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Mitigating Autogenous Shrinkage by Internal Curing

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Synopsis: The use of internal curing is a highly effective means of mitigating autogenous shrinkage in cement mortars (w/cm=0.35, 8 % silica fume). Two different sources of internal water supply are compared: 1) replacement of a portion of the sand by partially saturated lightweight fine aggregate and 2) the addition of superabsorbent polymer particles (SAP). At equal water addition rates, the SAP system is seen to be more efficient in reducing autogenous shrinkage at later ages, most likely due to a more homogeneous distribution of the extra curing water within the three-dimensional mortar microstructure. A comparison of the water distribution in the different systems, based on computer modeling and direct observation of two-dimensional cross sections, is given.

Keywords: autogenous deformation; autogenous RH-change; early age cracking; internal curing; lightweight fine aggregates; mortar

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INTRODUCTION

The recent trend in concrete technology towards so-called high-performance, or low w/cm, concretes has not been without its problems. One of the major 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 durability. 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/cm, 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 reacting materials. The water menisci created by these empty pores in turn induce compressive stresses in the three-dimensional microstructure. The magnitude of these stresses is influenced by both the surface tension of the pore solution [4] and the meniscus radius of the largest water-filled pore within the microstructure [3]. In this paper, two engineering methods for reducing autogenous stresses and strains by internal water supply are compared: the replacement of sand by partially saturated lightweight fine aggregates (LWA) [5,6,7] and the addition of superabsorbent polymer particles (SAP) [8,9].

EXPERIMENTAL PROCEDURE

Mortars were prepared using a low-alkali Portland cement with a w/cm mass ratio of 0.35 and an 8 % 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 silica fume has a specific surface area of 23.2 m^2/g. The mortars were prepared with CEN standard sand EN 196-1 [10]. The reference mortar is designated FSF and consisted of 1540 g cement, 134 g silica fume, 586 g water, and 4050 g CEN sand. 10 to 25 g of a superplasticizer was added to each mortar mixture to assure adequate workability. For two of the mortars, either 8 % or 20 % of the sand by mass was replaced by lightweight aggregates (LWA) smaller than 4 mm. For the final mortar, a 0.04 % addition (mass fraction of cement) of superabsorbent polymer particles [8,9] was used.

A summary of the four mixtures tested is provided in Table 1, and particle size distributions for the CEN sand, the LWA, and the (expanded) superabsorbent polymer are given in Figure 1. All mortars were prepared by mixing in a 5 L 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 LWA or absorbed by the polymer particles.

The following measurements were performed: compressive strength of cylinders (diameter 60 mm, height 120 mm) after 7 days and 28 (or 27 or 29) days sealed curing, internal relative humidity (RH), and autogenous deformation using a custom-built dilatometer immersed in a constant temperature polyalkylene glycol bath [11,12]. All curing and measurements were conducted at 30 °C ± 0.5 °C and under sealed conditions. Typical standard deviations measured among companion specimens were 6 MPa, 0.2 % RH, and 10 microstrain, for compressive strength, internal RH, and autogenous deformation, respectively [4].

RESULTS AND DISCUSSION

The measured changes in internal RH with hydration time are provided in Figure 2. The measured internal RH is a function of temperature, and is projected to be about 3 % higher at 30 °C than at 20 °C [13]. After initial equilibrium of the sensors was 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]:

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

where γ is the surface tension of the pore solution, V_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. The introduction of either LWA or SAP will alter the size of the pores being emptied due to self-desiccation (hydration) of the paste. The largest water-filled pores empty first as the surrounding cement paste hydrates [15]. The effect can be observed in Figure 2. For the mixtures with an internal supply of water (either LWA or SAP), the RH remains higher than in the reference mixture throughout the course of the hydration, only falling to about 95 % after 12 days of hydration, as the larger pores in the LWA or the expanded SAP particles empty instead of the smaller capillary pores in the hydrating cement paste. According to equation 1, the emptying of these larger pores (higher values of r) will result in higher RH values, as is observed experimentally.

The water menisci created during self-desiccation will induce capillary stresses in the pore solution and therefore on the solid network containing the pore solution. Assuming a cylindrical pore geometry, the tensile stress in the pore solution, σ_{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.

The shrinkage strain of a partially saturated porous medium due to these capillary stresses in the water-filled pores can be estimated as [16,17]:

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

where ε is the shrinkage (negative strain), S is the degree of saturation (0 to 1) or volume 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 constituent of 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 3. The use of internal curing (by providing a supply of free water) is 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.

A comparison of the distribution (availability) of internal curing water in the three different mortars with internal curing has been undertaken using the NIST 3-D hard core-soft shell (HCSS) computer model of "water" distribution within mortar [18,19], based on the measured particle size distributions for the sand, LWA, and SAP (expanded) particles.The relative proximity of the hydrating cement paste to the internal water sources (LWA or SAP) is illustrated in Figure 4.

Because of the low permeability of high-performance cement paste, self-desiccation is completely prevented only within approximately 100 μm from an internal curing source.

Thus, according to the paste proximity plot provided in Figure 4, the mortar LWA20 should be protected, while the mortars LWA08 and SAP should undergo self-desiccation, at least locally, in agreement with the measured autogenous deformations shown in Figure 3. This is also illustrated in Figure 5, which shows 2-D images generated from the 3-D HCSS microstructures of the mortars LWA08, LWA20 and SAP, including sand, LWA or SAP, and the proximity of the hydrating paste to the LWA/SAP surfaces (paste <= 100 μm from LWA or SAP, or paste > 100 μm from LWA or SAP).
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 (Figure 3), most likely due to the more homogeneous distribution of the extra curing water within the three-dimensional mortar microstructure (Figure 5c vs. Figure 5a). At earlier ages (< 5 days), SAP and LWA08 perform equivalently with respect to autogenous deformation (Figure 3), as the internal curing water is able to travel distances greater than 100 μm within the more porous, higher permeability 'early-age' cement paste. Photos of polished sections of the mortars LWA20 and SAP are given in Figure 6. The spatial distribution of the LWA and SAP (voids) in the actual images of the mortars compare reasonably well with their respective simulated color 2-D images in Figure 5.

Finally, the results of the compressive strength testing are provided in Figure 7. The measured proportional gains in compressive strength between 7 days and later ages (27 days to 29 days) can be linked to the internal RH data presented in Figure 2. 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 [20,21,22]. 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 LWA or the hollow voids introduced by the SAP particles). In practice, the influence of specimen RH on measured compressive strength presents an additional complication [9,23].

CONCLUSIONS

The experimental results presented in this paper clearly demonstrate that autogenous shrinkage can be reduced by internal curing. Either the use of partially saturated lightweight aggregates (LWA) or the addition of superabsorbent polymer particles (SAP) can provide the extra curing water needed for cement hydration under sealed conditions. Autogenous shrinkage is reduced due to larger pores (within the LWA or formed by the SAP particles themselves) being emptied than those typically emptied in cement paste during sealed hydration. Clearly, both the water content and its spatial distribution within the paste are important factors. An additional benefit of the internal curing approach to 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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REFERENCES

1. Lura, P., van Breugel, K., and Maruyama, L., Effect of Curing Temperature and Type of Cement on Early-age Shrinkage of High Performance Concrete, Cem. Concr. Res., **31** (12) (2001) 1867-1872.

2. Shah, S.P., Weiss, W.J., and Yang, W., Shrinkage Cracking – Can It Be Prevented?, Concr. Inter. **20** (4) (1998) 51-55.

3. Bentz, D.P., and Jensen, O.M., Mitigation Strategies for Autogenous Shrinkage Cracking, submitted to Cement and Concrete Composites, 2002.

4. Bentz, D.P., Geiker, M.R., and Hansen, K.K., Shrinkage-reducing Admixtures and Early-age Desiccation in Cement Pastes and Mortars, Cem. Concr. Res. **31** (7) (2001) 1075-1085.

5. Weber, S., and Reinhardt, H.W., A New Generation of High Performance Concrete: Concrete with Autogenous Curing, Adv. Cem.-Based Mater. **6** (1997) 59-68.

6. van Breugel, K., and Lura, P., Effect of Initial Moisture Content and Particle Size Distribution of Lightweight Aggregates on Autogenous Deformation, in 'Proceedings of the Second International Symposium on Structural Lightweight Aggregate Concrete', Eds. S. Helland, I. Holand, and S. Smeplass (2000) 453-462.

7. Bentur, A., Igarashi, S., and Kovler, K., Prevention of Autogenous Shrinkage in High Strength Concrete by Internal Curing Using Wet Lightweight Aggregates, Cem. Concr. Res. **31** (11) (2001) 1587-1591.

8. Jensen, O.M., and Hansen, P.F., Water-entrained Cement-based Materials I. Principle and Theoretical Background, Cem. Concr. Res. **31** (2001) 647-654.

9. Jensen, O.M., and Hansen, P.F., Water-entrained Cement-based Materials II. Experimental Observations, Cem. Concr. Res. **32** (6) (2002) 973-978.

10. DIN EN 196: Pruefverfahren fuer Zement. (Deutsches Institut fuer Normung e.V., Berlin) 1990-1995.

11. Jensen, O.M., and Hansen, P.F., A Dilatometer for Measuring Autogenous Deformation in Hardening Portland Cement Paste, Mater. Struct. **28** (1995) 406-409.

12. Jensen, O.M., and Hansen, P.F., Autogenous Deformation and Change of Relative Humidity in Silica Fume Modified Cement Paste, ACI Mater. J. **93** (6) (1996) 539-543.

13. Jensen, O.M., and Hansen, P.F, Influence of Temperature on Autogenous Deformation and RH-change in Hardening Cement Paste, Cem. Concr. Res. **29** (4) (1999) 567-575)

14. Alberty, R.A., and Daniels, F., Physical Chemistry (John Wiley & Sons, New York, 1980).

15. Bentz, D.P, Hansen, K.K., Madsen, H.D., Vallee, F., and Griesel, E.J.: Drying/hydration in Cement Pastes During Curing, Mater. Struct. **34** (2000) 557-565.

16. MacKenzie, J.K., The Elastic Constants of a Solid Containing Spherical Holes, Proc. Phys. Soc. A **224** (1950) 526-544.

17. Bentz, D.P., Garboczi, E.J., and Quenard, D.A., Modelling Drying Shrinkage in Reconstructed Porous Materials: Application to Porous Vycor Glass, Modelling Simul. Mater. Sci. Eng. **6** (1998) 211-236.

18. Bentz, D.P., and Snyder, K.A., Protected Paste Volume in Concrete – Extension to Internal Curing Using Saturated Lightweight Fine Aggregate, Cem. Conc. Res. **29** (1999) 1863-1867.

19. Bentz, D.P., Garboczi, E.J., and Snyder, K.A., A Hard Core/Soft Shell Microstructural Model for Studying Percolation and Transport in Three-Dimensional Composite Media, NISTIR **6265**, U.S. Department of Commerce, January 1999.

20. Powers, T.C., A Discussion of Cement Hydration in Relation to the Curing of Concrete, Proc. Highway Res. Board **27** (1947) 178-188.

21. Parrott, L.J., Killoh, D.C., and Patel, R.G., Cement Hydration Under Partially Saturated Curing Conditions, in 'Proceedings of the 8th International Congress on the Chemistry of Cement', Rio de Janeiro, Vol. III (1986) 46-50.

22. Snyder, K.A., and Bentz, D.P., Early Age Cement Paste Hydration at 90 % Relative Humidity and the Loss of Freezable Water, to be published as a NISTIR, U.S. Department of Commerce, 2002.

23. Neville, A., Properties of Concrete, 4th edition (John Wiley & Sons, New York, 1996).

Table 1 - Differences in the mortar mixtures.

Mixture characteristic	FSF	LWA20	LWA08	SAP
Silica fume, 23.2 m^2/g (w/w replacement)	8 %	8 %	8 %	8 %
Lightweight aggregate, 0 mm to 4 mm (w/w)		20 % of sand	8 % of sand	
Assumed absorption of LWA (by mass)		25 %	25 %	
Superabsorbent polymer				0.04 %
Extra w/cm (internal curing water)		0.126	0.046	0.046

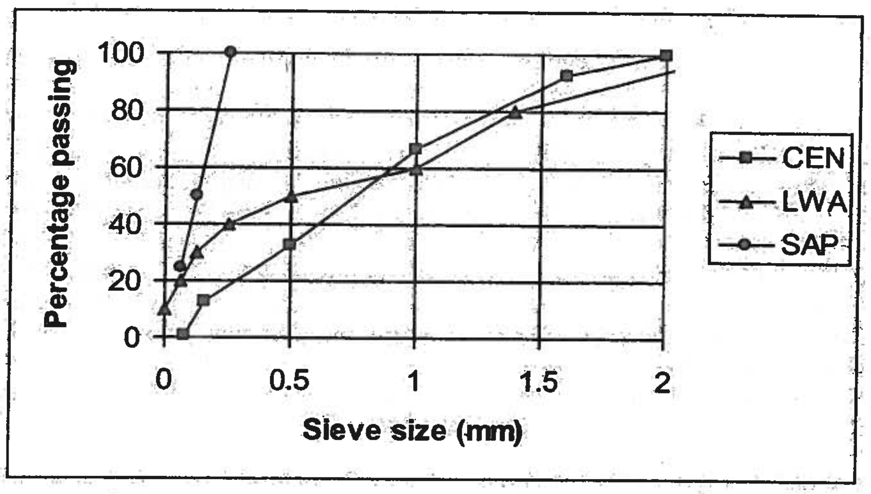

Fig. 1. Particle size distributions for the CEN sand, LWA, and the superabsorbent polymer.

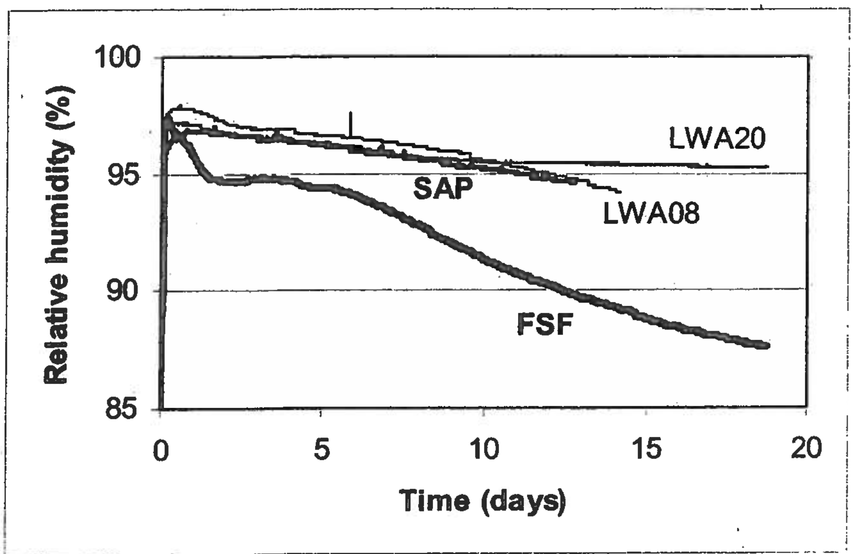

Fig. 2. Measured internal RH vs. time for the various mortars during sealed hydration at 30 °C.

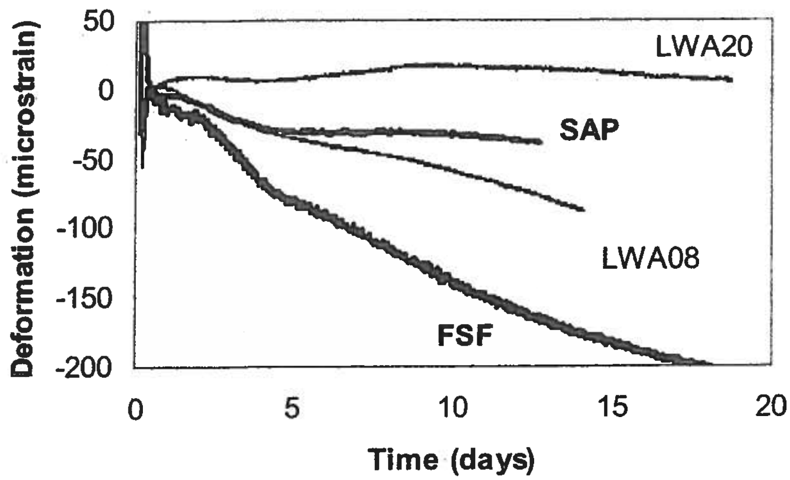

Fig. 3. Measured autogenous deformation vs. time for the various mortars during sealed hydration at 30 °C.

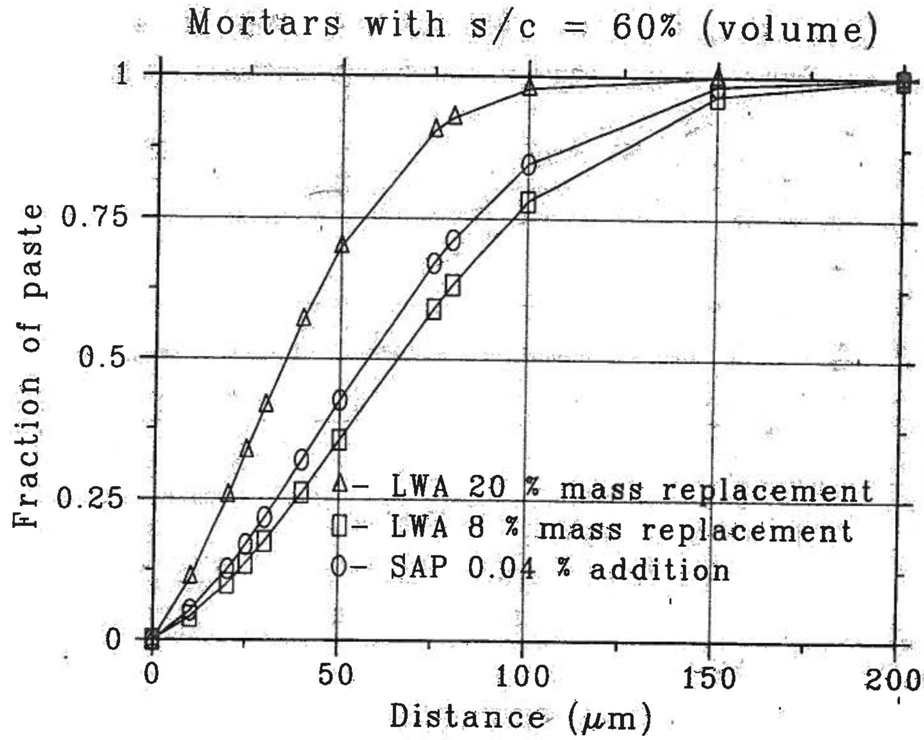

Fig. 4. Computer modeling of fraction of paste vs. distance from a LWA or SAP particle surface.

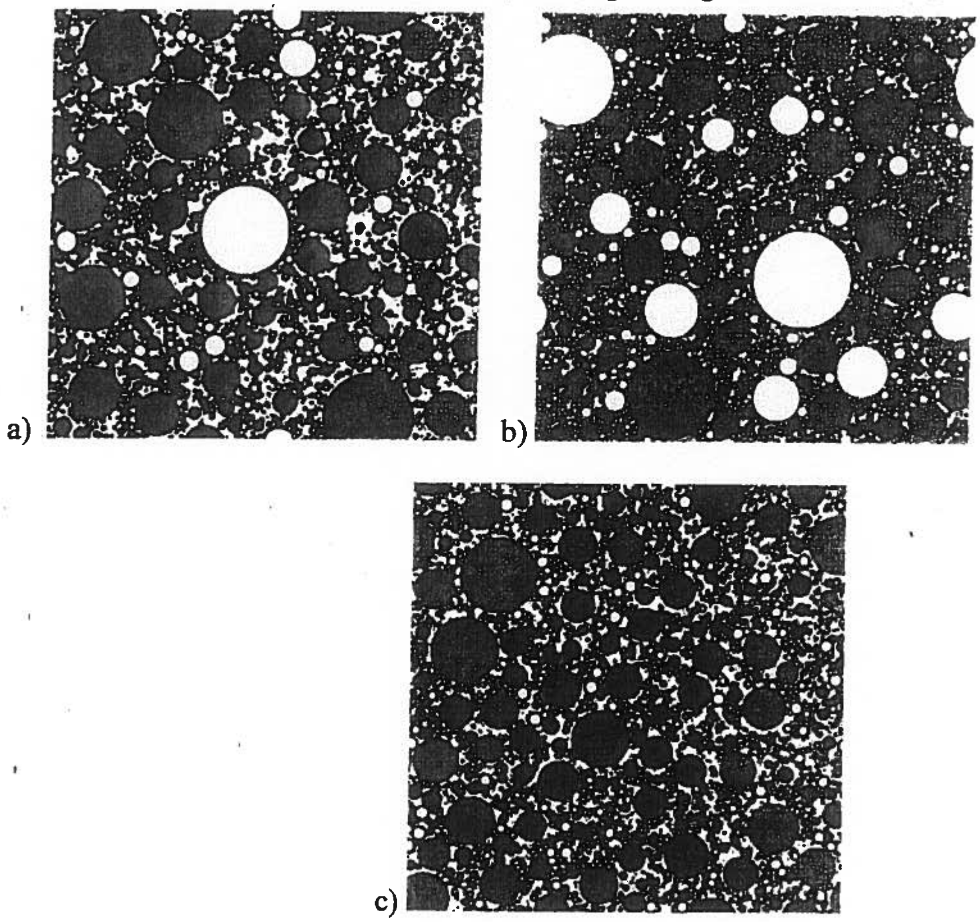

Fig. 5. Computer modeling of the distribution of phases. a: 8 % replacement (the white "unprotected" paste is 97 % percolated in 3-D) b: 20 % replacement of sand by LWA and c: 0.04 % addition of SAP particles (the white paste is 83 % percolated in 3-D). Color code: Red- sand, yellow- LWA or SAP, white- paste > 100 mm from LWA or SAP, blue- paste within 100 mm from LWA or SAP. Each 2-D image is 10 mm x 10 mm in size.

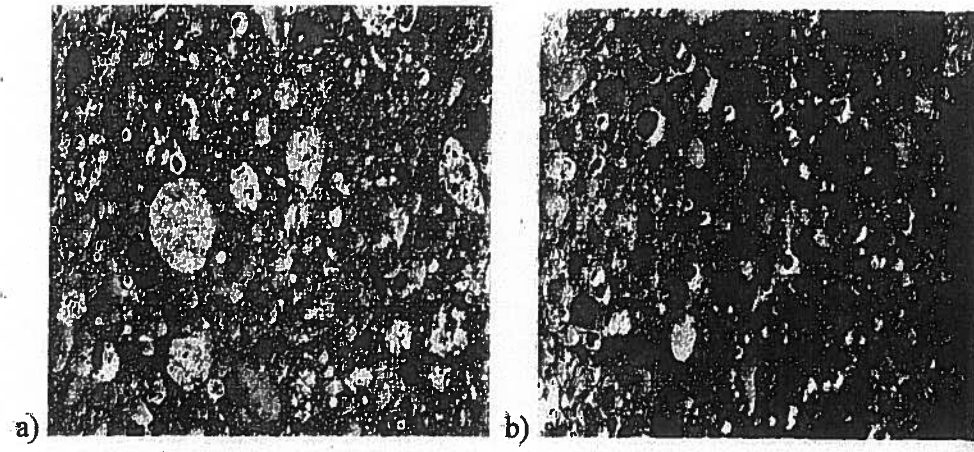

Fig. 6. 2-D microstructures for the a) LWA mortar with 20 % mass replacement (LWA20) and the b) SAP mortar systems. Polished specimens, optical microscope with a field width of 15 mm.

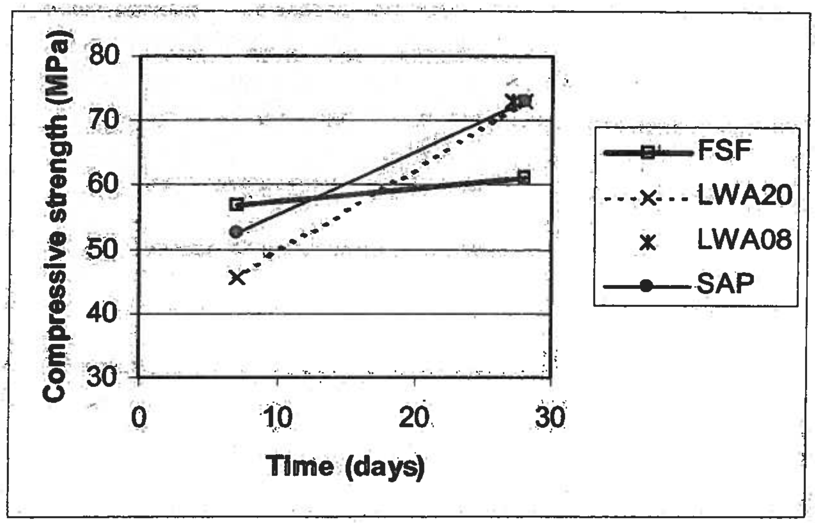

Fig. 7. Compressive strength development for the various mortars during sealed hydration at 30 °C.