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Influence of cement paste matrix properties on the autogenous curing of high-performance concrete

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Abstract

A novel approach to has been recently proposed mitigate self-desiccation, one of the foremost problems of high-performance concrete (HPC). It is based on incorporation of pre-soaked lightweight aggregate in the concrete mix. Such aggregate acts as an internal water reservoir preventing reduction of relative humidity in the cementitious matrix. This method is known as "autogenous" or "internal" curing. Recent studies demonstrated that this kind of curing could be successfully applied to obtain improved HPC with reduced sensitivity to cracking. However, the content of lightweight aggregate required to completely eliminate autogenous shrinkage was high, and this caused a reduction of compressive strength and an increase in the cost of the concrete.

Recently, a work has been conducted to optimize the internal curing strategy by eliminating autogenous shrinkage while using the smallest possible amount of lightweight aggregate. The effect of grain size, pore structure and type of the lightweight aggregate was studied. The next step in this study—the effect of the properties of the cement paste matrix on the effectiveness of internal curing is discussed in this paper.

Keywords: Internal curing; Autogenous shrinkage; Self-desiccation; High-performance concrete; Cement matrix; Lightweight aggregate; Pumice

1. Introduction

High-performance concrete (HPC) with extremely low water to binder (w/b) ratio is often characterized by high cracking sensitivity due to increased autogenous shrinkage [1–3]. The major reason for autogenous shrinkage—self-desiccation [4,5], which is, in turn, caused by chemical shrinkage, cannot be eliminated by traditional curing methods. A novel approach, that has been recently proposed, is autogenous curing. It is based on incorporation of pre-soaked lightweight aggregate into the mix, which acts as an internal water reservoir preventing reduction of relative humidity [6,7]. This method is called "autogenous" or "internal" curing. Previous experimental work demonstrated that autogenous curing could be successfully applied to obtain improved high strength concrete with reduced sensitivity to cracking [8–14]. However, the lightweight aggregate content needed to eliminate autogenous shrinkage was high, which resulted in reduced compressive strength and an increase in the cost of the concrete. This is a limitation with regards to practical implementation of autogenous curing.

Later, the concept of internal curing by means of saturated lightweight aggregate was applied with an attempt to optimize it to eliminate autogenous shrinkage with the smallest possible amount of lightweight aggregate [15]. In the course of this work, the grain size of the lightweight aggregate used as curing agent was reduced in order to minimize the paste–aggregate proximity, i.e. the distance to which the internal curing water should diffuse. The reduction of the grain size, down to 2–4 mm, was shown to be beneficial. However, the further reduction of grain size resulted in a decrease of curing efficiency. Since smaller particle sizes of pumice, the lightweight aggregate used in this experiments, had lower water absorption capacity, it was suggested that the pore size and aggregate distribution play a more significant role in the process of autogenous curing than the grain size [15–17].

These investigations considered only a w/b ratio of 0.33, so the influence of w/b ratio on the efficiency of autogenous curing remained vague. Reduction of w/b ratio in HPC is accompanied by a reduction in permeability, which may limit the efficiency of the saturated

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lightweight aggregate. For this reason, in mixes with much lower w/b ratio paste–aggregate proximity may become critical, and thus grain size may become crucial in controlling the efficiency of autogenous curing. Additionally, since microsilica has a substantial effect on the microstructure of concrete, it may have an effect on the autogenous curing as well.

The current study investigated the influence of the microstructure of the cement paste on the efficiency of autogenous curing.

2. Efficiency of lightweight aggregate for internal curing

The water content required to be introduced with lightweight aggregate in order to eliminate self-desiccation (W_{ic}) can be calculated from chemical shrinkage (Eq. (1) [15–17]).

$$W_{ic}(\text{kg water/m}^3\text{ concrete}) = C \cdot \text{CS} \cdot \alpha_{max} \quad (1)$$

where C is cement content, CS is chemical shrinkage in kg of water per kg of cement hydrated and α_{max} is the maximum anticipated degree of hydration. Accordingly, the lightweight aggregate content for internal curing can be calculated by Eq. (2).

$$W_{LWA} = \frac{W_{ic}}{S \cdot \phi} \quad (2)$$

In this equation ϕ denotes the water absorption capacity of the lightweight aggregate. Consequently, the content of normal weight aggregate should be reduced by a volume equal to the volume of the lightweight aggregate introduced to the mix. The current study used only fully saturated lightweight aggregates, i.e. with degree of saturation equal to one ($S = 1$).

In practice, elimination of autogenous shrinkage requires greater content of lightweight aggregates, than calculated from Eq. (2). This implies that not all of the internal water can become effectively available for internal curing. From an engineering point of view, one may address this effect by assigning an efficiency coefficient to the system (aggregates and matrix), which ranges between 0 and 1. This coefficient may be determined experimentally by actual observations of the autogenous shrinkage of a reference system without the lightweight aggregates, and the reduction in the autogenous shrinkage when they are present. The efficiency of lightweight aggregates can be expressed as:

$$\eta = \frac{W_{ic}}{S \cdot \phi \cdot W_{LWA}} \cdot \text{SR} \quad (3)$$

where SR is percentage of shrinkage reduction and W_{LWA} is the LWA content.

Previous work has shown that in certain conditions the efficiency could be quite high, about 80% [15]. The efficiency is dependent on several processes and parameters, which are not yet clearly resolved. Some of them are outlined below.

2.1. W/b ratio and addition of silica fume as factors controlling water transport in cement matrix

It is evident that the effectiveness of internal curing depends on the water transport characteristics within the cement paste, namely permeability, porosity and pore size distribution, which are functions of w/b ratio and degree of hydration.

The effect of w/b ratio is not well studied. Comparison of the influence of the same autogenous curing (i.e. the same lightweight aggregate content containing the same amount of water) on mixes with different w/b ratio has not been investigated. Most of the experimental studies of internal curing have been restricted to a single w/b ratio. However, the lightweight aggregate content, which can effectively reduce autogenous shrinkage for one w/b ratio may be less effective or not effective at all in the case of a lower w/b ratio.

Silica fume may also significantly influence autogenous curing effect since it has an impact on pore size distribution and permeability. Accordingly, three types of concrete were tested in this study: (i) w/b ratio 0.33 without silica fume, (ii) w/b ratio 0.25 without silica fume, and (iii) w/b ratio 0.25 with silica fume (0.25SF).

2.2. Lightweight aggregate grain size and paste–aggregate/aggregate–aggregate proximity

The effectiveness of internal curing depends not only on whether there is sufficient water in the lightweight aggregate, but on whether it is readily available to the surrounding cement paste as well. Hence, if the distance from some location in the cement paste to the nearest lightweight aggregate surface is too great, water cannot permeate fully within an acceptable time interval. This distance can be called the paste–aggregate proximity. Alternatively, aggregate distribution can be described by means of aggregate–aggregate proximity, which is the distance between two nearest lightweight aggregate surfaces, often called spacing. For a given amount of aggregate, the paste–aggregate proximity can be adjusted by the size of the aggregate. The finer the aggregate size, the closer will be the paste–aggregate proximity.

Probability density function or cumulative distribution function for both "paste–aggregate" or "aggregate–aggregate" proximities can be estimated by the analytical equations proposed by Lu and Torquato [18]. In the current study the mean value of paste–aggregate proximity calculated according to these equations was determined for the comparison between mixes with different aggregate size and content.

Although these equations do not consider effect of normal weight aggregate also present in the system, they are the most simple and accurate among different analytical equations giving statistical estimation of paste–aggregate proximity. In principle, one can overcome the limitation of two-phase models using three-dimensional computer models of concrete microstructure for determination of paste–aggregate proximity [16,19], but this development is out of scope of the current study.

3. Experimental

3.1. Lightweight aggregates for internal curing

Crushed pumice sand imported from Yali Island, Greece, was used as lightweight fine aggregate for internal curing.

The three single size fractions were separated from the pumice sand. These fractions were labeled "Pumice0", "Pumice1" and "Pumice2". Their properties are listed in Table 1.

Results of the water absorption are presented in Fig. 1. The test demonstrated that all fractions of pumice sand have continuous absorption during a period longer than a month. This not only makes the determination of water absorption capacity difficult, but also hampers the use of saturated pumice as an internal curing agent. In order to minimize the saturation time, absorption was carried out in boiling water for 72 h. The results of the absorption test for Pumice0, Pumice1 and Pumice2 in boiling water are shown in Fig. 2. As can be seen, saturation in boiling water is obtained within 2–3 days for all fractions. For convenience, the water absorption of pumice in boiling water after 72 h was taken here as water absorption capacity (see Table 1) for all the fractions.

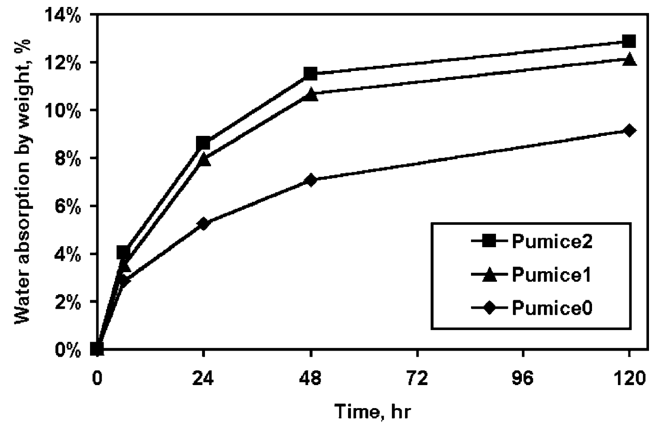

Fig. 1. Water absorption of pumice sand in water at 30 °C.

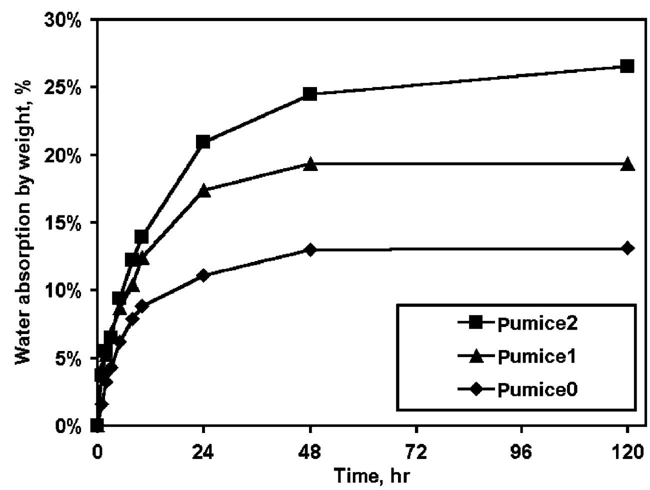

Fig. 2. Water absorption of pumice sand in boiling water.

3.2. Concrete constituents and mix proportions

3.2.1. Aggregates

The fine aggregate was natural quartz sea sand with a grain size below 0.6 mm. The effective water absorption, tested according to ASTM C128-01, was 0.4% by weight, with specific gravity of 2630 kg/m^3.

The coarse aggregate was crushed dolomite of 2.36 mm $< d <$ 9.5 mm. The effective water absorption, tested according to ASTM C127-01, was 1.5% by weight, with specific gravity of 2700 kg/m^3.

The properties of the lightweight fine aggregates are presented in Table 1.

Table 1
Properties of pumice aggregates

Aggregate	Specific gravity, kg/m^3	Grain size, mm	Water absorption capacity	
			% by weight	% by volume
Pumice0	1330	0.15–1.18	13.0	17.3
Pumice1	1310	1.18–2.36	19.0	24.9
Pumice2	1210	2.36–4.75	26.7	32.3

3.2.2. Cement

Commercially available ordinary Portland cement manufactured by Nesher—Israel Cement Enterprises Ltd. was used. The chemical composition of the Portland cement is given in Table 2. The loss on ignition was 4.2% by weight.

The specific surface area of the Portland cement, tested according to ASTM C204-00, was 323 m^2/kg.

3.2.3. Silica fume

In some mixes with w/b ratio of 0.25, silica fume was used in order to produce concrete with extremely low permeability. The silica fume had specific surface area of 18.2 m^2/g. The SiO_2 content was 92% by weight. The bulk specific gravity was 1390 kg/m^3.

Table 2
Chemical composition of Portland cement

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	K_2O	Na_2O	SO_3
% by weight	64.8	19.38	4.3	1.95	1.09	0.38	0.25	0.19	1.92

3.2.4. Concrete composition

The effect of saturated pumice sand on the autogenous shrinkage and the strength of high strength concretes was investigated on the mixes with w/b ratio 0.33. The superplasticizer used was of the naphthalene formaldehyde sulfonate type at content of 1.5% by weight of cement. In the mixes with lightweight aggregates, sand was replaced with an equal volume of lightweight aggregate.

For the evaluation of the interrelationship between w/b ratio and particle size effect, the aggregate content was adjusted according to Eq. (2) so that the aggregate contained the amount of water required to counteract self-desiccation calculated according to Eq. (1). The particle size effect was studied on w/b ratios of 0.33 and 0.25SF.

In order to study the effect of cement matrix quality on the internal curing process, the quantities of saturated pumice sand calculated according Eq. (2) were added to concretes with different w/b ratios. All the pumice fractions were tested in concretes with w/b ratio of 0.33 and 0.25SF (with silica fume). The Pumice2 aggregate was additionally tested with regard to w/b ratio of 0.25 (without silica fume). The compositions of the mixes are given in Tables 3–5.

3.3. Testing procedures

Shrinkage tests were conducted using the testing apparatus described in [20]. This system is computer-controlled, accurate, and allows measurement immediately after casting. The specimen size was 40 mm × 40 mm × 1000 mm.

Since the testing system had previously been shown to produce acceptable reproducibility, the shrinkage tests were not generally repeated. For this reason, the curves presented are the product of a typical test, and not the average of several tests, even when the tests were repeated. The duration of each shrinkage test was 168 h, i.e. one week.

The numerical value of shrinkage, for the comparison purposes and calculations, is taken as deformation from the peak of initial swelling to the point at the end of the test, i.e. at 168 h.

Cube specimens of 50 mm size were used to determine compressive strength. The compressive strength tests

Table 3
Mix proportions for w/b ratio 0.33 (kg/m^3)[a]

	Cement	Mix water	Sand	Gravel	Pumice	Replacement, % by volume
Reference WSAREF	506	167	574 (572)	1162 (1145)	0	0
Pumice0 + 20 kg water "Pumice0(20)033"	506	167	268 (267)	1162 (1145)	174 (154)	53.0
Pumice1 + 20 kg water "Pumice1(20)033"	506	167	362 (361)	1162 (1145)	125 (105)	36.0
Pumice2 + 20 kg water "Pumice2(20)033"	506	167	410 (408)	1162 (1145)	95 (75)	28.6

[a] Values in parentheses are: in the mix notation—absorbed water content; for aggregates—dry weights.

Table 4
Mix proportions for w/b ratio 0.25 using silica fume (kg/m^3)[a]

	Cement	Silica fume	Mix water	Sand	Gravel	Pumice	Replacement, % by volume
Reference WSAREF025SF	580	60	160	472 (470)	1162 (1145)	0	0
Pumice0 + 23 kg water "Pumice0(23)025SF"	580	60	160	117 (117)	1162 (1145)	199 (176)	75.1
Pumice1 + 23 kg water "Pumice1(23)025SF"	580	60	160	228 (227)	1162 (1145)	144 (121)	51.7
Pumice2 + 23 kg water "Pumice2(23)025SF"	580	60	160	286 (285)	1162 (1145)	108 (85)	60.6

[a] Values in parentheses are dry weights.

Table 5
Mix proportions for w/b ratio 0.25 (kg/m^3)[a]

	Cement	Mix water	Sand	Gravel	Pumice	Replacement, % by volume
Reference WSAREF025	600	150	596 (594)	1162 (1145)	0	0
Pumice2 + 24 kg water "Pumice2(24)025"	600	150	400 (398)	1162 (1145)	114 (90)	33.0

[a] Values in parentheses are dry weights.

were carried out at the age of 1, 3, 7 and 28 days. For all mixtures, five specimens were tested for every age and the presented compressive strength is the average value.

Free shrinkage and strength specimens were cast immediately after slump tests. Molds of the shrinkage apparatus were filled with concrete in one layer and compacted by tamping. Molds for strength specimens were filled with concrete in one layer and compacted by means of vibrating table.

All specimens were cured in sealed conditions in a room at a constant temperature of 30 ± 1 °C. The sealing was provided by polyethylene sheets, which covered the concrete by at least five layers. The cubes were demolded and sealed after 24 h.

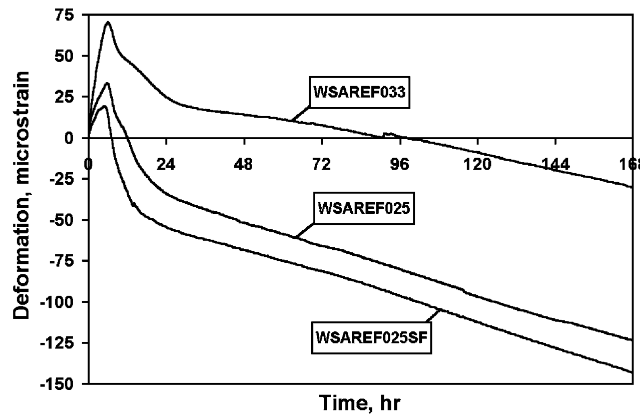

Fig. 3. Effect of w/b ratio on free shrinkage of reference mixes.

4. Results and discussion

4.1. References

Results of free shrinkage tests performed on reference mixes are presented in Fig. 3. During the first 5–6 h the concrete exhibited continuous expansion, which drastically turned into continuous shrinkage forming a peak in the deformation–time curve. Total shrinkage of the reference mixes, was 100.5, 156.3 and 162.3 microstrain for w/b ratios of 0.33, 0.25 and 0.25SF, respectively.

4.2. Effect of cement paste properties

All pumice mixes, on which the effect of w/b ratio was studied, were made with lightweight aggregate content required to counteract self-desiccation, calculated according to Eq. (2), which corresponds to the 20, 24 and 23 kg of internal curing water per m^3 of concrete for w/b ratios of 0.33, 0.25 and 0.25SF, respectively.

The results of free shrinkage tests performed on the mixes containing presoaked Pumice2 are presented in Fig. 4. The mixes Pumice2(20)033, Pumice2(24)025 and Pumice2(23)025SF exhibited shrinkage of 19.7, 31.7 and 66.0 microstrain, respectively.

The efficiency factors for these mixes are 80.4%, 79.7% and 59.3% for the mixes with w/b ratio of 0.33, 0.25 and 0.25SF, respectively. It can be seen that substantial reduction of w/b ratio from 0.33 to 0.25 resulted in a modest decline of efficiency factor of less than 1%.

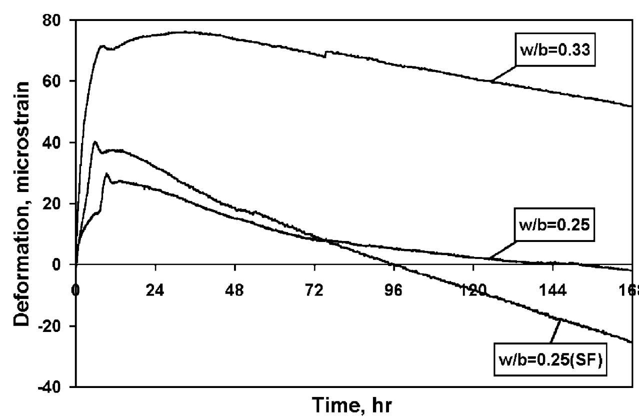

Fig. 4. Effect of w/b ratio on free shrinkage of mixes containing calculated amount of Pumice2 aggregate sufficient to counteract self-desiccation.

At the same time, addition of silica fume without any change in w/b ratio led to the drastic reduction of internal curing efficiency (Fig. 5).

4.3. Influence of cement paste matrix on grain size effect

The effect of grain size of lightweight aggregates on free shrinkage of high strength concrete was studied on mixes containing presoaked Pumice2, Pumice1 and Pumice0. The results of free shrinkage tests performed on mixes with w/b ratio of 0.33 and 0.25SF are presented

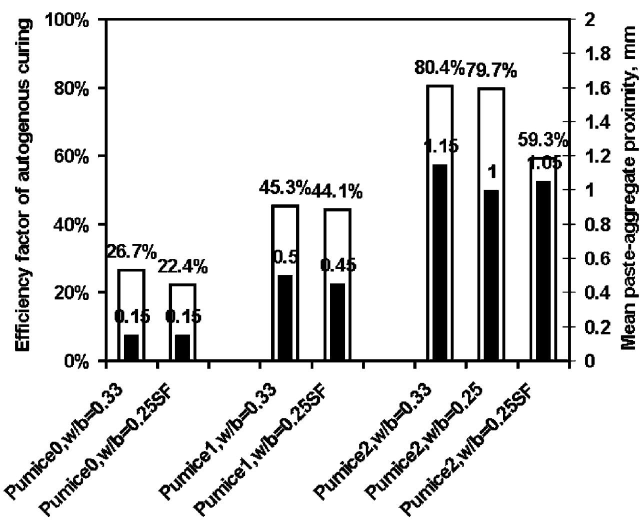

Fig. 5. Effect of w/b ratio, silica fume and pumice particle size on the efficiency factor of autogenous curing (empty columns) and mean paste–aggregate proximity (black columns).

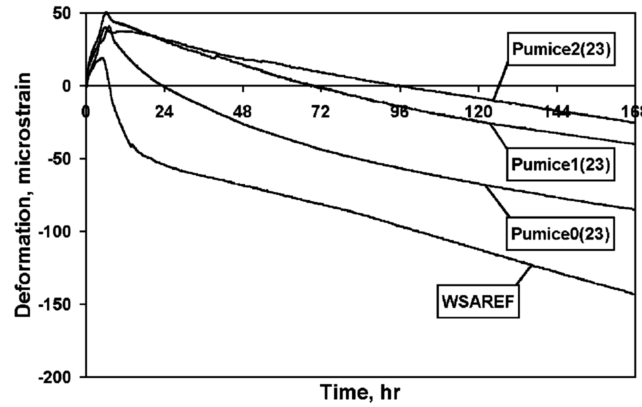

Fig. 7. Effect of grain size on free shrinkage of mixes with w/b ratio 0.25 using silica fume and containing amount of Pumice required to counteract self-desiccation.

in Figs. 6 and 7. It can be seen that during the first hours these concretes exhibited continuous expansion, similar to the reference mixes, and continuous shrinkage after that.

The mixes Pumice2(20)033, Pumice1(20)033 and Pumice0(20)033 exhibited shrinkage of 19.7, 55.0 and 73.7 microstrain, respectively. The mixes Pumice2(23)025SF, Pumice1(23)025SF and Pumice0(23)025SF exhibited shrinkage of 66.0, 90.7 and 126.0 microstrain, respectively.

The efficiency factors for the mixes with w/b ratio of 0.33 were 80.4%, 45.3% and 26.7% for the mixes with Pumice2, Pumice1 and Pumice0, respectively. Accordingly, for the mixes with w/b ratio of 0.25SF, the efficiency factors of 59.3%, 44.1% and 22.4% are obtained for the mixes with Pumice2, Pumice1 and Pumice0.

It can be seen that for the mixes with Pumice1 and Pumice0 reduction of w/b ratio from 0.33 to 0.25SF does not result in considerable decline in the efficiency factor, while the same change in w/b ratio in the mixes with Pumice2 led to the significant reduction of internal curing efficiency. This can be readily explained by the greater tightness of the silica fume mix, resulting in a smaller distance to which water can permeate from the lightweight aggregate to the surrounding matrix. This implies that the effective "sphere of influence" of the lightweight aggregate is greater than the paste–aggregate proximity in the mixes without silica fume, and it becomes smaller than this proximity in the mixes with silica fume, especially when the coarse pumice sand is introduced (see Fig. 5).

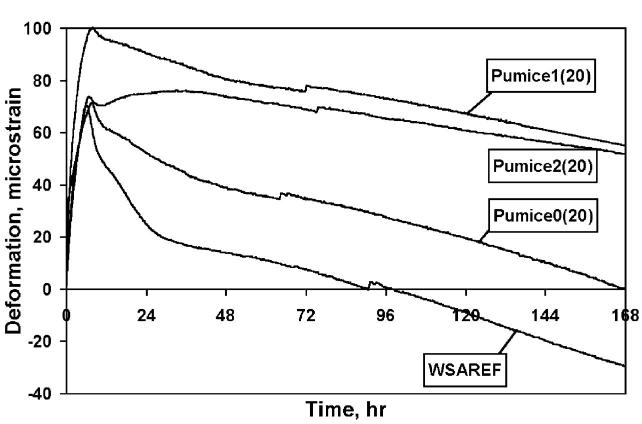

Fig. 6. Effect of grain size on free shrinkage of mixes with w/b ratio 0.33 containing amount of pumice required to counteract self-desiccation.

4.4. SEM observations

Concrete mixes, in which pumice sand of different grain sizes was used, exhibited different effectiveness in shrinkage reduction. The reasonable explanation for this may be that they have a different pore structure. In order to confirm this hypothesis pore structure of Pumice0 and Pumice2 was studied using SEM. Images obtained via the SEM are presented in Figs. 8–13.

In the SEM images shown here, two types of pores in the pumice aggregates can be distinguished: (i) small isolated pores and (ii) bigger connected pores, which are formed by merging small pores. As can be seen in Figs. 11 and 12, Pumice2 aggregate has a larger amount of pores of the second type, while in Pumice0 the pores of the first type seems to be dominant (Figs. 8 and 9). This observation can explain why concrete mixes with Pumice2 performed better than those with Pumice0, despite the difference in paste–aggregate proximity.

4.5. Strength

Compressive strength is one of the most important characteristics, especially when it concerns high-strength

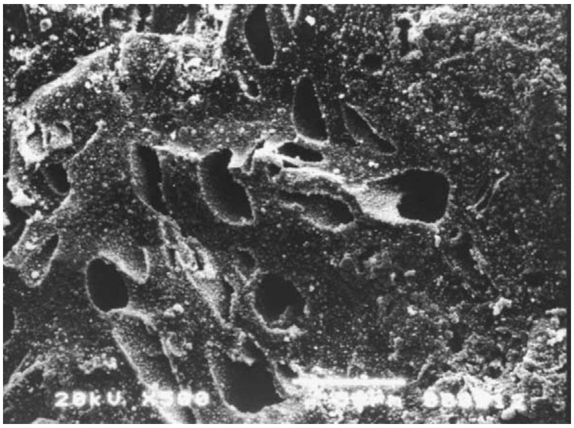

Fig. 8. The view of Pumice0 (×500).

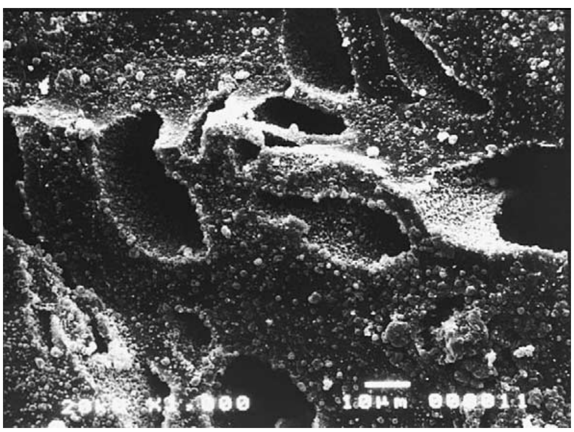

Fig. 9. The view of Pumice2 (×500).

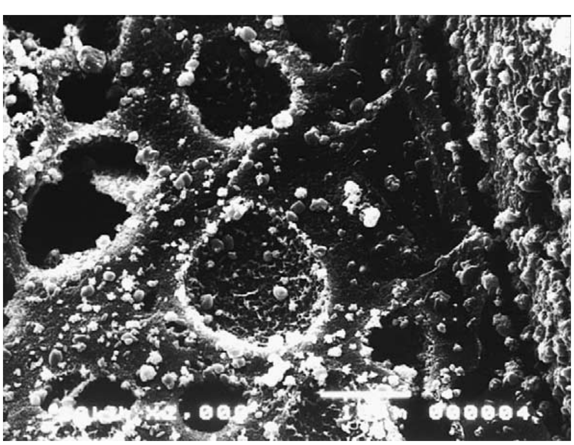

Fig. 10. The view of Pumice0 (×1000).

concrete. However, introduction of lightweight aggregate into the HSC may have a detrimental influence on strength. For this reason, compressive strength of all the internally cured mixes was measured and compared to the compressive strength of the reference mixes. Results of compressive strength tests, as well as slump and unit weight for mixes with w/b ratio of 0.33, 0.25SF and 0.25 are presented in Tables 6–8, respectively.

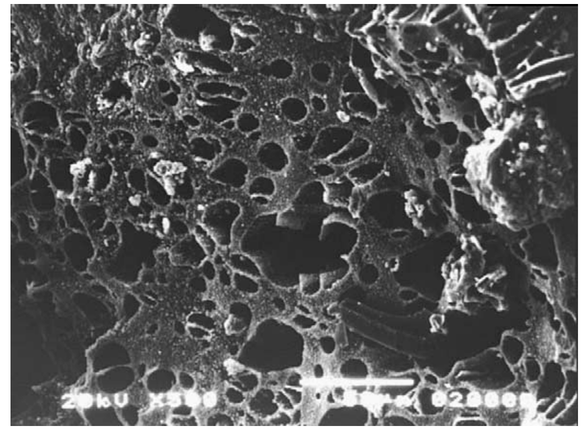

Fig. 11. The view of Pumice2 (×1000).

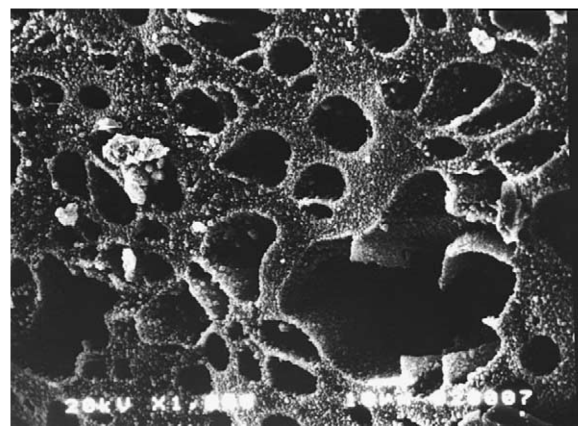

Fig. 12. The view of Pumice0 (×2000).

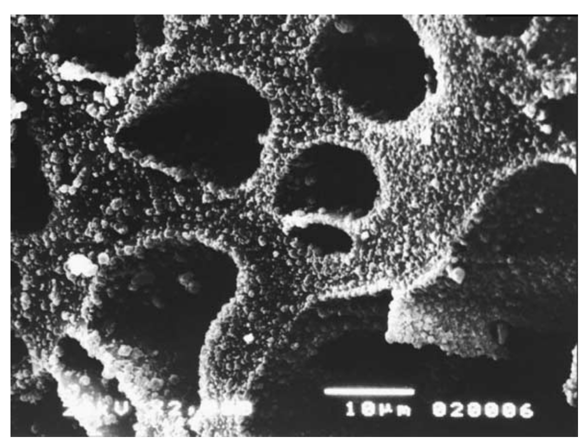

Fig. 13. The view of Pumice2 (×2000).

Relative strength, which is relation of strength of given mix to the strength of reference mix, is plotted in Figs. 14 and 15 for w/b ratio of 0.33 and 0.25SF, respectively. It can be seen that incorporation of saturated lightweight aggregates had a detrimental effect only on early-age strength, i.e. at the age of 1–7 days, of mixes with w/b ratio of 0.33. However, the 28-day strength of

Table 6
Strength, specific weight and slump for w/b ratio 0.33

	Slump, mm	Specific weight, kg/m^3	Strength, MPa			
			1	3	7	28
WSAREF033	62	2443	34.3	53.6	60.0	72.0
Pumice0(20)033	58	2351	25.3	49.4	57.1	70.2
Pumice1(20)033	53	2381	23.5	45.7	56.4	70.5
Pumice2(20)033	47	2366	27.9	47.6	57.6	67.8

Table 7
Strength, specific weight and slump for w/b ratio 0.25 using silica fume

	Slump, mm	Specific weight, kg/m^3	Strength, MPa			
			1	3	7	28
WSAREF025SF	105	2452	41.6	69.8	77.2	94.2
Pumice0(23)025SF	80	2346	41.1	67.5	73.4	88.0
Pumice1(23)025SF	57	2370	40.9	67.5	76.2	93.3
Pumice2(23)025SF	84	2405	38.3	66.9	78.9	95.4

Table 8
Strength, specific weight and slump for w/b ratio 0.25

	Slump, mm	Specific weight, kg/m^3	Strength, MPa			
			1	3	7	28
WSAREF025	65	2482	50.5	73.7	82.8	92.1
Pumice2(24)025	115	2381	44.7	67.8	80.41	93.3

the internally cured mixes with w/b ratio of 0.33 was close to reference (see Fig. 14). In the mixes with w/b ratio of 0.25 with silica fume neither the early age nor 28-day strength was negatively affected (see Fig. 15).

The lower early strength can be explained by the fact that the aggregates used were not only SSD but had a wet surface. This can lead to the formation of a weak interfacial transition zone (ITZ) between the aggregates and the cement paste, especially in the case of lightweight aggregates.

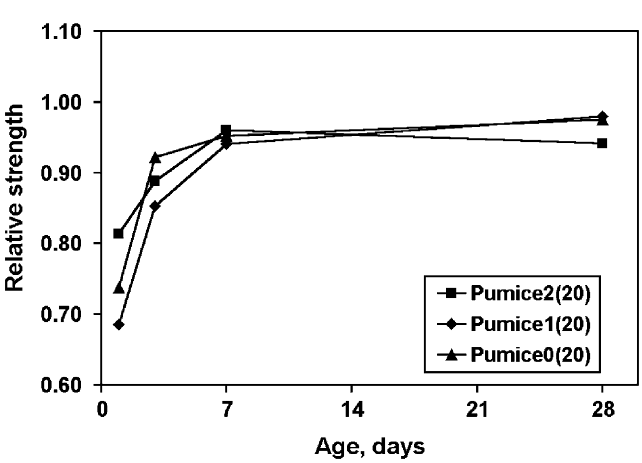

Fig. 14. Effect of grain size on relative strength of mixes with w/b ratio 0.33 containing the calculated amount of pumice.

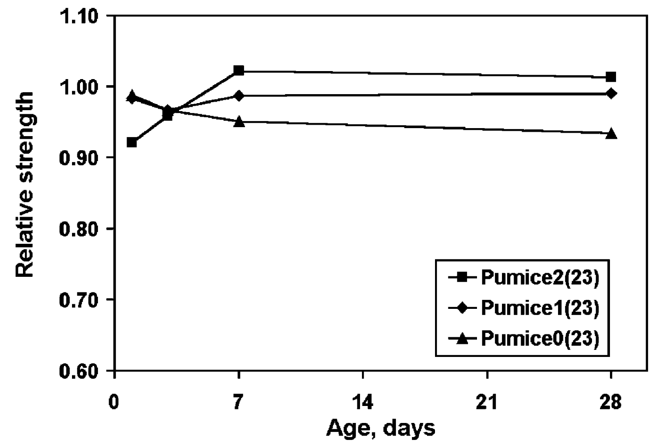

Fig. 15. Effect of grain size on relative strength of mixes with w/b ratio 0.25 using silica fume containing the calculated amount of pumice.

It is well known that in the presence of silica fume, the ITZ is dense to start with, due to the presence of the small silica fume particles, which are placed in the water film surrounding the aggregates. This may account for the observation that in the case of the silica fume mixes the lightweight aggregates did not lead to lower strength even at early age. The fact that in the mixes with silica fume the early-age strength was not reduced provides evidence for this, since microsilica improves ITZ properties.

Summarizing the effect on strength, it can be concluded that fine lightweight aggregate can be used for internal curing without considerable detrimental effects on strength when added in the amounts just required to eliminate self-desiccation.

5. Conclusions

The results of the present study indicate that by controlling the size and the porosity of the lightweight aggregates, highly efficient systems of internal curing can be obtained. In these systems the presence of the saturated lightweight aggregates can eliminate almost all of the autogenous shrinkage, without any need for external water curing. In the optimized systems the content of the aggregates is sufficiently low to have only a small effect on reduction in strength.

It is shown that substantial reduction of w/b ratio, from 0.33 to 0.25, resulted only in a very slight decline of the efficiency factor for all the sizes of pumice sand use for internal curing, by less than 1%. At the same time, addition of silica fume at the same w/b ratio of 0.25 led to a drastic reduction in internal curing efficiency, when the coarse pumice sand was introduced. This can be readily explained by the greater tightness of the silica fume mix, resulting in a smaller distance which water can permeate from the lightweight aggregate to the surrounding matrix. This implies that the effective "sphere of influence" of the lightweight aggregate is greater than the paste–aggregate proximity in the mixes without silica fume, and it becomes smaller that this proximity in the mixes with silica fume, especially when the coarse pumice sand is introduced.

Two types of pores in the pumice aggregates have been distinguished: (i) small isolated pores and (ii) bigger connected pores. The coarse aggregate has a larger amount of pores of the second type, while in the fine aggregate the pores of the first type are dominant. This observation explains why concrete mixes with coarse aggregate performed better, despite the difference in paste–aggregate proximity.

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References

[1] Bentur A, Igarashi S, Kovler K. Control of autogenous shrinkage and cracking of high strength concrete. In: Proc 5th International Symposium of High Strength/High Performance Concrete, Sandefjord, Norway, 20–24 June 1999. p. 1017–26.

[2] Sellevold E, Bjøntegaard Ø, Justnes H, Dahl PA. High performance concrete: early volume change and cracking tendency. In: Springenschmidt R, editor. Proceedings of International RILEM Symposium Thermal Cracking in Concrete at Early Ages, Munich, Germany, October 1994. p. 229–36.

[3] Schrage I, Summer T. Factors influencing early cracking of high strength concrete. In: Springenschmidt R, editor. Proceedings of International RILEM Symposium. Thermal Cracking in Concrete at Early Ages, Munich, Germany, October 1994. p. 237–44.

[4] Bentz DP, Snyder KA, Stutzman PE. Microstructural modeling of self-desiccation during hydration. In: Persson B, Fagerlund G, editors. Proceeding of an International Research Seminar in Lund, Self-Desiccation and Its Importance in Concrete Technology, Sweden, 1997. p. 132–40.

[5] Koenders EAB, van Breugel K. Modeling dimensional changes in low water/cement ratio pastes. In: Persson B, Fagerlund G, editors. Proceedings of an International Research Seminar in Lund, Self-Desiccation and Its Importance in Concrete Technology, 1997. p. 158–73.

[6] Weber S, Reinhardt HW. A blend of aggregates to support curing of concrete. In: Holand I, Hammer TA, Fluge F, editors. Proceedings of International Symposium on Structural Lightweight Concrete, Sandefjord, Norway, 1996. p. 662–71.

[7] Weber S, Reinhardt HW. A new generation of high performance concrete: concrete with autogenous curing. Adv Cement Based Mater 1997;6:59–68.

[8] Takada, K, van Breugel K, Koenders EAB, Kaptijn N. Experimental evaluation of autogenous shrinkage of lightweight aggregate concrete. In: Tazawa E, editor. Proceedings of International Workshop on Autogenous Shrinkage of Concrete, JCI, 13–14 June 1998, Hiroshima, Japan. p. 221–30.

[9] Bentur A, Igarashi S, Kovler K. Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates. Cement Concrete Res 2001;31:1587–91.

[10] Kohno K, Okamoto T, Isikawa Y, Sibata T, Mori H. Effects of artificial lightweight aggregate on autogenous shrinkage of concrete. Cement Concrete Res 1999;29:611–4.

[11] Schwesinger P, Sickert G. Reducing shrinkage in HPC by internal curing by using pre-soaked LWA. In: Proceedings of International Workshop on Control of Cracking in Early-Age Concrete, Tohoku University, Japan 2000. p. 313–8.

[12] van Breugel K, Outwerk H, de Vries J. Effect of mixture composition and size effect on shrinkage of high strength concrete. In: Proceedings of International RILEM Workshop on Shrinkage of Concrete, Paris 2000.

[13] Lura P, van Breugel K. Moisture exchange as a basic phenomenon to understand volume changes of lightweight aggregate concrete at early age. In: Proceedings of International RILEM Workshop on Shrinkage of Concrete, Paris 2000.

[14] Lura P, van Breugel K, Maruyama I. Autogenous and drying shrinkage of high-strength lightweight aggregate concrete at early ages—the effect of specimen size. In: Proceedings of RILEM International Conference on Early Age Cracking in Cementitious Systems, Haifa, Israel 2001. p. 337–44.

[15] Zhutovsky S, Kovler K, Bentur A. Influence of wet lightweight aggregate on mechanical properties of concrete at early ages. Mater Struct 2002;35:97–101.

[16] Bentz DP, Snyder KA. Protected paste volume in concrete. Extension to internal curing using saturated lightweight fine aggregate. Cement Concrete Res 1999;29:1863–7.

[17] Zhutovsky S, Kovler K, Bentur A. Influence of wet lightweight aggregate on autogenous shrinkage of concrete at early ages. In: Ulm F-J, Bazant ZP, Wittmann FH, editors. Proc 6th Int Conf Creep, Shrinkage and Durability Mechanics of Concrete and Other Quasi-Brittle Materials, Cambridge (MA), USA, 20–22 August 2001. Elsevier; 2001. p. 697–702.

[18] Lu B, Torquato S. Nearest-surface distribution functions for polydispersed particle system. Phys Rev 1992;45:5530–44.

[19] Zhutovsky, S, Kovler K, Bentur A. Assessment of distance of water migration in internal curing of high-strength concrete. Presented at the session of "Autogenous Deformation of Concrete" at American Concrete Institute Fall Convention, Phoenix, Arizona, October 2002. Also submitted for an ACI special publication.

[20] Kovler K. Testing system for determining the mechanical behavior of early age concrete under restrained and free uniaxial shrinkage. Mater Struct 1994;27:324–30.