Discussion

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Shrinkage and creep of concrete as affected by the fineness of Portland cement*

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Contribution by A. de Sousa Coutinho

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I should like to congratulate Dr Bennett and Dr Loat upon their important initiative in the measurement of the stresses due to restrained shrinkage. We, too, think that it is not worth while spending much effort on measuring unrestrained shrinkage; what matters is the stress that arises from it. In concrete construction, the highest stresses do not arise from the highest strains due to shrinkage; they are more a matter of the rate of relaxation, which has very little or nothing to do with shrinkage.

It is regrettable that so little research has been done on this subject. Nevertheless, the correct interpretation of restrained shrinkage tests and their results presents many difficulties. The humidity gradient that is bound to occur, and from which shrinkage and stress gradients arise in the cross-section of the specimens, leads to confusion with the real strength of the concrete. These gradients of internal stresses, when superimposed upon the restrained shrinkage, become the main cause of rupture, reducing the strength of the specimen, and not that of the concrete.

The most important step towards overcoming this difficulty is to eliminate the humidity gradient in the cross-section of the specimen. But how is this to be achieved? Unfortunately we cannot answer. Reducing the relative humidity of the atmosphere at a rate equal to that of the diffusion of water vapour inside the concrete specimen is perhaps a means of eliminating the humidity gradient in the cross-section of the ring,

but in this way we can use only one rate of shrinkage. If we use a fully cured specimen, we shall know only one ratio between unrestrained and restrained shrinkage; besides, it is not possible to foresee what cracking will take place in that condition.

One point I should like to raise concerns the designation 'partial cracking of concrete' in Figure 7. I apologize for disagreeing with Dr Bennett and Dr Loat on this point. The reduction of stress in the restrained shrinkage ring is a phenomenon that has nothing to do with cracking; it is simply due to the fact that the relaxation rate is higher than the shrinkage rate, at the level of applied stress. In the very numerous experiments I have carried out, this phenomenon has often been observed: even during the time unrestrained shrinkage remains constant, there is a decrease in stress. This decrease is greater as relative humidity is less.

At the end of the test, even when there is no cracking, I have also noticed that the rupture stress of the restrained concrete ring and its variation were equal to those of the unrestrained one. I think there are no signs of cracking or even increase in the density of flaws in concrete subject to restrained shrinkage.

Another point is the question of the rigidity of the metal ring, which seems to me to have been small; the ratio between thickness and diameter is only 0.09. In my tests it was 0.12, and the metal ring often reached the point of instability: the distribution of stress along the perimeter of the ring was not uniform, and this is a cause of rupture. The extraordinary sensitivity of the

*Pages 69 to 78 of *Magazine* No. 71

silicon semi-conductor strain gauges used by Dr Bennett and Dr Loat would have made it possible to increase the thickness of the ring and to use a metal with a lower modulus of elasticity, for instance aluminium or magnesium, instead of steel.

It is rather surprising that shrinkage and creep should be only slightly affected by such a tremendous difference in fineness of cement. This is perhaps due to the fact that specific surfaces were compared, and not the grading of cement particles. The specific surface does not tell us very much about cement properties, as

these depend mainly upon a certain size fraction of particles, and not upon the finest particles. We know that the finest particles contribute more towards shrinkage, but not towards strength, and perhaps not towards creep (and therefore towards relaxation). What is the particle size which contributes most towards creep? I think we do not yet know.

A better comparison of the properties of cement samples used by the authors would be possible if the distribution of particle sizes in them were given.

Contribution by A. R. Mears

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The dilemma of the concrete technologist is that he cannot simultaneously optimize every physical property of his material at the behest of the structural engineer. Dr Bennett and Dr Loat have shown in their paper, however, that the concrete made with a very fine cement can, while achieving a very high early strength, be kept to an acceptable value of shrinkage, by increasing the gypsum content. It has been shown⁽¹⁾ that there is a linear relationship between shrinkage and cement fineness when the gypsum content is held constant. The results in the present paper refer, however, to only one cement and this has a composition with a tricalcium aluminate content of 14%, which is unusually high, and a high gypsum content. It has been shown^(2,3) that the increase in shrinkage with cement fineness could be controlled by increasing the gypsum content, but only when the tricalcium aluminate content was high. This behaviour was probably due to the increased formation of ettringite, and expansive component of the hydrated cement. Have Dr Bennett and Dr Loat examined very fine cements of other compositions, with lower tricalcium aluminate contents, to see whether the addition of extra gypsum is always

effective in controlling shrinkage?

It is unfortunate that temperature measurements on the shrinkage specimens could not be made, because they might have revealed the cause of the contraction during the first three days of moist curing (see Figure 2) of the concrete made with the finest cement. Thermal contraction could also explain the higher initial shrinkage of the concrete made with the finest cement and cured for only one day.

The two coarser cements at a water/cement ratio of 0.45 do not give concretes of lower shrinkage after 28 days curing than those cured for 1 day when shrinkage is measured from the start of drying. This can be deduced from Figure 2 and Table 2, and may also apply to the results given for the other three water/cement ratios.

It would be interesting to know the workabilities of concrete mixes made with the finest cement for more practical aggregate/cement ratios than 3.0. One expects that more aggregate would rapidly decrease the workability and that the extra water necessary to counteract this would considerably raise the shrinkage.

Reply by the authors

We are grateful to Mr Coutinho and Mr Mears for their constructive observations and criticisms, Mr Coutinho's comments being particularly appreciated because of his own work in developing the ring test for restrained shrinkage.

The differential shrinkage and resulting stress gradient across the section of a concrete specimen certainly constitute an intractable problem, introducing as they do a troublesome size effect when any attempt is made to apply laboratory test results to larger mem-

bers. In using the ring test, however, one may derive some comfort from the fact that the stress gradient induced by the restraint of the steel ring is of opposite sign to the stress gradient due to differential shrinkage, resulting in more uniform stressing of the concrete ring.

Although we agree with Mr Coutinho that a relatively high rate of relaxation could reduce the stress in the concrete ring, we cannot accept this interpretation of the falling branch of the stress curves in our own tests. Since the tensile strength of the concrete increases with time, it seems inherently improbable that tensile failure should occur not only at a stress much lower

†Mr Mears has now joined the British Standards Institution.

than the maximum, *but also at a greater age*. A more direct piece of evidence in favour of the crack propagation hypothesis is the fact that, in certain tests, fine cracks on the surface of the concrete were observed to increase in width as the measured stress decreased.

Uneven shrinkage of the concrete appears to be responsible for the difference in the readings of the three gauges. The resulting non-uniform pressure would cause bending of the steel ring but, since the maximum stress in the steel was only about 12 N/mm², elastic instability does not seem likely; moreover, the differences in the gauge readings were sometimes greatest at the lowest stresses, as in Figure 6. Although the flexural rigidity of the ring might be increased without loss of sensitivity by using a thicker ring with a lower modulus of elasticity, changes of temperature would affect the results if the coefficient of thermal expansion, unlike that of steel, differed appreciably from that of concrete. The coefficient of expansion of aluminium is more than twice that of steel.

A particle size distribution of samples of the Portland cement of the three degrees of fineness used is given in Table I. It is perhaps surprising that the effect of specific surface upon shrinkage was not greater, although in tests of neat cement paste the difference would have been more pronounced.

Mr Mears correctly points out that the shrinkage of the finer cements was reduced by an increased gypsum content, and it would certainly have been interesting to test cements of lower C₃A content had these been available. It may be noted in this connection that Lerch⁽²⁾ and Pickett⁽⁴⁾ found that not only cements with a high C₃A content, but also cements rich in alkalis, were sensitive to changes in the gypsum content.

Although temperature measurements were not made in the actual shrinkage tests reported, other tests, such as that shown in Figure 5 of reference 21 of the paper, have indicated that, even in larger specimens, the temperature of concrete made with the finest cement had

TABLE I: Particle size analysis of samples of the cements tested (Andreassen method).

Particle size (μm)	Percentage		
	Ordinary Portland cement	Rapid-hardening Portland cement	Extremely fine Portland cement
< 3	4	13	9
< 5	9	19	29
< 10	19	33	57
< 25	27	56	97
< 44	59	80	100
< 64	71	87	100
< 89	89	96	100
< 152	98	99	100
< 211	99	99	100
< 295	100	100	100

returned to the ambient level after about one day, so that thermal contraction does not seem to be the explanation of the high early shrinkage and absence of swelling under moist curing. It would rather appear to be a phenomenon associated with the greatly accelerated hydration of the fine cement.

Workability measurements are unfortunately not available for concretes with an aggregate/cement ratio higher than 3, but it is well known that a higher aggregate content would reduce the shrinkage at a given water/cement ratio as well as increase the water requirement to maintain the same workability, so that it cannot be said with certainty that the over-all effect would be an increase in shrinkage. On the contrary, the workability of leaner mixes would almost certainly be less sensitive to the fineness of the cement, so that in comparison with coarser cements the result might well be more favourable.

REFERENCES

1. VÉNUAT, M. Nouvelle contribution à l'étude du ciment à retrait minimal. (New contribution to the study of low shrinkage cement.) *Revue des Matériaux de Construction et de Travaux Publics*. No. 625. 1967. pp. 345–354.
2. LERCH, W. The influence of gypsum on the hydration and properties of portland cement pastes. *Proceedings of the American Society for Testing and Materials*. Vol. 46. 1946. pp. 1252–96.
3. PICKETT, G. Shrinkage stresses in concrete. *Journal of the American Concrete Institute. Proceedings* Vol. 42. January 1946. pp. 165–204. February 1946. pp. 361–398.
4. PICKETT, G. Effect of gypsum content and other factors on shrinkage of concrete prisms. *Journal of the American Concrete Institute. Proceedings* Vol. 44. October 1947. pp. 149–175.