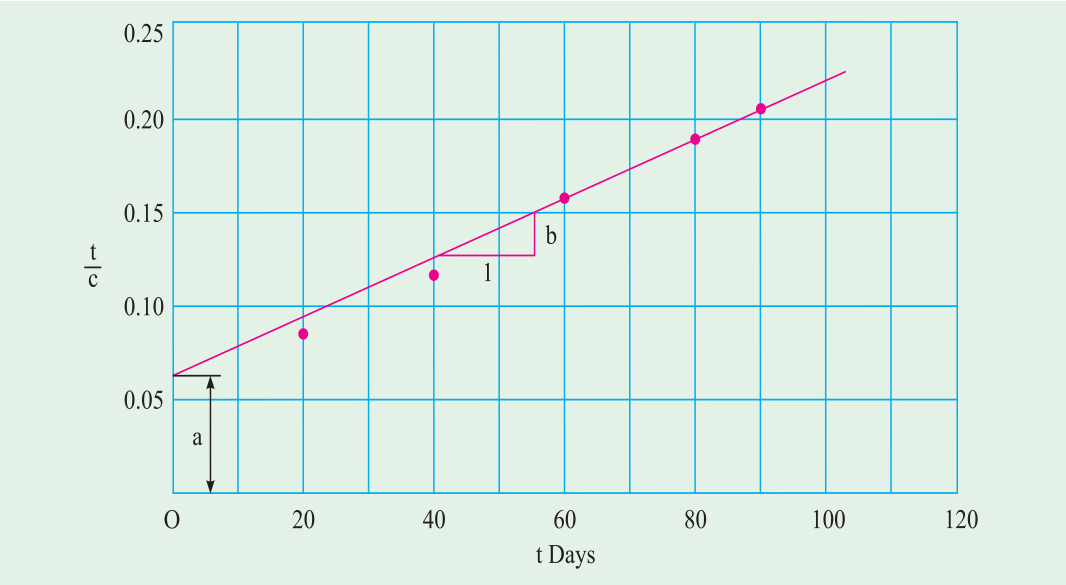
It is generally assumed that the creep continues to assume a limiting value after an infinite time under load. It is estimated that 26 per cent of the 20 year creep occurs in 2 weeks. 55 per cent of 20 year creep occurs in 3 months and 76 per cent of 20 year creep occurs in one year.

If creep after one year is taken as unity, then the average value of creep at later ages are:

1.14 after 2 years
1.20 after 5 years
1.26 after 10 years
1.33 after 20 years and
1.36 after 30 years

There are many expressions to give the magnitude of ultimate creep in concrete member. Ross suggested the relation between specific creep (creep strain per unit stress) 'c' and time under load 't' in the form[8.4]

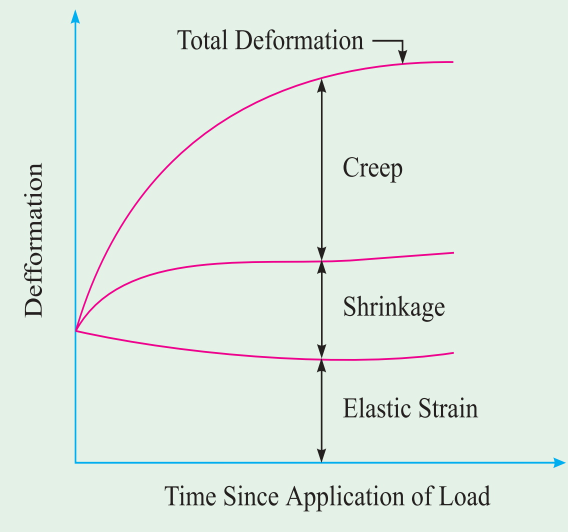
$$c = \frac{t}{a + bt}$$

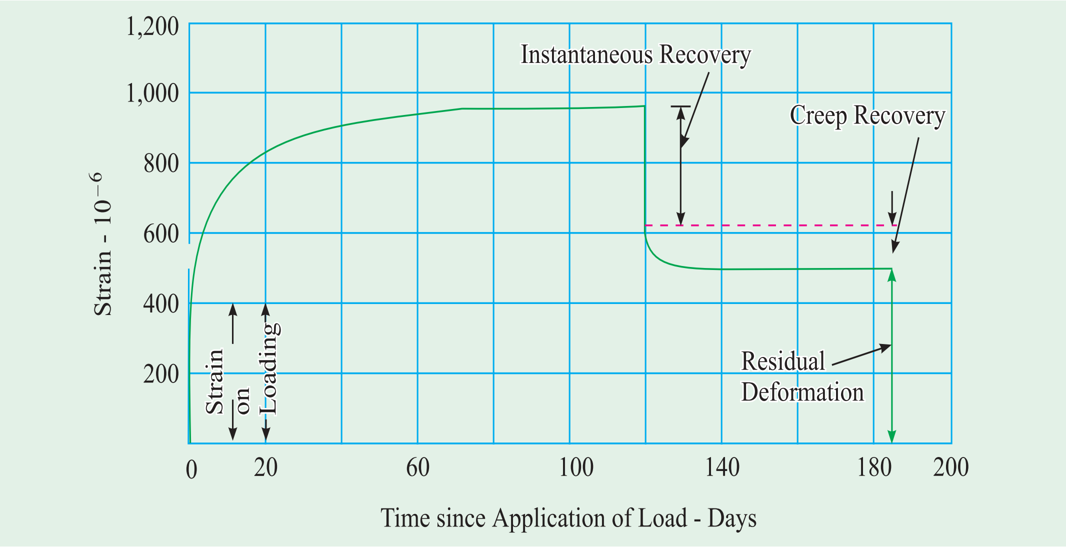


where 'a' and 'b' are constants. If a graph is drawn with t in the x-axis and t/c in the y-axis it shows a straight line of slope b and the intercept on the $\frac{t}{c}$ *is equal to a.*

Then the constant can be easily found out. Refer Figure 8.11. The ultimate crep at infinite time will be $\frac{1}{b}$ *from the above expression. It is interesting to observe that when* $t = a/b$, $c = \frac{1}{2}b$. *i.e., one half of the ultimate creep is realised at time* $t = a/b$.

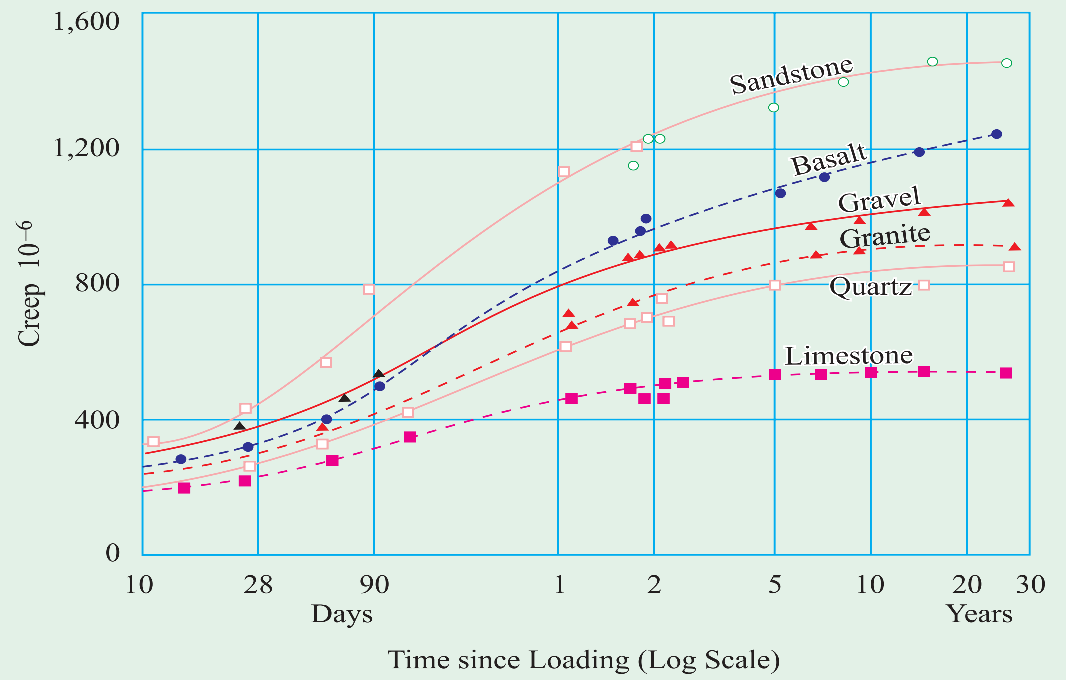
As indicated earlier if a loaded concrete member is kept in atmoshphere subjected to shrinkage, the member will undergo deformation from 3 different causes: namely elastic deformation, drying shrinkage and creep deformation. Figure 8.12 shows the time dependent deformation in concrete subjected to sustained load. In order to estimate the magnitude of creep in a member subjected to drying, a companion specimen is always placed at the same temperature and humidity condition and the shrinkage of the unloaded specimen is found and this magnitude of deformation is subtracted from the total deformation of the loaded member. Knowing the instantaneous elastic deformation, the creep deformation can be calculated. In this, for simplicity sake it is assumed that the shrinkage of concrete does not effect the creep in addition to the load. In fact it is to be noted that in addition to the load,





the shrinkage also will have some influence on the magnitude of creep, and creep on shrinkage.

If a member is loaded and if this load is sustained for some length of time and then removed, the specimen instantaneously recovers the elastic strain. The magnitude of instantaneous recovery of the elastic strain is something less than that of the magnitude of the elastic strain on loading. With time, certain amount of creep strain is also recovered. It is estimated that about 15 per cent of creep is only recoverable. The member will have certain amount of residual strain. This shows that the creep is not a simply reversible phenomenon. Figure 8.13 shows the pattern of strain of a loaded specimen and the recovery of strain on unloading after some time.



Factors Affecting Creep

Influence of Aggregate: Aggregate undergoes very little creep. It is really the paste which is responsible for the creep. However, the aggregate influences the creep of concrete through a restraining effect on the magnitude of creep. The paste which is creeping under load is restrained by aggregate which do not creep. The stronger the aggregate the more is the restraining effect and hence the less is the magnitude of creep. Figure 8.14 shows the effect of the quality of aggregate on the magnitude of creep.

The grading, the shape, the maximum size of aggregate have been suggested as factors affecting creep. But it is later shown that the effect of aggregate and their properties mentioned above per se do not effect the creep , but indirectly they affect the creep from the point of view of total aggregate content in the concrete. The modulus of elasticity of aggregate is one of the important factors influencing creep. It can be easily imagined that the higher the modulus of elasticity the less is the creep. Light weight aggregate shows substantially higher creep than normal weight aggregate. Persuambly this is because of lower modulus of elasticity.

Influence of Mix Proportions: The amount of paste content and its quality is one of the most important factors influencing creep. A poorer paste structure undergoes higher creep. Therefore, it can be said that creep increases with increase in water/cement ratio. In other words, it can also be said that creep is inversely proportional to the strength of concrete. Broadly speaking, all other factors which are affecting the water/cement ratio is also affecting the creep. The following table shows the creep of concretes of different strength.

Table 8.2. Creep of Concrete of Different Strength

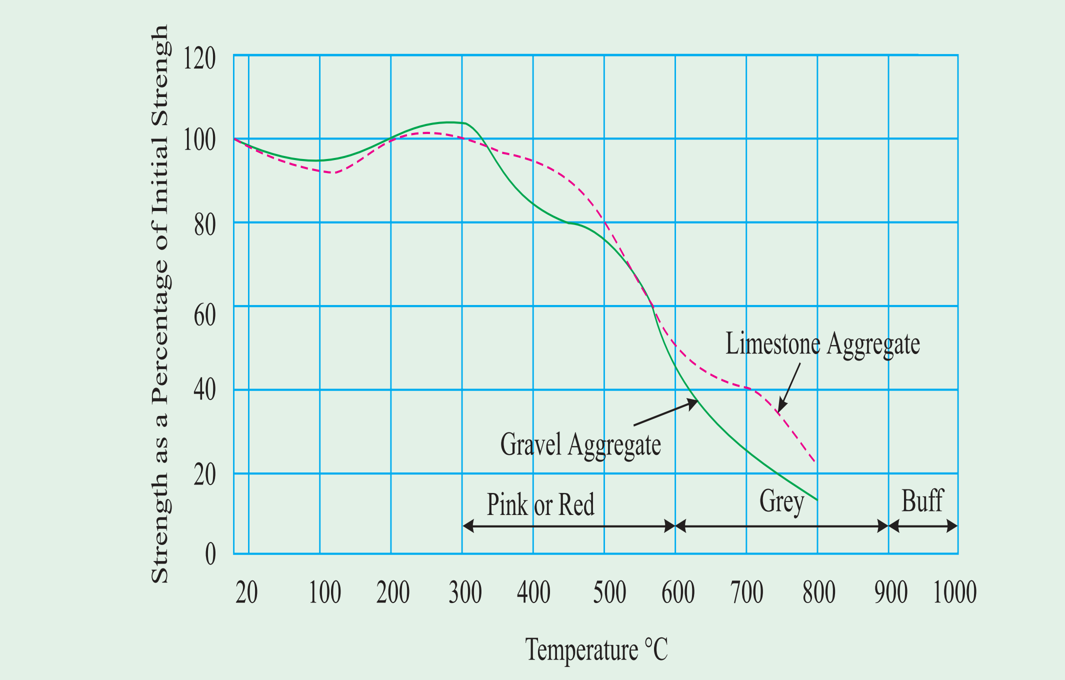
Compressive strength at the time of application of load MPa	Ultimate specific creep 10^{-6} per MPa	Ultimate creep at stress-strength ratio of 30 per cent 10^{-6}
14	999	933
28	114	1067
42	78	1100
56	57	1067

Figure 8.15. hows the specific creep as a function of water/cement ratio.

Influence of Age: Age at which a concrete members is loaded will have a predominant effect on the magnitude of creep. This can be easily understood from the fact that the quality of gel improves with time. Such gel creeps less, whereas a young gel under load being not so stronger creeps more. What is said above is not a very accurate statement because of the fact that the moisture content of the concrete being different at different age, also influences the magnitude of creep.

Effects of Creep: The magnitude of creep is dependent on many factors, the main factors being time and leval of stress. In reinforced concrete beams, creep increases the deflection with time and may be a critical consideration in design.

In reinforced concrete columns, creep property of concrete is useful. Under load immediately elastic deformation takes place. Concrete creeps and deforms. It can not deform independent of steel reinforcement. There will be gradual transfer of stress from concrete to steel. The extra load in the steel is required to be shared by concrete and this situation results



in employment and development of full strength of both the materials. However, in eccentrically loaded columns, creep increases the deflection and can load to buckling.

In case of statically indeterminate structures and column and beam junctions creep may relieve the stress concentration induced by shrinkage, temperatures changes or movement of support. Creep property of concrete will be useful in all concrete structures to reduce the internal stresses due to non-uniform load or restrained shrinkage.

***In mass concrete structures such as dams,** on account of differential temperature conditions at the interior and surface, creep is harmful and by itself may be a cause of cracking in the interior of dams. Therefore, all precautions and steps must be taken to see that increase in temperature does not take place in the interior of mass concrete structure.*

Loss of prestress due to creep of concrete in prestressed concrete structure is well known and provision is made for the loss of prestress in the design of such structures.

Shrinkage

It has been indicated in the earlier chapter that concrete is subjected to changes in volume either autogenous or induced. Volume change is one of the most detrimental properties of concrete, which affects the long-term strength and durability. To the practical engineer, the aspect of volume change in concrete is important from the point of view that it causes unsightly cracks in concrete. We have discussed elsewhere the effect of volume change due to thermal properties of aggregate and concrete, due to alkali/aggregate reaction, due to sulphate action etc. Presently we shall discuss the volume change on account of inherenet properties of concrete "shrinkage".

One of the most objectionable defects in concrete is the presence of cracks, particularly in floors and pavements. One of the important factors that contribute to the cracks in floors and pavements is that due to shrinkage. It is difficult to make concrete which does not shrink and crack. It is only a question of magnitude. Now the question is how to reduce the *shrinkage and shrinkage cracks in concrete structures. As shrinkage is an inherent property of concrete it demands greater understanding of the various properties of concrete, which influence its shrinkage characteristics. It is only when the mechanism of all kinds of shrinkage and the factors affecting the shrinkage are understood, an engineer will be in a better position to control and limit the shrinkage in the body of concrete.*

The term shrinkage is loosely used to describe the various aspects of volume changes in concrete due to loss of moisture at different stages due to different reasons. To understand this aspect more closely, shrinkage can be classified in the following way:

(a) Plastic Shrinkage ; *(b) Drying Shrinkage;*

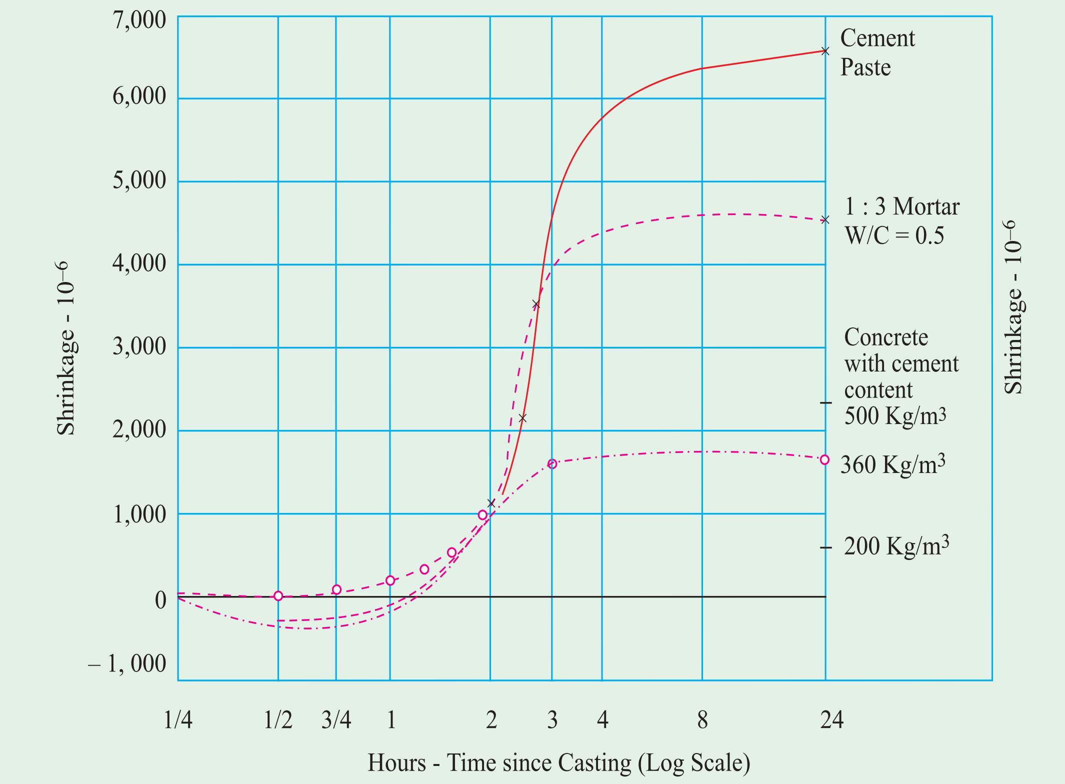
(c) Autogeneous Shrinkage; *(d) Carbonation Shrinkage.*

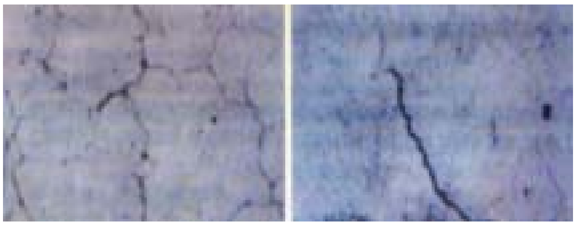
Plastic Shrinkage

Shrinkage of this type manifests itself soon after the concrete is placed in the forms while the concrete is still in the plastic state. Loss of water by evaporation from the surface of concrete or by the absorption by aggregate or subgrade, is believed to be the reasons of plastic shrinkage. The loss of water results in the reduction of volume. The aggregate particles or the reinforcement comes in the way of subsidence due to which cracks may appear at the surface or internally around the aggregate or reinforcement.

In case of floors and pavements where the surface area exposed to drying is large as compared to depth, when this large surface is exposed to hot sun and drying wind, the surface of concrete dries very fast which results in plastic shrinkage.

Sometimes even if the concrete is not subjected to severe drying, but poorly made with a high water/cement ratio, large quantity of water bleeds and accumulates at the surface.



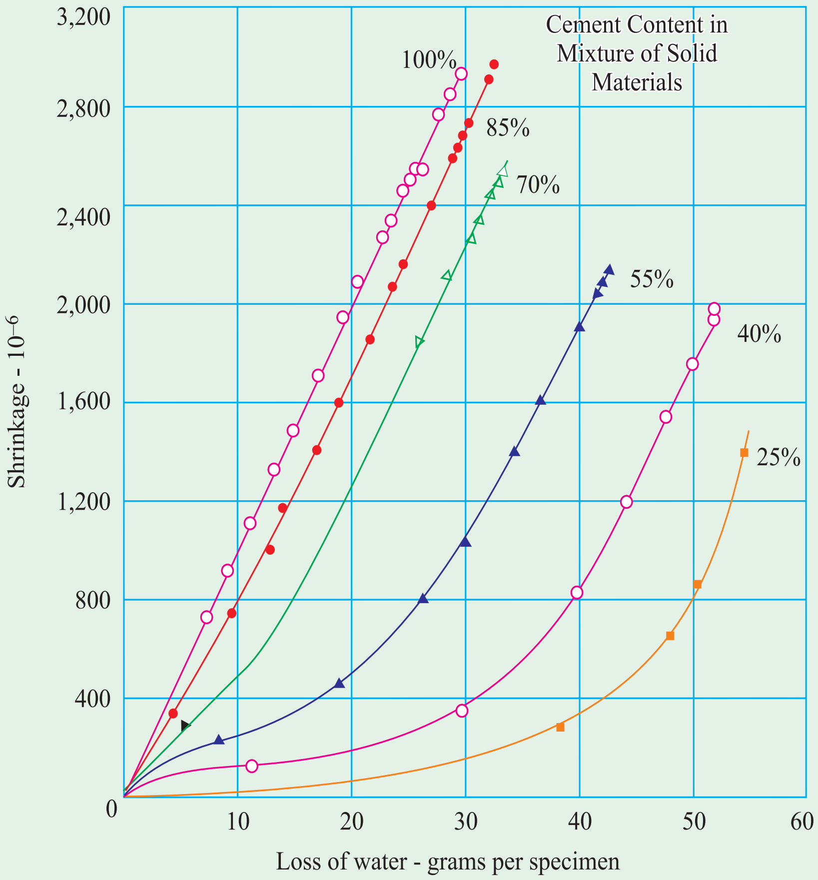


Typical Plastic Shrinkage cracks due to rapid evaporation of water from hot sun and drying wind.

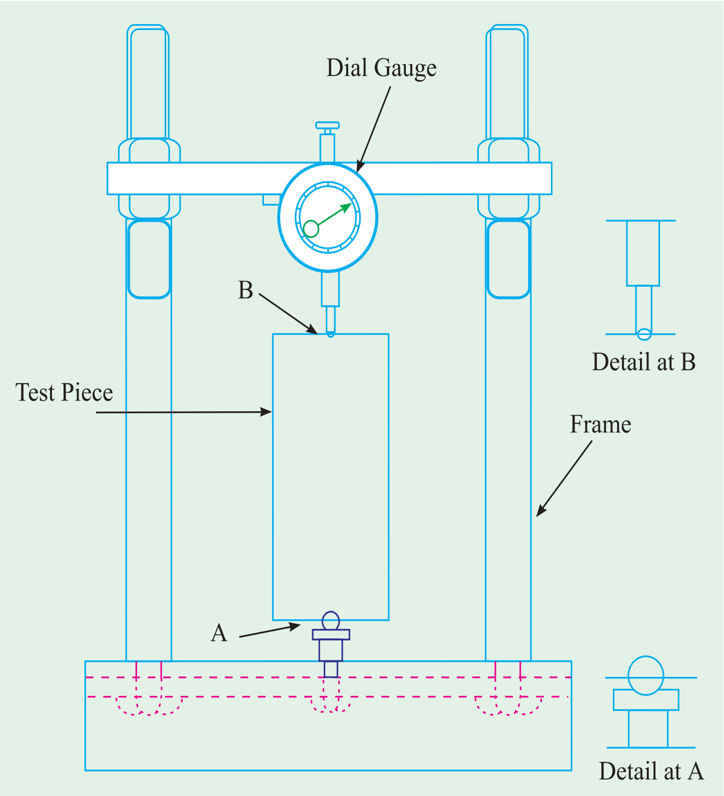
When this water at the surface dries out, the surface concrete collapses causing cracks.

Plastic concrete is sometimes subjected to unintended vibration or yielding of formwork support which again causes plastic shrinkage cracks as the concrete at this stage has not developed enough strength. From the above it can be inferred that high water/cement ratio, badly proportioned concrete, rapid drying, greater bleeding, unintended vibration etc., are some of the reasons for plastic shrinkage. It can also be further added that richer concrete undergoes greater plastic shrinkage. Figure 8.16 shows the influence of cement content on plastic shrinkage.[8.5]

Plastic shrinkage can be reduced mainly by preventing the rapid loss of water from surface. This can be done by covering the surface with polyethylene sheeting immediately on finishing operation; by monomolecular coatings by fog spray that keeps the surface moist; or by working at night. An effective method of removing plastic shrinkage cracks is to revibrate the concrete in a controlled manner. Use of small quantity of aluminium power is also suggested to offset the effect of plastic shrinkage. Similarly, expansive cement or shrinkage

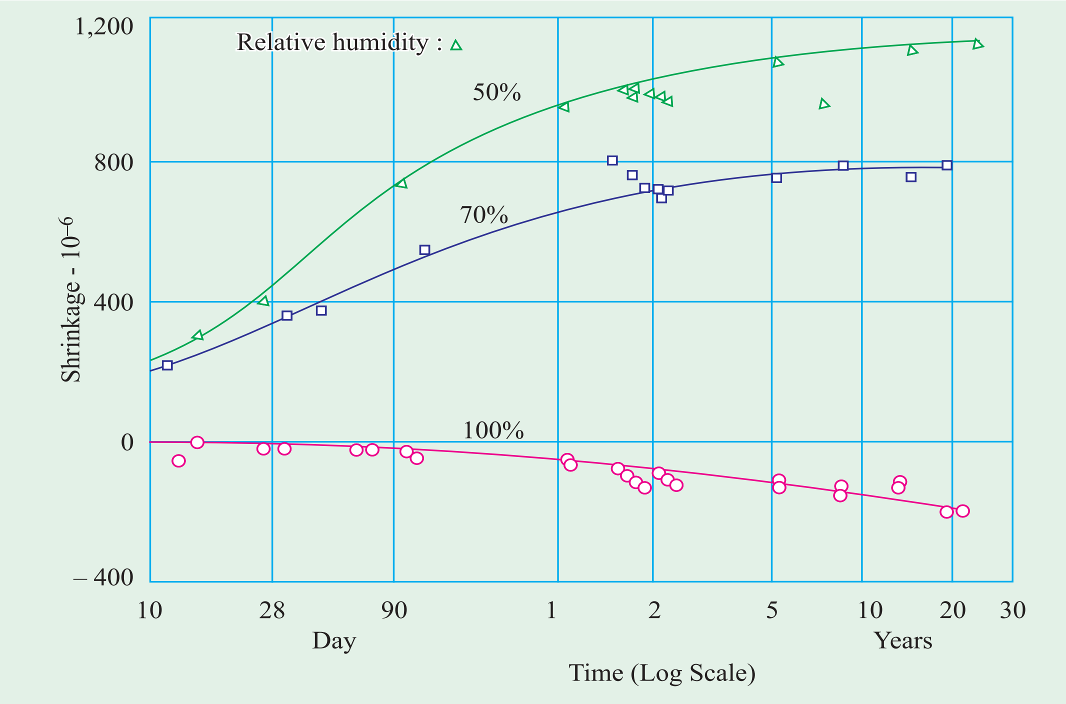


compensating cement also can be used for controlling the shrinkage during the setting of concrete. The principal property of such cement is that the expansion induced in the plastic concrete will almost offset the normal shrinkage due to loss of moisture. Under correct usage, the distance between the joints can sometimes be tripled without increasing the level of shrinkage cracking. Further, use of unneeded high slump concrete, over sanded mix, higher air entraining should be discouraged in order to reduce the higher plastic shrinkage.



Drying Shrinkage

Just as the hydration of cement is an ever lasting process, the drying shrinkage is also an ever lasting process when



concrete is subjected to drying conditions. The drying shrinkage of concrete is analogous to the mechanism of drying of timber specimen. The loss of free water contained in hardened concrete, does not result in any appreciable dimension change. It is the loss of water held in gel pores that causes the change in the volume. Figure 8.17 shows the relationship between loss of moisture and shrinkage. Under drying conditions, the gel water is lost progressively over a long time, as long as the concrete is kept in drying conditions. It is theoretically estimated that the total linear change due to long time drying shrinkage could be of the order of 10,000 x 10^{-6}. But values upto 4,000 x 10^{-6} have been actually observed. Figure 8.18 shows the typical apparatus for measuring shrinkage.

Cement paste shrinks more than mortar and mortar shrinks more than concrete. Concrete made with smaller size aggregate shrinks more than concrete made with bigger size aggregate. The magnitude of drying shrinkage is also a function of the fineness of gel. The finer the gel the more is the shrinkage. It has been pointed out earlier that the high pressure steam cured concrete with low specific surface of gel, shrinks much less than that of normally cured cement gel.

Factors Affecting Shrinkage

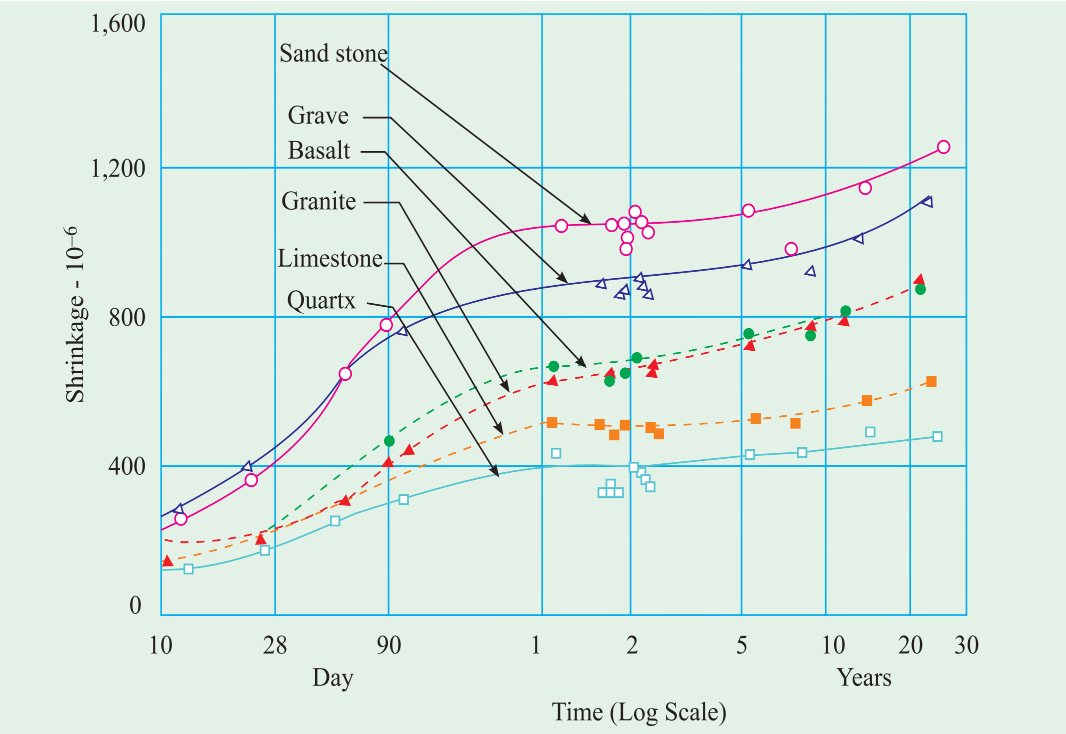
One of the most important factors that affects shrinkage is the drying condition or in other words, the relative humidity of the atmoshphere at which the concrete specimen is kept. If the concrete is placed in 100 per cent relative humidity for any length of time, there will not be any shrinkage, instead there will be a slight swelling. The typical relationship between shrinkage and time for which concrete is stored at different relative humidities is shown in Figure 8.19. The graph shows that the magnitude of shrinkage increases with time and also with the reduction of relative humidity. The rate of shrinkage decreases rapidly with time. It is observed that 14 to 34 per cent of the 20 year shrinkage occurs in 2 weeks, 40 to 80 per cent of the 20 year shrinkage occurs in 3 months and 66 to 85 per cent of the 20 year shrinkage occurs in one year.

Another important factor which influences the magnitude of shrinkage is water/cement ratio of the concrete. As mentioned earlier, the richness of the concrete also has a significant influence on shrinkage. Table 8.3 shows the typical values of shrinkage of mortar and concrete specimens, for different aggregate/cement ratio, and water/cement ratio.

Table 8.3. Typical Values of Shrinkage of Mortar and Concrete Specimens, 125 mm square in cross-section; Stored at a Relative Humidity of 50 per cent and 21°C.[8.8]

Aggregate/cement ratio	Shrinkage after six months (10^{6}) for water/cement ratio of			
	0.4	0.5	0.6	0.7
3	800	1200	–	–
4	550	850	1,050	
5	400	600	750	850
6	300	400	550	650
7	200	300	400	500

Aggregate plays an important role in the shrinkage properties of concrete. The quantum of an aggregate, its size, and its modulus of elasticity influence the magnitude of drying



shrinkage. The grading of aggregate by itself may not directly make any significant influence. But since it affects the quantum of paste and water/cement ratio, it definitely influences the drying shrinkage indirectly. The aggregate particles restrain the shrinkage of the paste. The harder aggregate does not shrink in unison with the shrinking of the paste whereby it results in higher shrinkage stresses, but low magnitude of total shrinkage. But a softer aggregate yields to the shrinkage stresses of the paste and thereby experiences lower magnitude of shrinkage stresses within the body, but greater magnitude of total shrinkage.

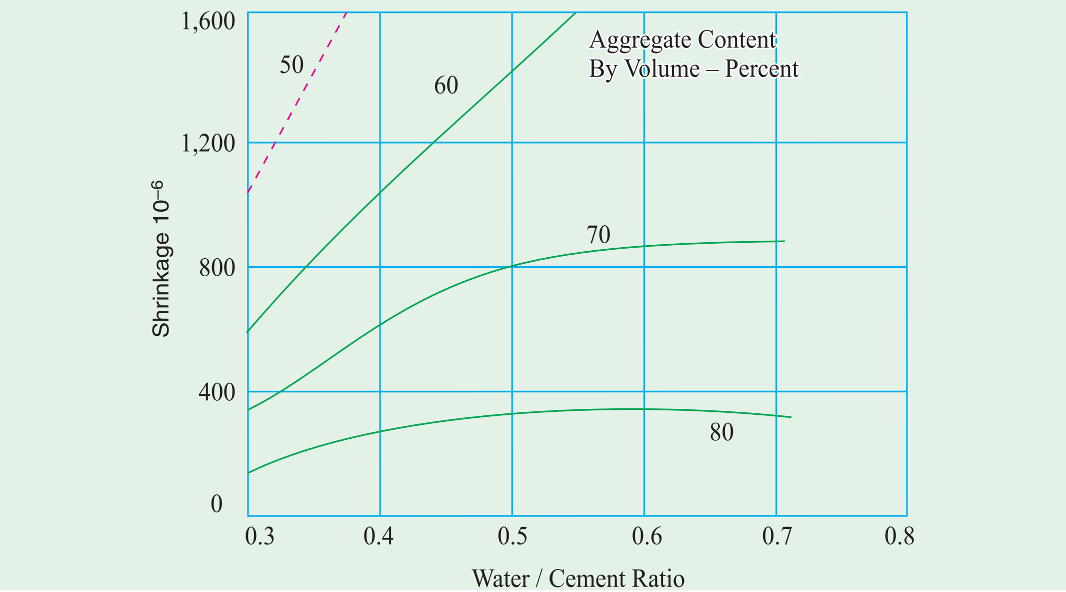


Figure 8.20 shows the typical values of shrinkage of concrete made with different kinds of aggregate. It can be seen from the sketch that a harder aggregate with higher modulus of elasticity like quartz shrinks much less than softer aggregates such as sandstone. It is to be also noted that internal stress and the resultant micro cracks will also be more in case of quartz than that of the sandstone on account of shrinkage stress. The light-weight aggregate usually leads to higher shrinkage, largely because such aggregate having lower modulus of elasticity offers lesser restraint to the potential shrinkage of the cement paste.

The volume fraction of aggregate will have some influence on the total shrinkage. The ratio of shrinkage of concrete S_c to shrinkage of neat paste S_p depends on the aggregate content in the concrete, a. This can be written as

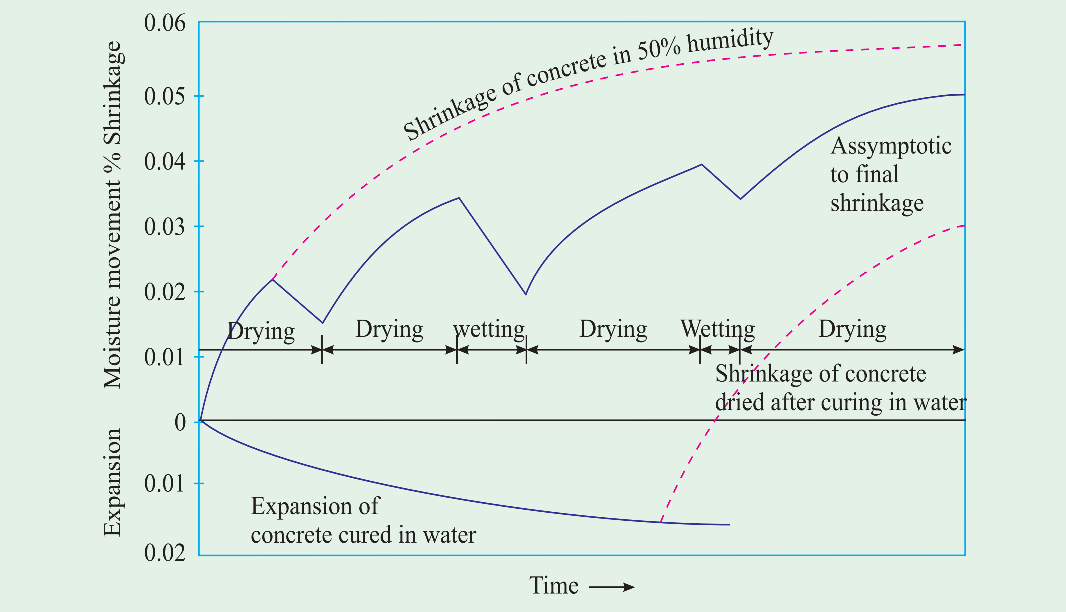
$$S_c = S_p (1-a)^n$$

Experimental values of 'n' vary between 1.2 and 1.7. Figure 8.21 also shows the influence of water/cement ratio and aggregate content on shrinkage.

It is to be viewed that the drying shrinkage is one of the most detrimental properties of concrete. From the mechanism of shrinkage it can be seen that the long term drying shrinkage is an inherent property of concrete.

At best, by taking proper precautions the magnitude of shrinkage can only be reduced, but cannot be eliminated. The restraining effect of aggregate and reinforcement causes high internal stresses and induces internal micro cracks which not only impairs the structural integrity and strength but also reduces the durability of concrete. Another aspect to be seen with respect to the drying shrinkage is that moisture loss takes place at the surface of the member, which may not be compensated in the same rate by the movement of moisture from interior to the surface. As a result, moisture gradient is set up in a concrete specimen. The moisture gradient induces differential stresses, which again induces cracks.

As the drying takes place at the surface of the concrete, the magnitude of shrinkage varies considerably with the size and thickness of the specimen. Investigations have been carried out to find out the influence of the size of specimen on shrinkage. It is observed that



shrinkage decreases with an increase in the size of the specimen. But above some value, the size effect is no longer apparent.

It is pertinent at this point to bring out that the concrete or cement product undergoes long term drying shrinkage in varying magnitude depending upon the various factors mentioned in the proceeding paragraphs. The effect of this shrinkage is to cause cracks in the concrete. Ordinary Portland cement does not show good extensibility (the property to withstand greater, volume change without being cracked). In this respect low heat cement or Portland pozzolana cement will have higher extensibility. It may not be out of place to point out that addition of a certain quantity of lime will improve the extensibility of ordinary cement concrete. The superiority of lime mortar for internal plaster over cement mortar is from the point of view of the superior extensibility of lime mortar over cement mortar by about 7 times. A continuous surface, like plaster on the wall, undergoes tremendous change in volume, and as such cement mortar having low extensibility, is not able to withstand the volume change without cracking, where lime mortar or gauged mortar having higher extensibility gives better performance.

Moisture Movement

Concrete shrinks when allowed to dry in air at a lower relative humidity and it swells when kept at 100 per cent relative humidity or when placed in water. Just as drying shrinkage is an ever continuing process, swelling, when continuously placed in water is also an ever continuing process. If a concrete sample subjected to drying condition, at some stage, is subjected to wetting condition, it starts swelling. It is interesting to note that all the initial drying shrinkage is not recovered even after prolonged storage in water which shows that the phenomenon of drying shrinkage is not a fully reversible one. For the usual range of concrete, the irreversible part of shrinkage, represents between 0.3 and 0.6 of the drying shrinkage, the lower value being more common. Just as the drying shrinkage is due to loss of adsorbed water around gel particles, swelling is due to the adsorption of water by the cement gel. The water molecules act against the cohesive force and tend to force the gel particles further apart as a result of which swelling takes place. In addition, the ingress of water decreases the surface tension of the gel.

The property of swelling when placed in wet condition, and shrinking when placed in drying condition is referred as moisture movement in concrete. Figure 8.22 shows the typical moisture movement of 1:1 cement mortar mix, stored alternatively in water and dried in air to 50 per cent relative humidity. The moisture movement in concrete induces alternatively compressive stress and tensile stress which may cause fatigue in concrete which reduces the durability of concrete owing to reversal of stresses.

Autogeneous Shrinkage

In a conservative system i.e. where no moisture movement to or from the paste is permitted, when temperature is constant some shrinkage may occur. The shrinkage of such a conservative system is known as a autogeneous shrinkage.

Autogeneous shrinkage is of minor importance and is not applicable in practice to many situations except that of mass of concrete in the interior of a concrete dam. The magnitude of autogeneous shrinkage is in the order of about 100×10^{-6}.

Carbonation Shrinkage

Carbonation shrinkage is a phenomenon very recently recognised. Carbon dioxide present in the atmoshphere reacts in the presence of water with hydrated cement. Calcium *hydroxide [$Ca(OH)_2$] gets converted to calcium carbonate and also some other cement compounds are decomposed. Such a complete decomposition of calcium compound in hydrated cement is chemically possible even at the low pressure of carbon dioxide in normal atmoshphere. Carbonation penetrates beyond the exposed surface of concrete only very slowly.*

The rate of penetration of carbon dioxide depends also on the moisture content of the concrete and the relative humidity of the ambient medium. Carbonation is accompanied by an increase in weight of the concrete and by shrinkage. Carbonation shrinkage is probably caused by the dissolution of crystals of calcium hydroxide and deposition of calcium carbonate in its place. As the new product is less in volume than the product replaced, shrinkage takes place.

Carbonation of concrete also results in increased strength and reduced permeability, possibly because water released by carbonation promotes the process of hydration and also calcium carbonate reduces the voids within the cement paste. As the magnitude of carbonation shrinkage is very small when compared to long term drying shrinkage, this aspect is not of much significance. But carbonation reduces the alkalinity of concrete which gives a protective coating to the reinforcement against rusting. If depth of carbonation reaches upto steel reinforcements, the steel becomes liable for corrosion.

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