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Drying shrinkage of expansive cements

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Drying shrinkage behaviour of expansive cement pastes were studied and compared with those of portland cements. Results indicate that the shrinkage behaviour of these two cements is significantly different from each other. Generally, expansive cements shrink more than portland cements, and especially more so if they have not been adequately cured, i.e. curing period of at least 7 days is necessary to ensure good performance against shrinkage. Internal damage caused by large amounts of expansion leads to a large magnitude of shrinkage. In that event curing does not seem to have any beneficial impact on shrinkage performance. Steel reinforcement also seems to decrease shrinkage magnitude, but it has no effect on the shrinkage characteristic. Much of the research on expansive cements has so far been focused on the expansion behaviour rather than on the shrinkage behaviour. More research on shrinkage is needed to improve its field performance.

1. Introduction

Researchers and practitioners have attempted, for several decades, to correlate shrinkage with cracking and durability of portland-cement concretes. Cracks provide the easiest route for ingress of harmful chemicals such as salt solutions, acids, and sulphate waters to the interior of concrete. These chemicals may cause corrosion of the reinforcing metals, dissolution of strength-contributing substances, and formation of potentially deleterious products such as ettringite. The deleterious effects of drying shrinkage cracks on the durability of concrete may thus be important.

Expansive cements of shrinkage-compensating type have been developed in response to the problem of drying shrinkage in concretes. The principal objectives of expansive cements are to minimize, and if possible, to eliminate drying shrinkage cracks. The ACI Committee 223 [1] defines expansive cement as "a cement which, when mixed with water, forms a paste that, after setting, tends to increase in volume to a significantly greater degree than portland cement paste; used to compensate for volume decreases due to shrinkage or to induce tension stress in reinforcement". The product responsible for expansion in the sulphoaluminate-type expansive cement is ettringite ($C_6A\bar{S}_3H_{32}$)†. $C_4A_3\bar{S}$ in Type K, CA and $C_{12}A_7$ in Type M, and C_3A in Type S, are the sources of reactive alumina required for the formation of ettringite. Type K is the most widely used expansive cement in the United States [2]. Another type of expansion is in the form of free-lime expansion. This CaO-type expansive cement is not the subject of this investigation.

Because of the importance of concrete durability on ecomony, research interest on expansive cements has been significant, especially in the 1970s. For a while, it was believed that expansive cements could be substituted substantially for portland cements. However, this did not happen. Production of expansive cements in the US has fluctuated around 1% of the total production of portland cement. A major reason for such a small volume could be attributed to their higher cost (25% to 30%) relative to that of portland cement. Today, their use is most popular in water-retaining structures where the absence of cracks is important. Moreover, their uses in slabs and walls are justified by the fact that the required number of contraction joints per unit length is reduced.

Probably other reason for the small volume could be due to the lack of adequate knowledge of their shrinkage characteristics and, at times, their inability to prevent cracks. Even though crack sizes are generally smaller compared to those in portland-cement concrete, harmful chemicals could still penetrate to the interior, thus endangering durability. It appears that most of the research activities on expansive cements have been focused primarily on their expansive rather than on shrinkage characteristics.

The general purpose of this investigation was to evaluate the shrinkage characteristics, such as magnitude and rate, of Type K expansive cement pastes. The pastes were blends of ASTM Type I–II portland cement, natural gypsum and the expansive source was a pure $C_4A_3\bar{S}$. The principal objectives were to:

1. Compare the shrinkage characteristics of free (unreinforced/unrestrained) expansive cements and free portland cements;
2. Study the effects of duration of lime-water curing on shrinkage characteristics;
3. Study the differences in shrinkage characteristics between normal and abnormal expansive cement blends. The definitions of normal and abnormal blends are as follows [3, 4].

Normal blend: "A blend behaves normally when

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† Abbreviations: C = CaO, A = Al_2O_3, $\bar{S}$ = SO_3, H = H_2O, S = SiO_2, F = Fe_2O_3.

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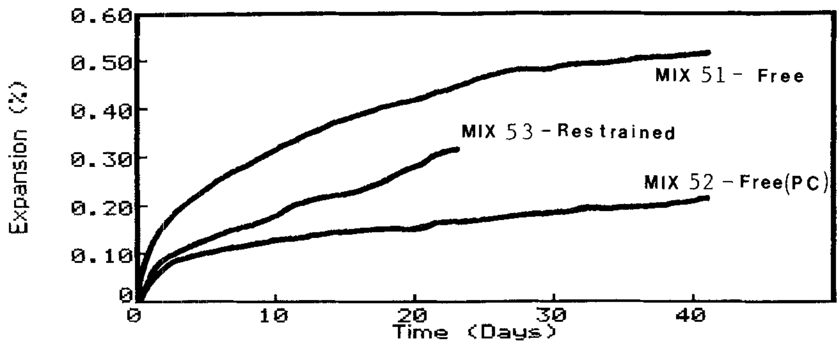

Figure 1 Expansion–time curves, Series 1.

the rate of expansion decreases monotonically from the time expansion begins and becomes essentially zero after a few days. The corresponding strength increases at a high rate at first and continues to increase, although at a decreasing rate, even when expansion stops".

Abnormal blend: "A blend behaves abnormally when the expansion starts to increase at a decreased rate, but then suddenly starts to increase more rapidly and continues for many days and perhaps weeks. This behaviour is called "double-curvature expansion", because there is a reversal in the curvature of the expansion against time curves. This abnormal expansion is accompanied by a "dynamic-modulus drop" or "strength drop". For example, the corresponding strength increases until the period of rapid expansion, when it starts to decrease. However, it starts to increase again once expansion stops".

2. Experimental investigation

2.1. Materials

1. Commercial grade ASTM Type I–II portland cement; designated PC S3210. It had a Blaine air-permeability surface area of $321\,m^2\,kg^{-1}$. The potential compound composition as obtained by the Bogue equations gave, $C_3S = 55\%$, $C_2S = 20\%$, $C_3A = 5\%$, $C_4AF = 12\%$, and $C\bar{S} = 4\%$.

2. Natural gypsum; designated G-1. It contained 78% $C\bar{S}$.

3. Expansive component; designated $C_4A_3\bar{S}$-83C. This was a 99.7% pure $C_4A_3\bar{S}$ with the remainder being free lime. It had a Blaine surface area of $250\,m^2\,kg^{-1}$.

2.2. Mixing, curing, and length measurements

Miniature paste specimens with dimensions $0.005\,m \times 0.015\,m \times 0.075\,m$ were used for free pastes and, for comparative evaluation, $0.005\,m \times 0.015\,m \times 0.0574\,m$ specimens for reinforced pastes. It has been shown that miniature paste specimens give a fair indication of shrinkage [3, 5, 6] and expansion [3, 4, 6–9] mechanisms.

The reinforced paste specimens were restrained longitudinally with a stainless steel wire of $5.08 \times 10^{-4}\,m$ diameter, giving a steel ratio of 0.27%. Correlation of the data of free and reinforced pastes provided insight into the role of reinforcement in the absence of sand during drying shrinkage.

All samples were continuously cured in saturated lime water at $23 \pm 1°C$. Lengths were monitored on a daily basis, using a dial indicator with $\pm 1\,\mu m$ accuracy. Specific details of the apparatus involving the mixing, curing and measuring devices, are described elsewhere [4, 7, 8].

After different curing periods the specimens were placed in an environmental chamber and left to dry in air at $45 \pm 3\%$ r.h./$23 \pm 1°C$. Drying shrinkage magnitude was then monitored periodically.

2.3. Mix composition

Two series of tests were carried out. The mix compositions in each series are given in Table I. The objectives in Series 1 were to compare the shrinkage characteristics of: (a) pastes of portland cement and expansive cement without restraint: free – mixes 51 and 52; (b) pastes of expansive cements with and without restraint – mixes 51 and 53.

The specific interest in Series 2 was to see if excessive expansion resulting in deterioration, as in the abnormal blend (mix 60), exhibits different shrinkage characteristics.

TABLE I Mix composition

Series	Mix no.	Type*	Expansive component and its concentration (wt %)	Natural gypsum, G-1 (wt %)	Portland cement, PC S3210 (wt %)	%R†	Water: cement ratio
1	51	FP	$3.5C_4A_3\bar{S}$ 83C	7.55	88.95	70	0.4
	52	FP	–	–	100	–	0.4
	53	RP	$3.5C_4A_3\bar{S}$ 83C	7.55	88.95	70	0.4
2	51	FP	$3.5C_4A_3\bar{S}$ 83C	7.55	88.95	70	0.4
	60	FP	$4.5C_4A_3\bar{S}$ 83C	9.09	86.41	70	9.4

*FP = free paste; RP = uniaxially reinforced paste.
†%R = extent of reaction [3, 4, 8, 9].
Note: Abbreviations and symbols G-1, PC S3210, and 83C are material designations referred to in Section 2.1 of the text.

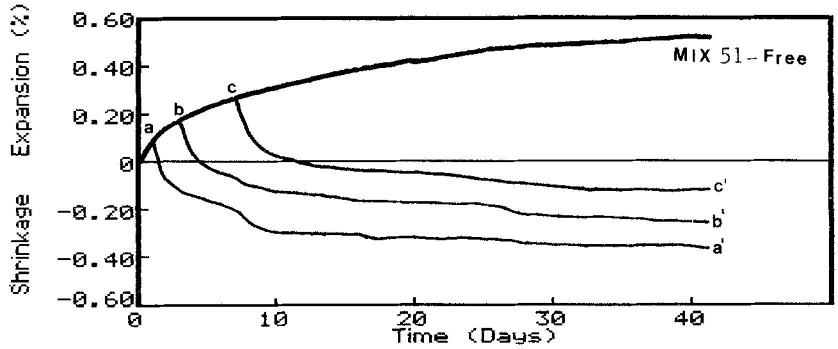

Figure 2 Expansion–shrinkage curves, Mix 51, Series 1.

3. Results and discussion

3.1. Series 1

The expansion versus time curves of the three mixes (51, 52 and 53) in saturated lime-water, are shown in Fig. 1. As expected, mix 51, the free expansion paste, exhibits the largest expansion, followed by mix 53 (the reinforced expansive paste) and mix 52 (the free portland cement paste).

Fig. 2 shows the lime-water expansion/drying shrinkage curves of mix 51. Mixes 52 and 53 had a similar trend. Lines 0aa′, 0bb′, and 0cc′ represent samples subjected to drying in air as described above, after 1, 3, and 7 days of curing. Therefore, samples were being subjected to shrinkage before their total expansion potential was obtained.

Each shrinkage sample was left to dry for 40 days. The shrinkage behaviour of lines 0aa′, 0bb′, 0cc′, etc., were analysed based on the 40 day data points and a least square exponential curve fitting using the equation:

$$S = S_0 [1 - \exp(-t/\tau)]$$

where S = shrinkage at time t (measured from points a, b, etc.), S_0 = ultimate shrinkage, t = time, τ = time constant.

Fig. 3 shows the ultimate shrinkage S_0 of specimens as a function of their duration of water curing prior to drying. It can be seen that there are differences in the shrinkage values and in the shape of the curves. The expansive cement pastes exhibited a maximum in the shrinkage for 2 days of water curing, while in the portland cement paste, increased curing time was associated in reduction of shrinkage: the reduction in shrinkage was significant for the first 3 days of water curing; beyond that period the shrinkage was practically constant and almost independent of the curing time.

The observation that the shrinkage curves of free and restrained expansive cements show a maxima for specimens cured for 2 days (Fig. 3) could possibly be explained by the role of CSH gel in the healing of microcracks. It is conceivable that damage caused by expansion at early ages could not be quickly healed by the CSH gel and thus the higher shrinkage magnitude. With increase in curing and adequate healing, the shrinkage magnitude drops, but still maintains a higher level than portland cement. No peak was present in the portland cement because there was no damaging expansion.

Results here clearly indicate that shrinkage behaviour of expansive cements is different from portland cement. Although in both cements the same factors are involved, there may exist processes such as formation or pores/microcracks during expansion [10, 11] caused by the destructive nature of ettringite crystal growth [3, 4, 6, 9], interaction of expansion and shrinkage during drying causing surface tensile stresses (surface contraction) balanced by internal compressive stresses (internal expansion), and decomposition of ettringite to other substances of different volume, that are of greater significance in expansive cements and which could render the expansive cement shrinkage behaviour different.

3.2. Series 2

Results of Series 2 (mixes 51 and 60 – 3.5% and 4.5% $C_4A_3\bar{S}$ blends, respectively), are presented in Figs 4 to 6. Fig. 4 shows the expansion–time relationship of the two mixes. The 3.5% $C_4A_3\bar{S}$ blend (mix 51) shows normal expansion. However, with an increase of 1% $C_4A_3\bar{S}$ to 4.5% (mix 60), a drastic difference is observed. This addition resulted in an abnormal behaviour of excessive expansion and disintegration. In fact, the specimens disintegrated completely and expansion measurements were not possible after the 15th day.

Fig. 5 represents the expansion–shrinkage curves of

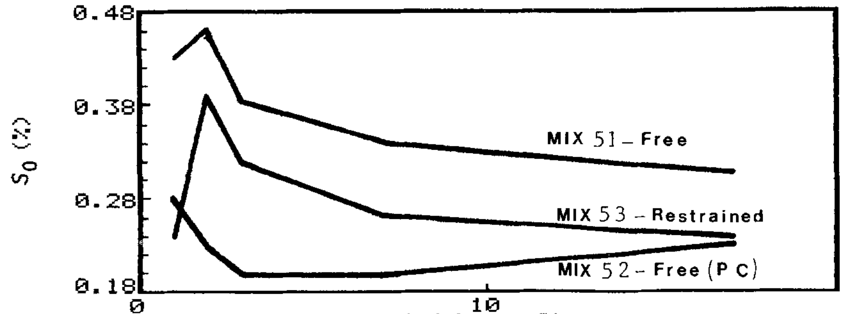

Figure 3 Ultimate shrinkage, S_0, Series 1.

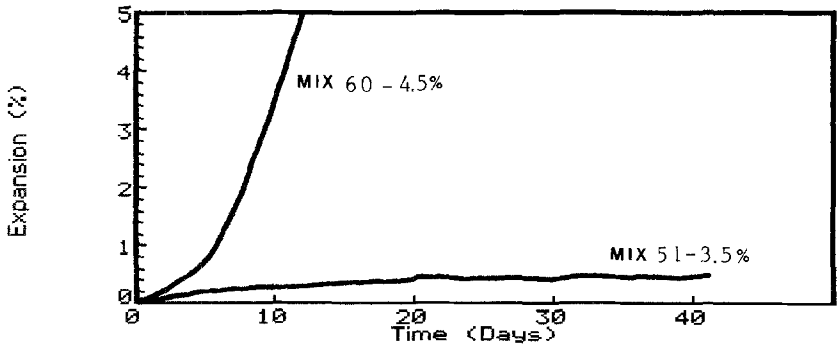

Figure 4 Expansion–time curves, Series 2.

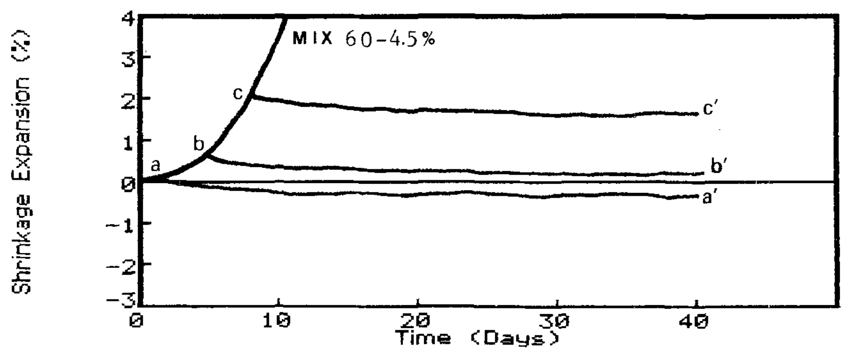

Figure 5 Expansion–shrinkage curves, Mix 60, Series 2.

mix 60, and Fig. 6 shows the ultimate shrinkage S_0 against curing time of mixes 51 and 60.

As described earlier for Series 1, the normal blend (mix 51) showed a peak at the second day followed by a continuous drop in the S_0 values. However, in the abnormal blend (mix 60), Fig. 6, there are two points of extremum – the 4-day sample (maximum) and the 5-day sample (minimum). After that, shrinkage increases with curing, though at a smaller rate.

Thus the important observation made here is that a large amount of expansive component resulting in excessive expansion and strength drop can lead to higher shrinkage magnitudes.

4. Conclusions

Several important conclusions can be drawn from this study.

For Series 1:

1. Shrinkage characteristics of free expansion paste are different from free portland cement paste, both in behaviour and in magnitude. In general, the former shrinks more than the latter.

2. Expansive paste shows a maximum shrinkage peak for samples cured for 2 days. With increase in curing, shrinkage magnitude drops. However, portland cement paste shows a minimum shrinkage for samples cured between 3 and 7 days.

3. Reinforced expansion paste specimens shrink less than free expansion paste specimens due to the restraining effect of the steel wire. However, shrinkage trends for both cases are similar.

For Series 2: the shrinkage behaviour of expansive cements is a function of the expansion characteristics. A large amount of expansive component, resulting in excessive expansion and strength drop, may ultimately lead to higher shrinkage magnitudes. Therefore, in the design and curing of expansive cements, a rigid control on expansion is required to ensure proper field performance.

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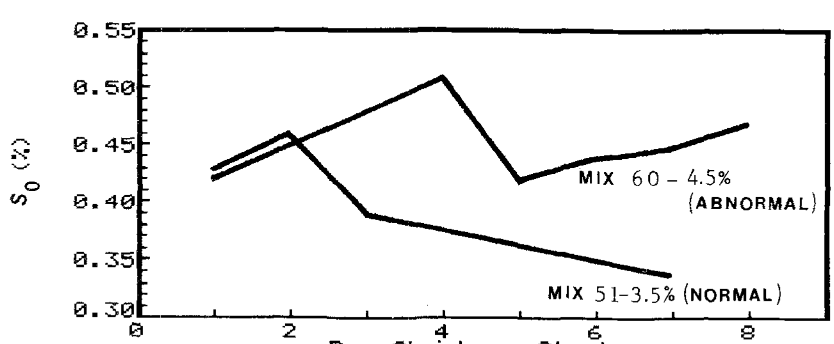

Figure 6 Ultimate shrinkage, S_0, Series 2.

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