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Current Problems Regarding Concrete Under Sustained Loading

Problèmes actuels concernant le béton soumis à des chargements de longue durée

Beton unter Dauerbelastung — Aktuelle Probleme

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Introduction

In practice, every concrete member is subjected to sustained loading, if only its self weight, and it is therefore important to be clear about the areas where our knowledge of the behaviour of concrete under sustained loading is inadequate. The effects of sustained loading range from possible changes in the structure of the cement paste, its elasticity and strength, to effects in different types of structures. Obviously, all of these cannot be covered exhaustively in the present paper, which is limited to the most important effects of sustained loading in concrete as a material.

Strength of Concrete

Let us first look upon the effects of a sustained load on strength and elasticity of concrete. This is still quite controversial, probably because the stress-strength ratio influences the sign of the effect. If the stress-strength ratio is high, over 80% or thereabouts, the applied load leads to failure with time. Thus failure occurs at a stress below the short-term nominal failing stress. This behaviour is believed to be due to creep which increases the axial strain, and when the concrete reaches its characteristic limiting strain, failure takes place [1]. In other words, it is the limiting strain that is the criterion of failure under uniaxial stress, and not the maximum stress or any of the kindred criteria. Verification of this hypothesis is still required. It would also be interesting to investigate the effect of shrinkage strain on the ultimate strain.

Tests made by SELL [2] show that there is, however, a slight complication in the form of an opposite effect of aging. This means an increase in strength with time, and therefore a reduction in the effective stress-strength ratio. In practice, aging is significant only in young concrete, and if the weakening effect does not take place soon, it will not take place at all as the aging effect becomes dominant. This observation is of practical interest insofar as, with young concrete, we can feel safe provided the concrete has survived the early period under a high sustained load.

It may be proper to observe that although long-term strength and creep are related, creep does not normally affect adversely the strength of concrete structures. In fact, in many cases, owing to a redistribution of stresses, the strength of a structure is improved by creep [3].

Let us now look at the effect on strength of a low stress intensity such as may exist in practical structures under loads within the design range. This has been investigated by RODRIGUES [4]. The stress-strength ratio in his tests was 8 to 17%. He found an increase in strength of 10 to 12% after 500 days under load. PELTIER [30] found a similar increase after 12 hours of application of a stress-strength ratio of 50%. What is the reason for this behaviour? Densification of concrete, i.e., an effective reduction in the void content of concrete? Hardening under pressure, i.e., the formation of a denser gel? Or some other cause, such as the effective prestress against tensile stresses due to shrinkage?

A possible answer lies in STÖCKL's [5] tests, who observed an increase in strength of 3 to 18%. This increase is greater the greater the applied stress between 50 and 90% of the ultimate, the greater the duration of load, the earlier the application of load, and for a constant stress-strength ratio, the stronger the concrete. There is need for a study of concrete or cement paste to learn what happens to it under the action of a sustained load in terms of void ratio, gel porosity, and gel structure.

Creep of Concrete

Since the problem of creep was recently reviewed [6] only some special features of this phenomenon will be considered. One of these is the influence of temperature on creep. This was studied by ENGLAND and ROSS [7], and by NASSER and NEVILLE [8]. The important point is that at some temperature, about 170° F, the water becomes desorbed, and the gel becomes the sole phase to molecular diffusion and shear flow. Consequently, the rate of creep decreases. Is this mechanism of creep tenable? We have some sort of seepage but the equation is viscous in character.

Laboratory tests are usually conducted at a constant temperature and humidity. Creep has therefore been expressed as a function of relative humidity, but this approach was disturbed when it was found that a variable relative humidity increases creep. Hansen [9] investigated this problem, and KESLER [10] offered a hypothesis explaining that, while only a small change in vapour pressure is due to the applied stress, a change in water content produces a high stress because adsorbed water is effective on the entire area of material.

It is interesting to note that JOHANSEN and BEST [11] found that alternating temperature has a similar effect to alternating humidity. Are the causes of the two phenomena related to one another and to some activating effect of transfer of energy?

Tests of JOHANSEN and BEST [11] have received little notice but they may contain a clue to the nature of creep. Especially significant seems the observation that a change in temperature produces an irreversible change in strain just as is the case upon first drying of concrete. The change may be positive or negative.

It is relevant to note that GLÜCKLICH [12] and MULLEN [13] found that there is no creep in specimens that contain no evaporable water. This may point to seepage as being responsible for creep. But is it so, necessarily? Or is it that the position of gel particles is changed to a minimum spacing when gel water has been removed? As GLÜCKLICH [12] says, the asymptotic limit of creep is the same as the instantaneous deformation of a similar body with the same content of *empty* voids under the same load.

Earlier studies [14] on the influence on creep of strength of concrete while under load have been continued [15]. It has been found, as expected, that the two phenomena are related, creep at a constant stress (and a given initial stress-strength ratio) being higher the lower the fractional increase in strength. This is increase in strength from the time of loading as a fraction of strength at the time of loading. Since for an earlier loading age the increase in strength is greater than for later loading, it follows that for the same initial stress-strength ratio creep is larger the later the load is applied. This seems at variance with reports of earlier investigators. But they are right, of course, if the stress is adjusted continually so as to maintain the stress-strength ratio constant. The rate at which the ultimate creep is reached depends on the relative strength increase of the concrete. Numerical procedures for variable stress have been developed [16]. It seems thus that changes in strength, and therefore in degree of hydration, are intimately related to changes in creep. Does this give a better clue to the nature of creep, to a resolution of the seepage-viscous flow controversy?

A brief comment about relation between creep and shrinkage. HANSEN [17] observed that revibration of concrete reduces shrinkage but not creep. Hence, it would appear that the theory that the effect of drying on creep is in fact an effect of internal shrinkage stresses is not valid.

An interesting observation can be made from KEETON's tests [18]. He found that both shrinkage under conditions of drying, and swelling at a 100%

relative humidity are greater the smaller the specimen. It follows, therefore, that there is a relative humidity at which the specimen is in hygral equilibrium with the ambient medium, and that this is about 94%. This was suggested by LORMAN [19] over twenty years ago, but, curiously enough, Keeton makes no reference to Lorman's work. Our observation from KEETON's data [18] is of interest with regard to vapour pressure of concrete. As far as is known, creep has not been studied at 94% relative humidity, and it would be interesting to explore the influence of relative humidity on creep of drying concrete, as well as of concrete in hygral equilibrium, in the region 90 to 100% relative humidity.

Incidentally, as ROSS [20] pointed out several years ago, many of our studies of shrinkage, while of scientific interest, may be somewhat misleading in practice since in real structures shrinkage is always restrained either by the inner core of a member, or by reinforcement, or by connections. Thus the tensile stress due to shrinkage is moderated by creep in tension. For this reason the greatest practical effect of shrinkage — cracking — is affected by both creep and elastic strains, and it is, therefore, not necessarily the weakest concrete, or the concrete with the highest shrinkage, that cracks most.

A word about creep of lightweight aggregate concrete. It is true that in many cases lightweight aggregate leads to a higher creep than ordinary aggregate, but the ratio of creep to elastic deformations is smaller for lightweight aggregate. The reason is that, for the same strength, the modulus of elasticity of lightweight aggregate concrete is smaller, and therefore the elastic deformation is larger than for ordinary concrete.

Incidentally, the creep recovery of lightweight concrete under similar conditions is smaller, possibly again because of the lower modulus of elasticity. All these comparisons were made on concretes of the same strength, tested by RADKEVICH in Russia [21].

A great step forward in utilizing creep data has been made by HANSEN [22] who showed how to convert creep data to relaxation data. The method has been improved by MCCOY [23] who suggested a finite difference method for the range of stresses involved. This field of relaxation still needs good working over.

It is important to note that we must not transfer our experience with creep of plain concrete direct to reinforced concrete. The creep deflection is smaller than would be expected from creep measurements in plain concrete, since in a beam the neutral axis goes down as the reinforcement becomes relatively stiffer with a concomitant reduction in compressive stress, and a consequent reduction in creep. This has been pointed out by RÜSCH [24] who, unlike SORETZ [25], disregards creep on the tension side of the beam since, after a few cycles of loading and unloading, the tensile strain in concrete will be the same as in the steel. But the recovery of creep deflections is small: in prestressed concrete beams BRECKENRIDGE and BUGG [26] showed it to be no more than 15% which agrees with recovery results on plain concrete [27]. It is worth noting though, that a prestressed concrete beam can be so designed that it will have no creep deflection at a given point [28].

Regarding the restricting action, we should remember that compressive reinforcement reduces both shrinkage and creep deflections in proportion to the amount of steel up to a 50% reduction when tension and compression steels are equal [29]. Since beams with a high length-depth ratio deflect a great deal, it is in such beams that the addition of compressive steel, even if not required by design, is particularly useful.

Conclusions

These are then some of the pressing problems:

1. Criterion of failure of concrete, especially under a high sustained load.
2. Reasons for increase in strength under a moderate sustained load.
3. An explanation of temperature effect on creep.
4. Effect on creep of alternating humidity and especially of alternating temperature.
5. Seepage versus viscous theory of creep.
6. Relation of creep to a change in strength of concrete.
7. Further study of reasons for absence of creep when there is no evaporable water.
8. Study of effects such as revibration that affect creep and shrinkage in a different way.
9. Shrinkage and creep in the vicinity of 95% relative humidity.
10. Creep of lightweight concrete.

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Summary

The main areas of current interest with regard to the behaviour of concrete under sustained loading are discussed. Special reference is made to strength and creep, and topics for future research are suggested.

Résumé

L'auteur passe en revue les principaux domaines dans lesquels un intérêt se manifeste actuellement eu égard au comportement du béton soumis à des chargements de longue durée. On s'intéresse plus particulièrement à la résistance et au fluage et l'on propose des thèmes sur lesquels pourraient utilement porter de futures recherches.

Zusammenfassung

Es werden die Hauptgebiete besprochen, bei denen das Verhalten des Betons unter Dauerbelastung gegenwärtig von Interesse ist. Die Festigkeit und das Kriechen werden besonders behandelt und der Autor schlägt Themen für die zukünftige Forschung vor.

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