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Volume Change and Creep of Concrete

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Please note

The resistance to deformation that makes concrete a useful material means also that volume changes of the concrete itself can have important implications in use. Any potential growth or shrinkage may lead to complications, externally because of structural interaction with other components or internally when the concrete is reinforced. There may even be distress if either the cement paste or the aggregate changes dimension, with tensile stresses set up in one component and compressive stresses in the other. Cracks may be produced when the relatively low tensile strength of the concrete or its constituent materials is exceeded.

Cracking not only impairs the ability of a structure to carry its design load but may also affect its durability and damage its appearance. In addition, shrinkage and creep may increase deflections in one member of a structure, adversely affecting the stability of the whole. These factors have to be considered in design. Volume change of concrete is not usually associated with changes that occur before the hardened state is attained. Quality and durability, on the other hand, are dependent on what occurs from the time the concrete mix has been placed in the mold.

Settlement and Bleeding

Concrete is said to be in a plastic state before it begins to set. The aggregate is dispersed by the cement paste and the particles in the paste are dispersed in the water. After placing, there is a period of settlement when the particles come closer together; most of this settlement usually occurs within an hour or so of placement. Total volume change may, in extreme cases, amount to 1 per cent or more, but it is not of great significance because the concrete is in a plastic or semiplastic state and no appreciable stresses can result from these changes. During settlement, water often appears at the surface, having exuded from the plastic mass. This phenomenon is called bleeding.

Accumulation of water at the top of a mass of concrete is often undesirable; for example, when concrete is placed continuously in a deep form, the upper part can gain progressively more water as the filling of the form progresses, leading to relatively poor quality at the top. On the other hand, the accumulation of some water at the surface is not always undesirable because surface water is required to prevent plastic shrinkage and to lubricate the tools used for finishing the surface. Again, an excess of surface water may lead to a thin layer of slurry on the finished surface and a weak susceptible layer on the surface of the concrete. Care must be taken that finishing does not begin before the bleeding period is over.

Settlement may give rise to structural flaws. A layer of water may be left under horizontal reinforcing bars so that half the area of contact between the steel and concrete is lost. This problem can be eliminated by proper vibration or revibration of the plastic concrete, care being taken not to touch reinforcing. It must not be overlooked, however, that settlement and bleeding do result in a reduction of water content. If not offset by one of the undesirable features discussed, the effect is beneficial to strength, permeability and volume stability.

Plastic Shrinkage

When the evaporation rate exceeds the rate of bleeding and the free settlement period is ended, a hydrostatic tension begins to develop throughout the mass owing to the formation of menisci at the water surfaces in the capillaries. This results in vertical as well as lateral compressive forces and may be manifested in a slab by pattern cracking. It is called plastic shrinkage cracking. Remedial measures may involve sun shades and windbreaks, application of water sprays or application of a curing compound to arrest evaporation.

Nature of Hydrated Portland Cement and Mechanism of Volume Change

Following hydration and hardening, cement consists of a mixture of several compounds, all chemically combined with water in different ways. The compound that has the greatest influence on the characteristics of hydrated cement, including shrinkage, is calcium silicate, which has a large internal surface area of 25 to 50 thousand square yards per pound. This internal surface is composed of the walls of the tiny pores and fissures within the physical dimensions of the specimen. (It is the character of this surface that makes hydrated cement an effective cementing agent and provides the versatility of concrete in forming bodies of high strength and almost any desired shape. When surfaces are very close to each other there is a mutual gravitation-like attraction that forms a strong "weld." When the internal surface area is high the many strong welds develop the strength and rigidity of the body.)

Thus concrete is not a solid inert mass but a vast number of small pores or capillaries that in total can account for up to 50 per cent of the volume of the concrete. During curing the pores and capillaries are usually full of water and no stresses exist. As drying takes place, three mechanisms cause shrinkage:

1. The unstable nature of newly-formed calcium silicate hydrate results in shrinkage as drying occurs; the exact nature of this mechanism is not clearly understood but it is permanent and irreversible;
2. Compressive stresses are set up in the concrete because of the development of menisci in the capillaries as drying progresses;
3. Energy changes occur at the surface of calcium silicate as the water evaporates.

These mechanisms (phenomena) acting separately or in combination cause initial drying shrinkage of the concrete. Part of it, 30 per cent or more, is irreversible.

Autogenous Volume Changes and Expansive Cements

Before volume changes resulting from drying or wetting of hardened concrete are discussed, autogenous volume changes should be mentioned because they occur where little or no change in total moisture content is possible and are of particular importance in the interior of mass concrete. Two opposing effects can be produced. As reaction between water and the unhydrated cement proceeds, the actual volume of the solid increases. This causes stresses through the set structure and results in expansion. At later ages, the water available for the reaction will decrease, resulting in self-desiccation of the cement paste and a shrinkage ranging from 0.001 to more than 0.015 per cent.

The increase in volume of some constituents during their formation has been used as the basis for developing expansive cements. Some, specially prepared, undergo relatively large expansions at early age so that if used in concrete that is restrained they develop compressive stresses. Later, when drying occurs, the resulting shrinkage that would have developed is partly or completely offset, and compressive stresses no longer exist in the concrete.

Volume Changes due to Moisture Changes

Although the mechanism of volume change that occurs during moisture change is not fully understood, much has been learned to provide useful information for engineering purposes. When concrete is dried, the first water to be removed causes no change in volume. This is considered to be free water held in rather large "pores." With continued drying, shrinkage becomes quite large and at equilibrium in 50 per cent RH values in excess of 0.10 per cent have been recorded for some concretes. The above behaviour is somewhat similar to that of wood (in a qualitative manner). Shrinkage values for neat cement paste have been observed in excess of 0.40 per cent; the difference of this value from that of concrete is due to various restraints. A large portion of concrete is made up of relatively inert aggregate (from 3 to 7 times the weight of cement) and this, together with reinforcement, reduces shrinkage. In addition to internal restraints, some restraint arises from non-uniform shrinkage within the concrete member itself. Moisture loss takes place at the surface so that a moisture gradient is established. The resultant differential shrinkage is associated with internal stresses, tensile near the surface and compressive in the core, and may result in warping or cracking.

If concrete that has been allowed to dry in air at 50 per cent RH is subsequently placed in water, it will swell. Not all initial shrinkage obtained on drying is recovered, however, even after prolonged storage. For the usual range of concretes the irreversible part of shrinkage is about 30 to 60 per cent of total drying shrinkage, the lower value being more common. Because shrinkage has such an influence on the performance of concrete structures much work has been carried out to obtain information on the factors affecting it.

Effect of Cement and Water Contents on Shrinkage

Water content is probably the largest single factor influencing the shrinkage of paste and concrete. Typical shrinkage values for concrete specimens with a 5 to 1 aggregate-cement ratio are 0.04, 0.06, 0.075 and 0.085 per cent for water-cement ratios of 0.4, 0.5, 0.6 and 0.7, respectively. One of the reasons is that the density and composition of calcium silicate formed at different water-cement ratios may be slightly different. In general, a higher cement content increases the shrinkage of concrete; the relative shrinkages of neat paste, mortar and concrete may be of the order of about 5, 2 and 1. For given materials, however, and a uniform water content, the shrinkage of concrete varies little for a wide range of cement contents; a richer mix will have a lower water-cement ratio and these factors offset each other.

Properties of Cement

Fineness of cement seems to be a factor in shrinkage and particles coarser than No. 200 sieve, which react with water very slowly, have a restraining effect similar to that of aggregate. Thus, high-early-strength cement, which is finely ground, shrinks about 10 per cent more than normal cement. Low-heat and portland-pozzolan cements shrink a further 20 and 35 per cent, respectively. This is believed to be caused by larger quantities of calcium silicate, the shrinking component, present in them.

Type and Gradation of Aggregate

As stated previously, the drying shrinkage of concrete is a fraction of that of neat cement because the aggregate particles not only dilute the paste but reinforce it against contraction. It has been shown that when readily compressible aggregate is used concrete will shrink as much as neat cement, and that expanded shale leads to shrinkage one-third more than that of ordinary aggregate. Steel aggregate on the other hand, leads to shrinkage one-third less than that of ordinary concrete. In general terms the elastic properties of aggregate determine the degree of restraint offered. The size and grading of aggregate do not, by themselves, influence the magnitude of shrinkage, but an aggregate incorporating larger sizes permits the use of a mix with less cement and hence a lower shrinkage. Increasing the maximum aggregate size and thereby the aggregate content by 20 per cent of the total volume of the concrete will ensure a substantial decrease in shrinkage.

The shrinkage of aggregates themselves may be of considerable importance in determining the shrinkage of concrete; some fine-grained sandstones, slate, basalt, trap rock and aggregates containing clay show large shrinkage. In general, concretes low in shrinkage often contain quartz, limestone, granite or feldspar. Various harmful effects of abnormal shrinkage of concretes, caused by the aggregate and observed in actual structures, have included excessive cracking, large deflection of reinforced beams and slabs and some spalling. It is essential that any new source of aggregate be tested to ascertain whether its use in concrete will cause excessive shrinkage to develop. Any shrinkage in excess of 0.08 per cent is taken to indicate an undesirable aggregate.

Effect of Admixtures

As can be predicted from the effect of water-cement ratio on shrinkage, admixtures that increase the water requirement of concrete increase shrinkage and those that decrease the water requirement decrease it. Calcium chloride in the amount often added as an accelerator - 2 per cent by weight of the amount of cement - may increase drying shrinkage by as much as 50 per cent.

The over-all effect of the use of air entrained concrete is not to increase shrinkage. Some admixtures, if used in somewhat larger than normal doses, do increase shrinkage greatly and care must be exercised in the proportioning.

Rate of Drying

The size of the specimen and conditions of exposure are important in assessing the relevance of the shrinkage problem. Drying of ordinary concrete exposed to an environment maintained at 50 per cent RH will affect moisture content to a depth of 3 in. in one month. Continued exposure to these conditions would be a significant factor in small concrete members but would be of no importance in massive elements.

Carbonation Shrinkage

Another mechanism that will result in shrinkage of concrete is the reaction between carbon dioxide and hydrated cement. Maximum shrinkage occurs when the concrete is at equilibrium in a 50 per cent RH environment. This shrinkage combined with drying shrinkage results in excessive crazing of exposed surfaces such as concrete floors when CO_2 levels are high, a condition often found on winter construction projects.

Carbonation during the curing of concrete products is sometimes used to encourage shrinkage and thus reduce shrinkage stresses when these units are incorporated into a structure. Carbonation also reduces permeability, presumably due to deposition of the reaction products in the pores and capillaries.

Creep of Concrete

Creep of concrete resulting from the action of a sustained stress is a gradual increase in strain with time; it can be of the same order of magnitude as drying shrinkage. As defined, creep does not include any immediate elastic strains caused by loading or any shrinkage or swelling caused by moisture changes. When a concrete structural element is dried under load the creep that occurs is one to two times as large as it would be under constant moisture conditions. Adding normal drying shrinkage to this and considering the fact that creep can be several times as large as the elastic strain on loading, it may be seen that these factors can cause considerable deflection and that they are of great importance in structural mechanics.

If a sustained load is removed, the strain decreases immediately by an amount equal to the elastic strain at the given age; this is generally lower than the elastic strain on loading since the elastic modulus has increased in the intervening period. This instantaneous recovery is followed by a gradual decrease in strain, called creep recovery. This recovery is not complete because creep is not simply a reversible phenomenon.

It is now believed that the major portion of creep is due to removal of water from between the sheets of a calcium silicate crystallite and to a possible rearrangement of bonds between the surfaces of the individual crystallites.

Factors Influencing Creep

Concrete that exhibits high shrinkage generally also shows a high creep, but how the two phenomena are connected is still not understood. Evidence suggests that they are closely related. When hydrated cement is completely dried, little or no creep occurs; for a given concrete the lower the relative humidity, the higher the creep.

Strength of concrete has a considerable influence on creep and within a wide range creep is inversely proportional to the strength of concrete at the time of application of load. From this it follows that creep is closely related to the water-cement ratio. There is no doubt also that the modulus of elasticity of aggregate controls the amount of creep that can be realized and concretes made with different aggregates exhibit creep of varying magnitudes.

Experiments have shown that creep continues for a very long time; detectable changes have been found after as long as 30 years. The rate decreases continuously, however, and it is generally assumed that creep tends to a limiting value. It has been estimated that 75 per cent of 20-year creep occurs during the first year.

Effects of Creep

Creep of plain concrete does not by itself affect strength, although under very high stresses creep hastens the approach of the limiting strain at which failure takes place. The influence of creep on the ultimate strength of a simply supported, reinforced concrete beam subjected to a sustained load is insignificant, but deflection increases considerably and may in many cases be a critical consideration in design. Another instance of the adverse effects of creep is its influence on the stability of the structure through increase in deformation and consequent transfer of load to other components. Thus, even when creep does not affect the ultimate strength of the component in which it takes place, its effect may be extremely serious as far as the performance of the structure as a whole is concerned.

The loss of prestress due to creep is well known and accounted for the failure of all early attempts at prestressing. Only with the introduction of high tensile steel did prestressing become a successful operation. The effects of creep may thus be harmful. On the whole, however, creep unlike shrinkage is beneficial in relieving stress concentrations and has contributed to the success of concrete as a structural material.

Concluding Comment

Volume change and creep of materials can be important considerations in design or construction, and can best be dealt with through improved understanding of the factors causing such behaviour. Concrete, like many other materials used in building, has a complex physical and chemical structure that is not yet completely understood. It is through appreciation of what is known and of the possible interactions involved that improved design and practice will develop.