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EFFECTS OF CONCRETE CONSTITUENTS, ENVIRONMENT, AND STRESS ON CREEP AND SHRINKAGE OF CONCRETE

Reported by ACI Committee 209

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This paper discusses the current state of knowledge in the area of time-dependent deformation of plain concrete. The paper is divided into three broad areas: effects of concrete constituents, effects of environment, and effects of stress.

Under the general heading of effects of concrete constituents the relation between creep and shrinkage and the structure of the gel, moisture movement, aggregate properties, internal microcracking and admixtures are discussed. Included in the second section, the effects of environment, are the subjects of temperature, humidity, maturity and time. The final section, effects of stress, considers type of stress, variation of stress, magnitude of stress and duration of loading.

Keywords: absorption; admixtures; age; aggregates; cement pastes; concretes; cracking (fracturing); creep properties; environments; gels; microcracking; modulus of elasticity; moisture content; plain concrete; reviews; shrinkage; stresses; temperature; water-cement ratio.

☐ In a recent symposium concerned with the European "Unified Code for Structural Concrete" Dr. S. C. C. Bate suggested that "The limit state of excess

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*Member of Subcommittee 1 which prepared this report.

ACI Committee 209 was organized to review critically available data on the factors affecting the magnitude of creep and volume changes of concrete; suggest and recommend topics of needed research; stimulate the preparation of papers; and interpret available information in a form that is useful to the designer.

The mission of Subcommittee 1 whose members wrote this paper, was to report on the current state of knowledge of time-dependent plain concrete.

deflection will form one of the three main criteria of serviceability of structures (the others being collapse and local damage)." In order to control excessive deflections the design engineer must first be able to reasonably predict the short time and long time deformational behavior of a given structure. This problem has been the subject of about 1500 research papers published since the turn of the century. In general, all of these efforts can be divided into two categories:

1. Attempts to understand the basic mechanisms and causes of creep and shrinkage of concrete.
2. Attempts to develop empirical design methods (based on the best available scientific information) that will enable the designer to control the deflection of structures, within specified limits of uncertainty.

In 1964 The American Concrete Institute released Special Publication No. 9, in which the available information on the subject of Concrete Creep and Shrinkage was summarized. Since that time the proliferation of publications in both of the aforementioned areas has continued. The paper that follows may be considered the second in what the authors hope will not be a long series of ACI Committee 209 papers concerning the state of the art of one of the major unsolved problems facing the civil engineer, the causes of creep and shrinkage of plain concrete.

As the title suggests, the paper will be divided into three broad areas. The effects of concrete constituents, including gel structure, water-cement aggregate interactions and admixtures, the effects of environment, broadly defined to include temperature, humidity, maturity and time; and the effects of stress, specifically applied stress.

THE EFFECTS OF CONCRETE CONSTITUENTS

EFFECT OF WATER-CEMENT-HYDRATE INTERACTION

General – The structure of cement paste can be described in terms of the following constituents: unhydrated cement; solid products of hydration including crystals, crystallites; and void space containing both strongly adsorbed and capillary water and air.[1,2,3]

The porous hydrate known as the gel comprising the solid products of hydration and gel pores has a minimum porosity of about 26 percent, which corresponds to about four times the quantity of water which would form a layer 1 molecule thick on the solid phase. Although dimension changes occur mainly in gel, secondary volume changes which accompany continuing hydration of the cement cannot be ignored in some cases.

Solid phases in the gel – Crystals are defined as those particles, for example calcium hydroxide, which are large enough to be seen with an optical microscope, while crystallites may be defined as smaller particles which are beyond the resolution of the optical microscope. In recent years the structure of crystallites has been deduced from electron diffraction and x-ray diffraction studies but it has not yet been possible to obtain real images of the smallest discrete particles. Both transmission and surface scanning electron microscopes have produced images of assemblies of primary particles or crystallites.

Fig. 1-1 shows a typical surface scanning electron micrograph of calcium silicate hydrate "flowers" growing from a nucleation site on the surface of a portland cement grain.[1] Fig. 1-2 shows a transmission electron micrograph of petal shaped rolled foils of calcium silicate hydrate from ball-milled portland cement ultrasonically dispersed.[1] The second photograph was taken in a transmission electron microscope and the fibrous material comprising the "petals" was identified by electron diffraction as C_3S.

It has been suggested[1] that the strengths of the bonds between primary particles in the "petals" are orders of magnitudes greater than those between "petals" and that the strength of cement paste is determined by the weaker bonds. It is clear that displacements of these structures contribute significant components of strain.

Water – Free water is defined as water located at distances outside the range of surface forces and may, for practical purposes, be assigned the properties of bulk water. It is assumed that such water may be evaporated at 98 percent relative humidity.

Capillary or pore water – defined as water between 1 mm and 30 A from gel surfaces. It is assumed that all such water may be evaporated at 40 to 50 percent relative humidity and may be assigned an average specific volume of 1.02 gm/cc.

Adsorbed water – water that is strongly attracted to the gel at distances between 0 and 30 A from gel surfaces. It may be evaporated over the range 40 to 0 percent relative humidity. It is this type of water that has been described as "load bearing water" by Powers,[3] as "active water" by Mills,[1] and as interlayer water by Feldman and Sereda.[4] It appears that the active nature of such water would influence mainly the dilation and collapse of spaces with the "petal" structure. Its density can be assumed to be about 0.90 cc/gm.

Water of hydration or "non-evaporable" water – that part of the total water which cannot be evaporated at 0 percent relative humidity. It is approximately equal to the water held at 110 C but lost at 1000 C. It can be regarded as part of the solid phase in the gel.

Air – more correctly water vapor, is located in the remaining void space. Even in sealed specimens the volume of vapor filled space increases as hydration proceeds and the accompanying meniscus forces may cause shrinkage.

It will be observed that statements which assign reduced specific volume to adsorbed water imply that such water is in compression. This would seem to follow logically from the fact that adsorbed water molecules are subjected to inward directed forces of adhesion to the solid in keeping with reduction of surface energy in the solid. It should also be noted that spaces separating primary particles of the solid are unlikely to be parallel and therefore the tendency of water molecules to migrate to all vacant sorption sites on one side of a tapering void would be restricted by the repulsive impulses of water molecules subjected to similar forces on the opposite face. The net result would be an increase in the frequency of collisions between molecules as the space between adjacent solid surfaces is diminished. Hence the water may be said to be compressed and this compression would result in alternation of solid-solid binding forces. Thus strain energy would be stored in the solids and this would result in the sides being drawn together upon removal of adsorbed water.

The time dependent deformation of concrete is in part a result of the response of the above components to stimuli which alter the pressure in, and the hygral equilibrium of, the cement paste. Deformations of primary particles in the gel structure are insignificant by comparison with deformations of the gross structure and, since dry concrete does not creep at normal stress levels, it is clear that the primary particles themselves do not creep. It is clear that the bulk of time dependent deformation is related to changes in the interaction of water and cement hydrate.

Free water and part of the capillary water is relative mobile and responds rapidly to pressure changes. These changes do not significantly contribute to long term creep.

Water that is bonded to the hydrophillic solids comprising the gel (adsorbed and the remaining capillary water) responds slowly to mechanical and thermodynamic stimuli. Because of the hydrophillic nature of the gel, adsorbed water will tend to return to its original position upon removal of the mechanical or thermodynamic stimuli causing motion. Such movement may be inhibited by permanent changes in the solid.

Time-dependent deformation and moisture movement[3,5,6,7] – Disturbance of the energy balance resulting from sustained mechanical load results in redistribution of water from areas of higher pressure to areas of lower pressure and/or relative humidity, or to the surrounding atmosphere.

In the early stages of loading the rapid responses of free water results in a minor volume change which is often regarded as stress induced shrinkage. This component of volume change may be recovered upon removal of the sustained load and re-saturation of the concrete.

The water more strongly attracted to the crystal and crystallite surfaces (capillary and adsorbed water) diffuses from its original position very slowly. The gel particles are brought closer together resulting in the major component of the time-dependent deformation of concrete (creep). This deformation takes place rather slowly and probably never completely reduces the adsorbed water layers to zero. Providing that there is no change in internal gel structure and the condition of the water, the associated deformation should be recoverable. However, measurements have shown that a large percentage of this deformation is not recoverable under ordinary circumstances. The origin of this irrecoverable component has been examined in relation to evidence of a permanent change of structure.

Mills[1] has described as "collapse of structure" the mechanism whereby the surfaces of the solids originally containing load bearing adsorbed water are drawn close enough together to form inter-molecular bonds which can be numerous and strong enough to resist penetration of water upon re-saturation and/or removal of load. The suspected collapsed structure of a calcium silicate flower is illustrated in Fig. 1-3. Fig. 1-3B is typical of flower structures in shrinkage specimens, while Fig. 1-3A illustrates the amorphous nature of collapsed structure found in creep specimens. A comparison of the two photographs suggests that sustained load results in a permanent sintering of the crystallites in the flower structure, while shrinkage does not.

The concept of collapse of structure suggests methods of alleviating creep. It is well known that high pressure steam curing reduces the surface area, shrinkage, and creep of the cement gel. Conversion of colloidal to microcrystalline material, which occurs during high pressure steam curing, can be considered collapse of structure of one type. Ishai[8] has shown that mechanically induced collapse of structure before loading materially reduces creep. It might also be possible to reduce the effect of collapse while the specimen is under load, by impregnating the material with a colloidal silicate or polymer which maintains the gel structure in a dilated state while evaporation of water takes place. The effective use of concrete made with low water cement ratios certainly merits investigation.

From the above it can be seen that the main variables associated with cement paste, that effect the creep of concrete, are those variables that depend ultimately on the quantity and equilibrium state of the active water in the system. The quantity of active water depends on the volume concentration of hydrated cement and this depends on the water-cement ratio and degree of hydration. Strength is a measure of both volume concentration of hydrate and volume of active water in a saturated paste. It is therefore not surprising that as an initial engineering approximation this component of creep can be evaluated in terms of the water-cement ratio, the age at time of loading, and the degree of hydration. Fig. 1-4[9,10] illustrates the influence of water cement ratio. Table 1-1[11] shows the relationship between strength and specific creep (creep per psi) and the effect of age at time of loading is illustrated in Fig. 1-5[5] where the creep of three specimen groups, moist cured an equal number of days but loaded at various times after curing, are plotted.

EFFECT OF AGGREGATE—CEMENT PASTE INTERACTION

Effect of aggregate – Since aggregates can be assumed to be volumetrically stable, it is to be expected that creep in concrete subjected to working loads reduces with an increase in the volume proportions of aggregate. Typical results are shown in Fig. 1-6.[12] The data shown in the figure may be represented mathematically by $\log \frac{Cp}{C} = a \log \frac{1}{1-g}$ where Cp is the creep of neat cement paste of the same quality used in the concrete, C is the creep of the concrete, g is the volumetric content of aggregate and a is a function of Poisson's ratio and the moduli of elasticity of the aggregate and paste.

Many investigators have shown that concretes made with different aggregates exhibit widely varying creep strains. Tests by Troxell et al[13] and by Rusch[14] suggest that variations associated with different petrological type of aggregate arise because of differences in elastic moduli of the aggregate. In addition, modulus of elasticity is related to the porosity or water sorption of the aggregate, as shown in Fig. 1-7a.[14] Although aggregates with higher absorptions will tend to remove water from the cement paste, thereby decreasing the creep potential, the decrease is in most cases offset by the lower modulus of elasticity of the aggregate. See Fig. 1-7b.[14]

Other aggregate variables such as grading, maximum size and shape of the aggregate particles have been suggested as factors affecting the creep of concrete. These variables most likely have their main influence in the effect they have on the aggregate content and the interaction of the aggregate paste interface.

Microcracking – Cracking at the aggregate cement paste (or mortar) interface strongly affects the deformational behavior of concrete subjected to both short time and long time loads.[15]

Two types of microcracks exist in the concrete system:

1. Bond or interfacial cracks observed at the aggregate paste interface, and
2. Mortar or paste cracks within the mortar or paste matrix.

Interfacial cracks exist in concrete before it is subjected to external load and are caused by settlement of aggregate, bleeding of the mixing water, and shrinkage stresses induced by the drying process [16] They increase in number, width, and length as the magnitude of the external load is increased. The onset and continued propagation of microcracks in concrete subjected to short time load has been directly related to the nonlinear behavior of the stress strain curve.[14]

The initial cracking under load occurs at the aggregate mortar interface after its unconfined bond strength is exceeded.[17] The cracked interface, if inclined to the axis of the load, continues to carry load through friction. As the load is increased, local cracks start to form through the mortar, at or near existing bond cracks, allowing the aggregate to slide relative to the mortar. As the load is further increased, the local stress in the uncracked portion of the system rises more rapidly than the average stress on the specimen, since the cracked interface can resist no additional load, until the compressive strength of the mortar is exceeded locally, causing the formation of mortar cracks. The continuation of this process leads to ultimate failure of the concrete system.[18]

It has been shown that for sustained loads below 70 percent of the ultimate strength of concrete, creep is accompanied by an increase in bond cracking.[15]

This is demonstrated in Fig. 1-8[15] where crack length is plotted versus strain for short time and long time loaded specimens as well as for unloaded specimens. This increase in cracking results in an increase in time dependent strain, as illustrated in Fig. 1-9[15] where the creep response of specimens in which cracks were induced (prior to the application of the sustained load) are plotted along with the creep response of non preloaded specimens.[15] The higher creep in the non preloaded specimens can be attributed to deformation associated with cracking (aggregate particles sliding relative to the mortar).[8]

Thus, it seems that for a given aggregate and water-cement ratio the effect of aggregate content is two fold. Firstly, as the interface area is increased (overall aggregate content or fineness increased) the incidence of cracking and therefore creep is increased. Secondly, as the aggregate content is increased, the creep is decreased by the addition of inert material. The first effect does not seem to be significant at working stress levels (see Fig. 1-6), but can have a marked effect at stress levels in the mortar cracking range (above .70 f'_c). The dual effect of aggregate content at high stress levels is demonstrated in Fig. 1-10, where the creep response of various concretes with the same water-cement ratio are plotted against volume of hardened cement paste. Fig. 1-10 shows, that up to a critical aggregate content, creep is increased by increasing aggregate cement ratios (the effect of the interface). Beyond the critical aggregate content, creep is decreased by increasing aggregate cement ratios (the effect of replacing cement with aggregate that does not creep).[19]

EFFECT OF ADMIXTURES

The inclusion of admixtures in the section on concrete constituents does not imply that admixtures are considered, by the authors, to be an integral part of all concrete mixes. The subject is placed here for convenience of presentation only. Admixtures which vary the water requirement of the fresh concrete or the rates of setting and hardening influence shrinkage and creep insofar as they change the volume concentrations of hydrate adsorbed water and capillary water. Other admixtures such as fly ash, blast furnace slag and gypsum may also yield hydration products which have important differences of behavior and morphology comparable to those occurring with various C_3A contents. The effects of commonly used admixtures will be discussed in relation to shrinkage and creep.

Shrinkage – It has generally not proved possible to predict the influence of admixtures on shrinkage. Although any admixture which increases the water requirement of a mix can generally be expected to lead to increased shrinkage, the converse is not necessarily true. Notable exceptions are calcium chloride and triethanolamine, both of which are commonly used to offset the retarding action of some water reducing admixtures and both of which invariably lead to increased drying shrinkage.[20] Simple air-entraining agents do not appear to affect shrinkage.[21]

Although it is generally believed that the chemical composition of cement affects shrinkage, the tricalcium aluminate having the most effect,[22] some investigators are of the opposite opinion.[23] Adverse shrinkage characteristics are believed to result from high C_3A contents[22] and a deficiency in calcium sulphate.[24]

The optimum amount of calcium sulphate for minimum shrinkage is believed to be slightly larger than the optimum calcium sulphate content necessary to avoid flash setting.[25] Wide variations of $CaSO_4$ and C_3A contents in commercial cement create special problems in relation to the general evaluation of the effect of additives on shrinkage. Although some attempt[26] has been made to overcome the problem by blending cements from different sources, it still becomes necessary to evaluate the performance of admixtures to specific concrete materials and the context of their use.[27]

Special care is necessary in the interpretation of shrinkage tests on laboratory specimens when additives are evaluated. Since shrinkage depends on moisture loss it is necessary to observe shrinkage as nearly as possible to its terminal value and to record the associated weight change. It is therefore desirable to conduct shrinkage tests for as long as possible, and 56 days is considered the minimum acceptable testing period.[8]

The sequence of the mixing operation also appears to be important as far as the relative rates of reaction of $CaSO_4$ with C_3A and C_3A with the additive are concerned, since these reactions determine the availability of the additive to participate in slower silicate reactions.[24,25,26] Delayed addition of the admixture results in a marked increase in its modifying influence. It appears that a delay of, say, two minutes before the addition of an admixture permits the calcium sulphate time to dissolve and coat the C_3A component of the cement. The coated C_3A is then unable to adsorb any appreciable amount of the admixture which leaves a large amount to modify the silicate hydration reactions. When the admixture is added with the mixing water it is already in the dissolved state and has time to react with, or be adsorbed on, the C_3A before the calcium sulphate has dissolved and is available for reaction with the C_3A. Thus relatively little additive remains available to modify the reaction of the silicates. This action of the C_3A is also the probable reason underlying the increased effectiveness of admixtures on cements with low C_3A vis-a-vis cements with high C_3A contents.

The use of blast furnace slag in portland cement concrete generally causes an increase in shrinkage.[28,20,30,31] Low carbon fly ash, unlike most other pozzolans, reduces shrinkage.[32,33]

Creep – Very little work has been reported concerning the influence of admixtures on the creep of concrete. Two papers[34,35] concerning the influence of water reducing set retarding admixtures on the creep of normal weight and lightweight concrete indicate that a considerable increase in creep can be experienced under certain conditions. It has also been found that blast furnace slag substitution for part of the portland cement increases creep,[29] but that certain types of fly ash reduce creep.[36] The reason for this behavior is not known nor is it known if the increased creep is a function of the particular combinations of admixture, cement and aggregate used for these tests. Tests with the same admixtures and several cements[37] indicate that the chemical composition of the cement has a bearing on the increased creep of a concrete containing either a lignosulphonic acid or hydroxylated carboxilic acid admixture. Some concretes show reduced creep with an admixture but this behavior is perhaps the exception rather than the norm. Certainly there is enough evidence at the present time to indicate that creep tests should precede the use of admixtures in structures in which an increase in the normal creep rates would be a cause for concern.

It seems likely that the presence of an additive modifies the gross morphological structure of cement paste. The hydration products of C_3A and also of C_4AF produced in the presence of lignosulphonic acid are markedly different from those produced in distilled water.[38,39] A similar behavior has not been observed, however, with the silicate compounds but since direct observation of the silicate hydrates is difficult a less pronounced modification in a structure would pass undetected.

The ease with which cement paste loses water on heating appears to be related to the rate of creep of mixes with and without water reducing admixtures. Calcium chloride is found to increase creep substantially under a wide range of test conditions.[40] The simultaneous use of triethanolamine and a lignosulphonic acid increases creep at early ages of loading but not at later ages.

EFFECT OF ENVIRONMENT

General – The effects of ambient temperature and humidity on shrinkage and creep before, during and after loading are important insofar as these factors influence the volume proportions of hydrate, adsorbed and capillary water, and the rate at which moisture diffuses in the concrete and evaporates to the atmosphere.

A concrete unit in service may be subjected simultaneously to: (a) drying (shrinkage) and cooling (contraction); (b) drying (shrinkage) and heating (expansion); (c) wetting (swelling) and cooling (contraction); or (d) wetting (swelling) and heating (expansion).

Curing period before loading – Both temperature and humidity influence the rate of hydration. The extent of hydration in saturated concrete is approximately proportional to the integral of temperature versus time, referred to a datum temperature at which the rate of hydration is negligible (about 11 F).[41] Powers[42] has suggested that hydration stops at about 80 percent relative humidity, but it has been shown that this effect is negligible at a depth of about four in. from a free surface. At very high temperatures (say 180 C) the morphology of the hydration is changed, the surface area is materially reduced, and both creep and shrinkage are of negligible magnitudes compared to concretes cured at room temperature.

Ambient temperature and humidity after loading – Increase in thermal activity of water, accompanying temperature rise, increases the reaction rate of diffusion controlled processes such as creep and shrinkage. According to K. B. Hickey,[43] after six months of continual drying of concrete while under a sustained compressive stress of 800 psi:

1. At an ambient temperature of 290 F and ambient relative humidity (RH) of less than 1 percent, creep is about five times that occurring at 73 F and 50 percent RH;
2. Creep at any age less than six months varies directly with ambient temperature; between 73 F and 180 F the variation is linear; between 180 and 240 F the variation is curvilinear; and

3. At ambient temperatures of 130 F (where RH is 4 percent) or higher (where RH becomes less than 1 percent), creep is very rapid during the first 14 days under sustained load; from 14 days to 180 days under load, the rate is considerably less and the creep approaches a constant value.

C. R. Cruz[44] also found that creep increases as the ambient temperature increases. After being subjected to constant sustained compressive stress of 1800 psi for 5 hr: (1) the creep of concrete in dry air maintained at 1200 F is nearly 33 times that in dry air maintained at 75 F; (2) at 900 F, nearly 15 times that at 75 F; (3) at 600 F, about six times that at 75 F; and (4) at 300 F, about three times that at 75 F. Work by Ross and England[45] also shows that creep of concrete stored in air and under simulated mass curing conditions increases with temperature, the increase being greater in the range 68 to 180 F than for higher temperature up to 280 F. Neville and Nasser[46] have shown that a similar temperature effect is present when the concrete is stored under water. Some of these results are shown graphically in Fig. 1-11.

Timusk and Ghosh[47] showed that creep is increased when cement paste hydrates while under load. The creep component associated with the hydration process diminished logarithmically with the age at loading and was completely eliminated when hydration was halted at various stages of hydration, prior to loading, by cooling the specimens to -11 C. (Fig. 1-12).

According to Mitzel & Klapoc[48]: creep in sealed specimens is about 20 percent less than similar unsealed specimens (values up to about 40 percent have been obtained). It should be noted that in structural members of substantial dimension the rate of moisture diffusion is sufficiently slow so that their behavior approximates that of sealed laboratory specimens.

EFFECT OF STRESS

EFFECT OF TYPE, VARIATION, MAGNITUDE AND DURATION

In the following discussion, creep is defined in its simplest context as the time-dependent strain caused by the application of a sustained stress. In general, uniaxial creep is determined experimentally by subtracting from the total strain at the time of observation, the algebraic sum of the initial strain at the application of stress and the shrinkage of an unstressed specimen between the time of stress application and the time of observation. In the case of torsion, shrinkage strains have no shear component and are, therefore, not subtracted from the time dependent torsional strains.

In the case of torsional or flexural loading, it is convenient to associate creep with sustained torques or moments instead of stresses, and the corresponding creep is measured as time dependent angular changes or deflections. Shrinkage strains are, again, neglected in interpreting the data.

Upon removal of stress (or load, torque or moment), there is an elastic recovery followed by a time dependent recovery designated creep recovery. The