ON THE MITIGATION OF EARLY AGE CRACKING

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Abstract

Potential means of limiting early age cracking of concrete structures have been investigated. Three different methods of mitigating autogenous strains and stresses in cement mortars (water-to-solid binder mass ratio = 0.35, 8 % silica fume) are compared: 1.) a reduction of the surface tension of the pore solution via addition of a shrinkage reducing chemical admixture, 2.) an increase of the internal water supply by replacement of a portion of the sand by saturated low-density fine aggregates or the addition of superabsorbent polymer particles, and 3.) the use of a slower reacting (coarser) silica fume. The effectiveness of each of these measures is presented, along with a basic physical explanation of self-desiccation and autogenous shrinkage.

1. Introduction

The recent trend in concrete technology towards so-called high-performance, or low water-to-solid binder mass ratio (w/s), concretes has not been without its problems. One of the major observed problems with these mixtures is their increased tendency to undergo early-age cracking. While this cracking may or may not compromise the (higher) compressive strengths of these concretes, it likely does compromise their long-term performance. The phenomenon of early-age cracking is complex and depends on thermal effects, autogenous strains and stresses, drying, stress relaxation, and structural detailing and execution [1,2]. In concretes with low w/s, a major contributor to early-age cracking can be the autogenous shrinkage induced by the self-desiccation that occurs during hydration under sealed or partially saturated conditions [3]. As the cementitious materials hydrate under sealed conditions, empty porosity is created within the 'set' microstructure, because the hydration products occupy less volume than the starting materials. The water menisci created by these empty pores in turn induce autogenous shrinkage stresses on the three-dimensional microstructure. The magnitude of these stresses is influenced by both the surface tension of the pore solution and the meniscus radius of the largest water-filled pore within the microstructure [3]. In this paper, a variety of engineering methods for reducing autogenous stresses and strains that focus on these two factors are explored. These methods include using a shrinkage-reducing admixture (SRA) [4], increasing the internal water supply via the replacement of sand by saturated low-density fine aggregates (LWA) [5,6,7] or the addition of superabsorbent polymer particles (SAP) [8,9], and using a coarser silica fume.

2. Experimental procedure

Mortars were prepared using a low-alkali Portland cement with a water-to-solid binder (w/s – where solid binder is cement + silica fume) mass ratio of 0.35 and an 8 % by mass fraction replacement of cement by silica fume. The cement has a Blaine fineness of 368 m^2/kg and a Bogue phase composition of 58 % C_3S, 25 % C_2S, 4.0 % C_3A, and 7.3 % C_4AF, with a 3.4 % calcium sulfate content. The two silica fumes used had specific surface areas of 23.2 m^2/g (reference) and 15 m^2/g (coarse), respectively. The mortars were prepared with CEN standard sand EN 196-1. For two of the mortars, either 8 % or 20 % of the sand by mass was replaced by low-density aggregates of size less than 4 mm. A summary of the six mixtures tested is provided in Table 1. All mortars were prepared by mixing in a 5-liter epicyclic mixer. All mixtures were prepared using freshly boiled (then cooled), distilled water. The 'extra' water in Table 1 refers to the water contained in the low-density aggregates or absorbed by the polymer particles.

Table 1 - Differences in the mortar mixtures.

Mixture characteristic	FSF	CSF	SRA	LWA20	LWA08	SAP
Silica fume, 23.2 m^2/g	X		X	X	X	X
Silica fume, 15 m^2/g		X				
Shrinkage-reducing admixture (2 % by mass of cement)			X			
Low-density aggregate 0-4 mm				20 % of sand	8 % of sand	
Assumed absorption of LWA (by mass)				25 %	25 %	
Superabsorbent polymer						X
Extra water/solid binder				0.126	0.046	0.046

The following measurements were performed: compressive strength of cylinders (diameter 60 mm, height 120 mm) after 7 d and 28 (or 27, 29, or 50) d sealed curing, internal relative humidity (RH), and autogenous deformation using a custom-built dilatometer immersed in a constant temperature oil bath [10,11]. All curing and measurements were conducted at a temperature of 30 °C ± 0.5 °C and under sealed conditions. Typical standard deviations measured on companion specimens were 5 MPa to 7 MPa, 0.17 % RH, and 5 microstrain to 17 microstrain, for compressive strength, internal RH, and autogenous deformation, respectively [4].

3. Results and discussion

The measured changes in internal RH with hydration time are provided in Figure 1. The measured internal RH is a function of temperature, and is projected to be about 3 % higher at 30 °C than at 20 °C [12,13]. After initial equilibrium of the sensors is achieved, the RH decreases with hydration time. This is a direct consequence of the creation of empty pores within the specimens hydrating under sealed conditions. The Kelvin equation describes the relationship between the size of these pores and the internal RH (assuming cylindrical pores and a contact angle of zero degrees between the pore solution and the pore walls) [14]:

$$\ln(RH) = \frac{-2\gamma V_m}{rRT} \tag{1}$$

$_m$ is its molar volume, r is the radius of the largest water-filled pore (or the smallest empty pore), R is the universal gas constant, and T is the absolute temperature. In the experiments presented in this paper, both â and r are a function of the different mixture proportions. The addition of the shrinkage-

either LWA or SAP will alter the size of the pores being emptied due to self-desiccation (hydration) of the paste. In general, it is assumed that the largest water-filled pores empty first as the surrounding cement paste hydrates.

These effects can be observed in Figure 1. The RH in the system containing the SRA remains above that of the ‘reference’ (FSF) system, remaining about 3 % RH higher after the first 15 d of hydration. For the mixtures with an internal supply of water (either LWA or SAP), the RH remains even higher throughout the course of the hydration, only falling to about 95 % after 12 d or so of hydration. While not shown in Figure 1 (for visual clarity), the results for the mortar containing coarser silica fume particles (CSF) were virtually identical to those measured for the mortar (FSF) with the fine silica fume.

The water menisci created during self-desiccation will induce capillary stresses in the pore solution (and on the solid network containing the pore solution). Assuming a cylindrical pore geometry, the tensile stress in the pore solution, ó$_{cap}$, is given by [14]:

$$\sigma_{cap} = \frac{2\gamma}{r} = \frac{-\ln(RH)RT}{V_m} \tag{2}$$

where all other terms have been defined above.

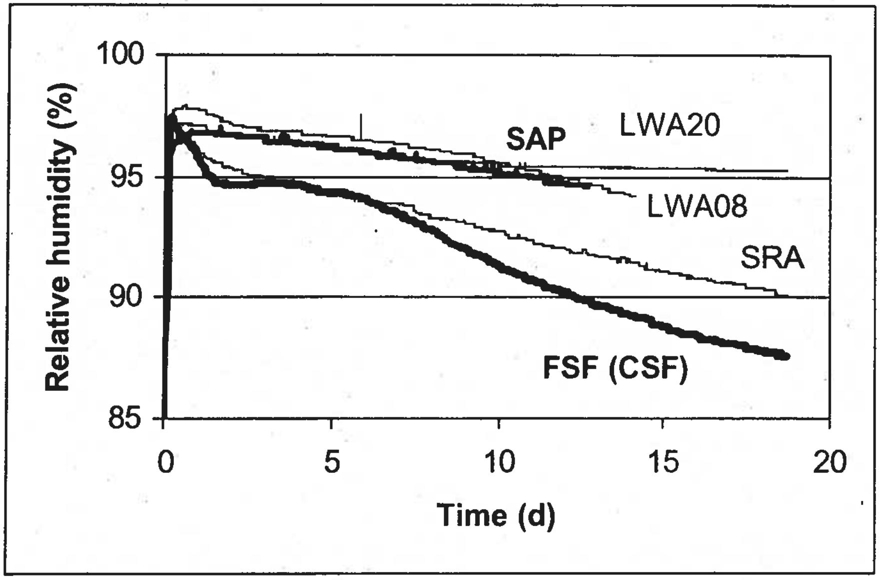

Figure 1 - Measured internal RH vs. time for the various mortars during sealed hydration at 30 °C.

The shrinkage strain of a partially saturated porous medium due to these capillary stresses in the water-filled pores can be estimated as [15]:

$$\varepsilon = \frac{S\sigma_{cap}}{3}\left(\frac{1}{K} - \frac{1}{K_s}\right) \tag{3}$$

where å is the shrinkage (negative strain), S is the degree of saturation (0 to 1) or fraction of water-filled pores, K is the bulk modulus of elasticity of the porous material, and K_s is the bulk modulus of the solid framework within the porous material. This equation is only approximate for a partially-saturated visco-elastic material such as hydrating cement paste, but still provides insight into the physical mechanism of autogenous shrinkage and the importance of various physical parameters.

The measured autogenous deformations for the various mixtures are provided in Figure 2. Once again, for clarity, the results for the CSF mortar are not shown but were basically identical to those shown for the reference FSF mortar. For the other mortars, however, major differences are observed. All of the other mixtures are somewhat effective in reducing/eliminating the autogenous shrinkage observed for the reference FSF mixture. The SRA reduces the autogenous shrinkage by a factor of two after 15 d of hydration. From the equations shown above, this reduction in measured shrinkage is consistent with the typical reduction in surface tension of the pore solution provided by addition of the SRA. For example, at NIST, a reduction in pore solution surface tension from (0.0665 ± 0.0006) N/m (standard deviation of five measurements) to (0.0400 ± 0.0003) N/m has been measured for pore solutions filtered from a cement paste (with and without a 2 % addition by mass of cement of SRA, w/s=0.45) 1 h after mixing [16].

The use of internal curing (by providing a supply of free water) is also seen to be a highly effective means of mitigating autogenous shrinkage. Each of the three internal curing mixtures (LWA08, LWA20, and SAP) either significantly reduces or eliminates the measured autogenous shrinkage. Because it provides the most extra curing water, the LWA20 mixture totally eliminates autogenous shrinkage, resulting instead in a small autogenous expansion, perhaps due to ettringite formation and/or swelling of the cement hydration products due to water absorption. While the SAP and LWA08 mortars contain basically the same quantity of 'extra' water (Table 1), the SAP mortar is more efficient in reducing autogenous shrinkage at later ages, most likely due to a more homogenous distribution of the extra curing water within the three-dimensional mortar microstructure. A comparison of the water distribution in these different mortars, based on computer modeling [17] and direct observation of two-dimensional cross sections, will be the subject of a future paper.

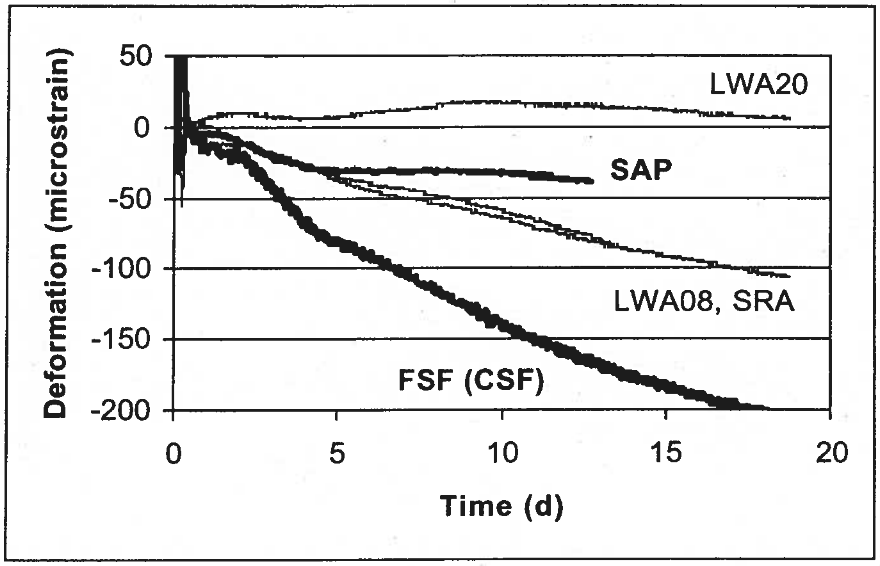

Figure 2 - Measured autogenous deformation vs. time for the various mortars during sealed hydration at 30 °C.

Figure 3 provides a plot of the autogenous deformation vs. the natural log of the internal RH for the different mixtures, during the first 12 d of hydration. According to equations (1) to (3), the local slope of this plot should be proportional to the ratio of the mixture saturation to its current elastic modulus (assuming that $K_s >> K$). Also, according to these equations, the relationship between autogenous shrinkage and relative humidity should be independent of the surface tension of the pore solution. Thus, any differences in slope between the mortars with and without the SRA are due instead to the fact that when lower RHs are finally achieved in the SRA mortar, the elastic modulus is higher and the system saturation is less (both due to its increased degree of hydration). This illustrates that if the development of autogenous stresses can be substantially delayed, the resulting shrinkage will be much less due to the increased stiffness developed by the hydrating cement paste.

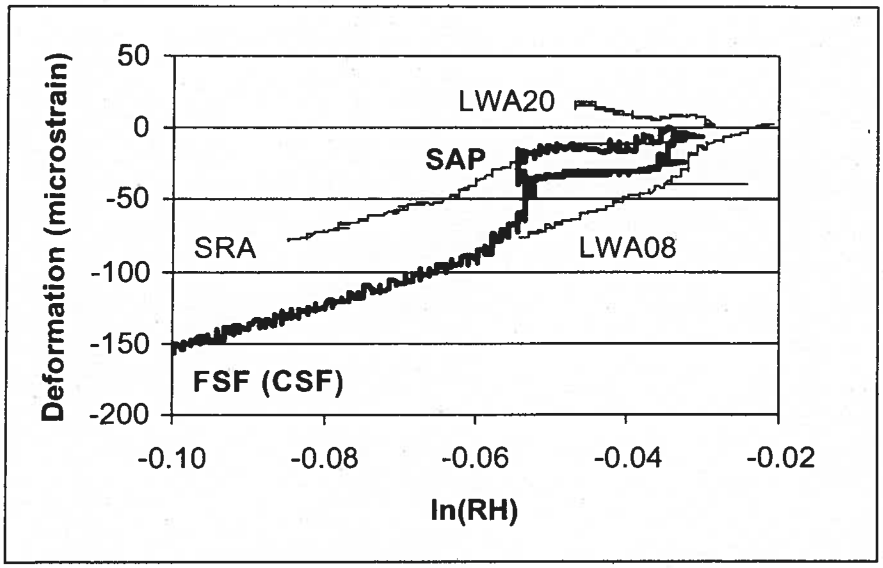

Figure 3 - Autogenous deformation vs. RH for the various mortars during sealed hydration at 30 °C.

Finally, the results of the compressive strength testing are provided in Figure 4. The measured proportional gains in compressive strength between 7 d and later ages (27 d to 56 d) can be linked to the internal RH data presented in Figure 1. It is consistently observed that for those specimens where a higher internal RH is maintained during this time period, a greater gain in compressive strength is found. This is a natural consequence of the linkages between moisture availability, hydration rates, and strength development. It is well known that hydration proceeds at a reduced rate as the specimen internal RH is decreased [18,19,20]. This highlights a possible secondary benefit of internal curing in addition to the primary reduction in autogenous deformation, namely the achievement of an increased degree of hydration and a potentially higher compressive strength (and lower permeability/diffusivity) under sealed curing conditions. The increased degree of hydration may not always lead to an increase in compressive strength for the mortar or concrete specimens, as the increased strength of the cement paste binder may be offset by the increased porosity of the composite as a whole (due to the internal porosity of the low-density aggregates or the hollow voids introduced by the SAP particles). In practice, the influence of specimen RH on measured compressive strength presents an additional complication [9,21].

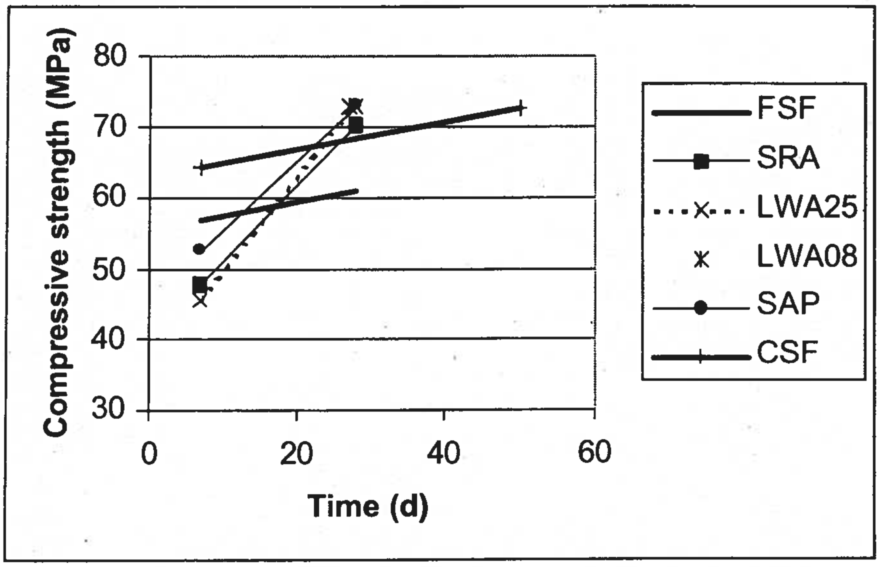

Figure 4 - Compressive strength development for the various mortars during sealed hydration at 30 °C.

4. Conclusions

The experimental results presented in this paper clearly demonstrate that autogenous shrinkage can be reduced by several different means. Shrinkage-reducing admixtures that reduce the surface tension of the pore solution reduce both the decrease in internal RH and the measured autogenous shrinkage. Internal curing, either by the use of saturated low-density fine aggregates or the addition of superabsorbent polymer particles, provides the extra curing water needed for cement hydration under sealed conditions. In this case, autogenous shrinkage is reduced due to the fact that much larger pores (within the LWA or formed by the SAP particles themselves) are being emptied than those typically emptied in cement paste during sealed hydration. The use of a coarser silica fume had a negligible influence on both internal RH development and measured autogenous shrinkage. An additional benefit of the approaches that were successful in reducing autogenous shrinkage may be an increased degree of hydration and measured compressive strength at later ages, due to the increased and persistent availability of moisture.

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