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11 NEW TEST METHOD TO SEPARATE MICROCRACKING FROM DRYING CREEP: CURVATURE CREEP AT EQUAL BENDING MOMENTS AND VARIOUS AXIAL FORCES

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Abstract
New test method has been conceived and verified to distinguish the drying creep mechanisms. Decomposition of the measured curvature creep confirms the existence of the mechanism of stress-induced shrinkage. The basic new idea is to compare measure curvature creeps in prisms at different axial forces which in one case allow microcracking and in another case suppress it. It is demonstrated that the apparent creep increase due to drying is caused by two distinct mechanisms: stress-induced shrinkage, and microcracking effect.
Keywords: Creep, Drying, Concrete, Mechanism, Shrinkage, Microcracking, Testing.

1 Introduction

The Pickett effect (Pickett, 1942), also called drying creep, is the excess of creep at drying over the sum of shrinkage and basic creep, as shown in Fig. 1. Most of the models try to explain the extra deformation by the so-called microcracking effect; e.g. Pickett (1942), Wittmann and Roelfstra (1980), Iding and Bresler (1982). The explanation is as follows.

Because of the non-uniformity of moisture distribution in a shrinkage specimen (specimen No. 1 in Fig. 1), the surface layer of the specimen is already drying and shrinking while the inner layer is still wet and does not yet shrink. Consequently, the surface layer is in tension while the inner layer is in compression at the initial stage of the drying process. This tensile stress causes microcracking in the surface layer. Due to the nonlinear inelastic behavior and irrecoverable creep of concrete caused by the tensile stress, these microcracks cannot fully close when the moisture distribution finally approaches a uniform state. As a result, the measured shrinkage of the specimen is always smaller than the true shrinkage of the specimen. On the other hand, for drying creep specimens (specimen No. 3 in Fig. 1), the whole cross section is in compression, and so there can be no microcracking effect. The specimen shrinkage will not be reduced by microcracking and other irreversible deformations, and so a larger shrinkage will occur in the compressed specimen than in the load-free specimen. Thus, the apparent drying creep is larger than the sum of the separate basic creep and shrinkage.

Partly differing from the others, Bažant and Chern (1985a, 1985b) concluded that microcracking (or tensile strain–softening) and other irreversible strains form only a part of the Pickett effect and another mechanism exists—stress-induced shrinkage. This mechanism has a different explanation, which is as follows.

Two different types of the moisture diffusion process can be distinguished: macrodiffusion (drying and wetting) and microdiffusion. The macrodiffusion, which consists of water transport through the passages of least resistance, that is the largest pores, has no measurable effect on deformation (this follows, e.g., from the tests of Hansen, 1960). The microdiffusion transports water locally between the capillary pores (macropores)

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and gel pores (micropores), and because it occurs in far smaller pores of molecular size it affects the deformation rate of the solid framework of cement gel. The movement of water through the gel pores, which are only a few molecules in size, promotes the breakage of bonds that are the source of creep, and thus intensifies creep.

However, there currently is no experimental data in the literature that clearly distinguish among the proposed mechanisms. The conventional creep test with centric loading and the bending creep test can only show the Pickett effect itself but cannot detect the different mechanisms involved. The purpose of the present drying creep experiment is to obtain a direct experimental distinction between the aforementioned mechanisms and thus provide a clear experimental basis for establishing the correct theoretical model. The idea of the present new experimental method was proposed at a recent conference (Bažant, 1989) and, along with some preliminary results, was subsequently presented at another conference (Bažant, Xi and Molina, 1991). The present paper expands these earlier reports.

2 New Experimental Procedure

The test specimens were eccentrically compressed prisms with two different loading eccentricities. The bending moment due to eccentricity produces curvature. The advantage of using curvature is that shrinkage can be ignored, since shrinkage (in a symmetric and symmetrically drying specimen) causes no bending. The axial loads and their eccentricities are adjusted so that the bending moments for the two loading cases be exactly the same while the axial forces are different, allowing microcracking in one specimen and suppressing it in another. By virtue of this idea, the curvature creep deformations due to microcracking can be separated from those due to a different mechanism of drying creep.

First, when the specimens of small eccentricity are loaded, the whole cross section is in compression (see Fig. 2), which eliminates the tensile microcracking effect. The deformation of specimen No. 1 is from basic creep. Therefore, if any extra deformation is observed on specimen No. 2, it means that stress-induced shrinkage exists and contributes to drying creep. Second, when the specimens of large eccentricity are loaded, there is both tension and compression in the cross section. The deformation of specimen No. 3 (see Fig. 3) is from basic creep. The irreversible deformations, especially microcracking, causes extra deformation in the tensile region of the cross section of specimen No. 4, and thus extra curvature. Therefore, any extra curvature in specimen No. 4 compared to specimen No. 2 indicates the deformation that is due to microcracking alone. This is the basic idea of the present experimental approach.

The experimental setup, shown in Fig. 4, is the standard setup recommended by ASTM. The specimens were square prisms of length 16 in. (30.48 cm) and side 4 in. (10.16 cm). The experiments were carried out in a humidity controlled room, with relative humidity 50%, and temperature 80 F. All the specimens used in both sets were cast identically, in a horizontal position, and cured identically. The ratios in the mix were water:cement:sand:gravel = 0.5:1.0:2.5:3.0 (by weight). Type I cement was used. The aggregate was crushed limestone with the maximum size of 3/4 in. The forms were removed after one day of moist curing at room temperature, and the sides of each specimen were sealed with siliconized acrylic latex caulk, in order to assure that the drying problem be one dimensional. Two sets of tests have been carried out. Information on the two sets is listed in Table 1.

3 Test Results and Discussions

Fig. 5 shows the averages of the lateral deflections for each pair of identical specimens. First, by comparing the deflections of the sealed and unsealed specimens with the small eccentricity (solid squares), one notices that there is an additional deformation, added to basic creep. Since, for small eccentricity, the whole cross section is in compression, microcracking in transverse planes cannot occur. Therefore, the addi-

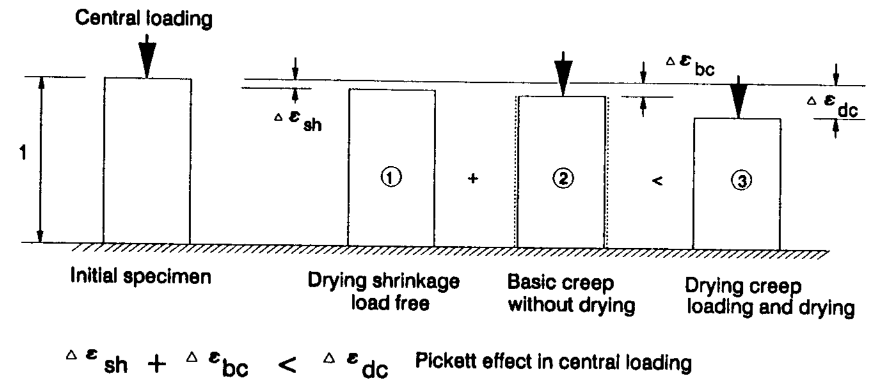

Fig. 1 Pickett effect

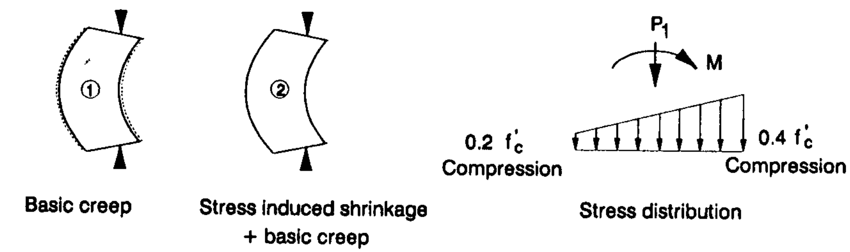

Fig. 2 Experimental plan I: small eccentricity

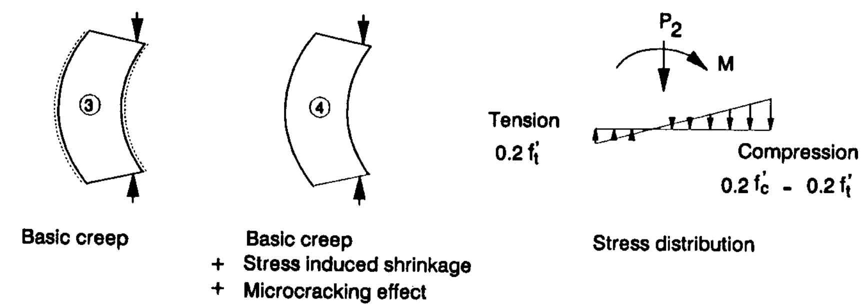

Fig. 3 Experimental plan II: large eccentricity

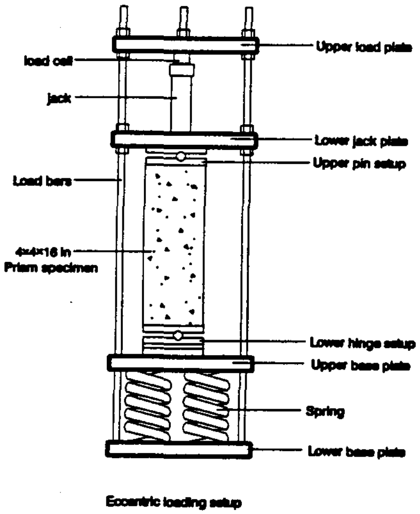

Fig. 4 Experiment setup

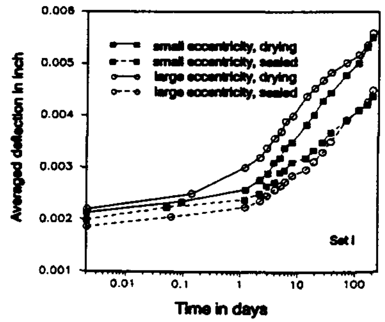

Fig. 5 Averaged deflections

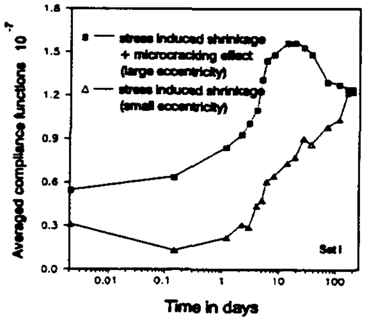

Fig. 6 Decomposition of different drying creep mechanisms

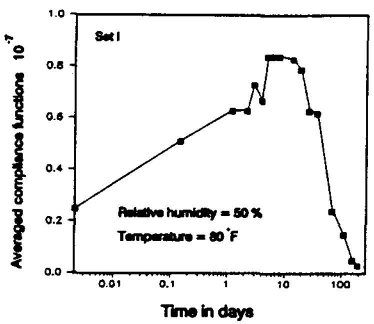

Fig. 7 Effect of microcracking on drying creep

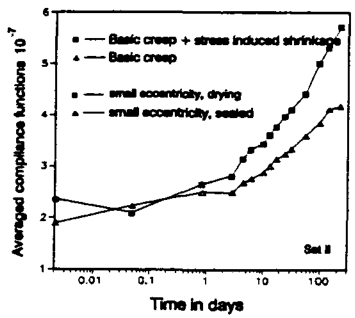

Fig. 8 Averaged compliance functions

tional deformation that is seen in Fig. 5 must originate solely from the stress-induced shrinkage. This is the first direct experimental proof of the existence of stress-induced shrinkage.

Second, comparing the sealed and unsealed specimens of large eccentricity (circles in Fig. 5), one notices that there is also an additional deformation, added to basic creep. This extra deformation combines the contributions from both mechanisms — microcracking and stress-induced shrinkage.

The deflection magnitude depends on many parameters, such as the prism length, cross-section size, and eccentricity. To compare the test results in general, the compliance function has to be employed. The compliance function, J, can be easily calculated from the measured mid-span lateral deflection, y . According to the theory of elastic buckling,

$$J = \frac{1}{E_c} = \frac{I}{P}\left[\frac{2}{l} \cos^{-1}\left(\frac{e_0}{y_{\max} + e_0}\right)\right]^2 \tag{1}$$

where P = axial load, I = centroidal moment of inertia of the cross section, l = length of the column, e_0 = initial eccentricity, $k = (P/E_c I)^{1/2}$, and E_c = elastic modulus of concrete. With a small P and small $y_{\max}, \cos(kl/2) \approx 1 - 0.5(kl/2)^2, e_0 + y_{\max} \simeq e_0$, and then Eq. 1 may be rearranged as

$$J = \frac{1}{E} = \frac{8I}{l^2 P e_0}\; y_{\max} \tag{2}$$

The effects of the initial moment Pe_0, column length l, and the shape of the cross section, I, have thus been eliminated from J. Therefore, the test results for different loading moments, column lengths, and cross sections can be compared with each other.

The different mechanisms can be decomposed as shown in Fig. 6. It is evident that the stress–induced shrinkage contribution increases with time. The microcracking contribution can further be decomposed as shown in Fig. 7. It appears that the microcracking contribution increases from the very beginning, reaches its maximum at about 10 days, and then decreases with increasing time. This is because moisture distribution gradually approaches a uniform state. However, even after a long time, the microcracking contribution developed in the early drying process is irreversible, because the cracks close only partly.

Fig. 8 shows the averaged compliance function from the results of Set II. It also clearly shows that there is an additional deformation, added to the basic creep. Since the whole cross section is also in compression for Set II, there is no microcracking effect. The observed additional deformation must come from the mechanism of stress-induced shrinkage. Noting that the bending moments and axial loads in Set II and Set I are different, we further conclude that the drying creep mechanisms, distinguished by the experiment in Set I, are true for various loading levels.

4 Conclusions

1. Decomposition of the measured the curvature creep of eccentrically loaded prisms confirms the existence of the mechanism of stress-induced shrinkage. It follows that the deformations observed in drying creep tests are composed of the following four mechanisms: free shrinkage, basic creep, stress-induced shrinkage, and microcracking effect.

2. The test results for different load levels indicate that the stress-induced shrinkage contributes to the total deformation at all load levels.

3. The stress-induced shrinkage increases with time. The microcracking effect increases at the beginning of drying, reaches a maximum, which occurs for the present specimen thickness at about t = 10 days, and then starts to decrease (the value of t may be expected to be approximately proportional to thickness-square).

Table 1 Information on the experiments

	Set I		Set II
	small e_0	large e_0	small e_0
e_0 (in)	0.21	0.97	0.44
No. spec.	4	4	4
f'_c (psi)	5619	5619	5418
size (in)	4 × 4 × 16	4 × 4 × 16	4 × 4 × 16
P (lb.)	26971	6112	26006
σ_{max} (psi)	2248	944	2847
σ_{min} (psi)	1124	-180	403

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