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On the origin of eigenstresses in lightweight aggregate concrete

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Abstract

This paper concerns the origin of eigenstresses in lightweight aggregate concrete (LWAC) caused by autogenous deformation and drying shrinkage. Autogenous deformation of LWAC, drying shrinkage of lightweight aggregates (LWAs) and drying shrinkage microcracking of special composites containing LWAs were investigated. From this study a number of differences between LWAC and normal weight concrete (NWC) emerged.

In sealed conditions, the internal curing provided by saturated LWAs causes expansion of the cement paste at early-age. Since no de-bonding of LWAs occurs, the expansion of the cement paste results in tensional stresses in the aggregates. When drying of the LWAC occurs, expansion changes into shrinkage. Like the aggregates in NWC under both sealed and drying conditions, the LWAs are compressed. The restraining effect of LWAs is lower than that of normal weight aggregates due to lower elastic modulus and shrinkage of LWAs upon drying. These aggregate properties lead to lower eigenstresses and greater bulk shrinkage in drying LWAC when compared to NWC. On the other hand, additional stresses due to non-uniform shrinkage might be larger in LWAC, because of steeper moisture gradients in combination with reduced aggregate-restraint.

Keywords: Lightweight aggregate concrete; Autogenous deformation; Drying shrinkage; Eigenstresses; Microcracking

1. Introduction

A low water/cement ratio and silica fume addition make high-performance concrete sensitive to self-desiccation and related self-desiccation shrinkage of the cement paste matrix [1]. Shrinkage is unwanted since it may induce micro- or macro-cracking that may impair the concrete quality. To limit early-age shrinkage, partial substitution of the normal weight aggregates (NWAs) with saturated lightweight aggregates (LWAs) can be effective [2]. Moreover, water transport between the porous saturated aggregates and the cement paste has positive effects on the hardening process [3]. Due to self-desiccation of the cement paste during hydration, a moisture flow from aggregate particles to the cement paste occurs [4]. As a consequence, the relative humidity (RH) in the cement paste remains higher than in normal weight concrete (NWC) [5]. When all the coarse aggregates are replaced with water-saturated LWA, in the first hours after casting expansion, in place of shrinkage, is observed [4]. A moderate expansion can be measured for several months [6]. The difference between lightweight aggregate concrete (LWAC) and NWC is not only due to internal curing. The mechanical interaction between cement paste and LWAs is also different and may have an influence on the global properties of LWAC. In this paper this second aspect of LWAC will be discussed.

Expansion of the cement paste in LWAC leads, if no de-bonding of the LWAs takes place, to hydrostatic tension in the aggregate and tensile radial stresses and compressive tangential stresses in the cement paste [7,8]. On the other hand, in NWC the cement paste shrinks due to self-desiccation: the aggregates will be in hydrostatic compression and stresses in the cement paste will be in compression radially and in tension tangentially [7]. Therefore, it can be expected that the restraining effect of the aggregates on autogenous deformation is different in LWAC and NWC, due to different mechanical properties of the aggregates and aggregate–matrix interaction.

In most practical applications concrete needs to equilibrate with the external conditions. When drying takes place in LWAC, the mechanical interaction

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between aggregates and cement paste will change. Depending on time and depth of drying, autogenous expansion of the cement paste eventually changes into shrinkage due to drying [9]. Also NWC shrinks when exposed to drying, but the mechanical properties of the aggregates are different: The LWAs are less stiff, the bond with the cement paste is stronger than for NWAs and they shrink upon drying. These properties influence the degree of aggregate-restraint and the bulk deformations of the composite [10].

Drying LWAC differs in another way from NWC. The process of internal water transport influences the RH gradient within the concrete. Due to saturation of the paste, the difference between the internal and external RH at the start of drying is higher than in NWC and the initial RH gradient is steeper. It is also expected that the water entrained in the LWAs will compensate some initial drying. Since the LWAs have a lower elastic modulus than the NWAs, they are less effective in restraining the shrinkage of the paste. All these factors lead to a greater shrinkage gradient between the surface and the core of the specimen in LWAC when compared to NWC. This gradient is the origin of self-restraint in drying specimens that results in stresses and cracking in concrete [11,12].

In this paper the interaction between saturated LWAs and the cement paste in LWAC is discussed on the basis of experimental results. Autogenous deformation was measured on LWAC to show the effect of internal curing. Drying shrinkage of LWA particles was measured to evaluate their behaviour in drying cement-based materials. Finally, the effect of the LWAs on aggregate-restraint and self-restraint was studied in special composites that show pronounced microcracking due to aforementioned types of restraint.

The principal aim of this paper is to distinguish meso-scale interactions between aggregates and cement paste that may occur in LWAC as opposed to NWC. Further research is needed, however, to verify the practical importance of these mechanisms in early-age and in drying LWAC.

2. Materials and methods

2.1. Autogenous deformation in LWAC

Autogenous deformation was measured with an Autogenous Deformation Testing Machine. A description of the experimental set-up and measuring procedures can be found in [13]. Three LWAC mixes with saturated LWAs were tested, differing in the dimension of the LWA particles: Liapor F8 8–16 mm, Liapor F8 4–8 mm and Liapor sand 0–4 mm (see Table 1). The volume content of LWAs was the same for all mixes, namely 30%. The LWAs were immersed in water for 1 day prior to mixing, absorbing about 18% water by weight, which corresponds to 80% of the long-term absorption [13].

Table 1
Mixture composition of the LWAC

Mixture composition (kg/m^3)	Type of lightweight aggregate		
	Liapor F8 4–8 mm	Liapor F8 8–16 mm	Liapor sand 0–4 mm
CEM III/B 42.5 HL HS (CEMIJ)	237.00	237.00	237.00
CEM I 52.5 R (ENCI)	238.00	238.00	238.00
Water (incl. water in admixtures)	175.75	175.75	175.75
Lightweight aggregate, dry	463.90	498.53	327.00
Sand 0–4 mm	772.51	772.51	772.51
Lignosulphonate	0.95	0.95	0.95
Naphthalene sulphonate	7.13	7.13	7.13
Silica fume (slurry, 50% solid)	50.00	50.00	50.00
Water in the LWA	82	88	58.00

2.2. Drying shrinkage of LWA particles

The volume stability of Liapor F8 aggregates, manufactured from expanded clay, was tested measuring the dimensional changes of single grains subjected to drying. The Liapor grains were immersed in water and then placed in a room at 50% RH and 20 °C for several days. The weight change of one aggregate particle was monitored and the changes of the diameter of 3 Liapor grains were measured continuously.

2.3. Drying shrinkage microcracking

Bisschop and van Mier [14] found that, in cement-based composites with 6 mm aggregates (glass spheres), restraint due to aggregates was more important than self-restraint (i.e. restraint due to the presence of a shrinkage gradient) in causing drying shrinkage microcracking. Therefore, this type of composite was used to investigate the effect of Liapor grains on drying shrinkage microcracking. Although the shrinkage cracking behaviour of these special composites is very different from the one of concrete used in practice, it offers a direct insight into the restraining behaviour of aggregates.

Three types of composites were studied, all with a cement paste volume percentage of 66.7% and an aggregate volume percentage of 33.3%, but with different contents of glass spheres (NWAs) versus Liapor grains (LWAs) (see Table 2). The glass spheres had an average size of 5.91 ± 0.15 mm and a Young's modulus of 77 GPa and were perfectly smooth. Spherical Liapor grains, with a diameter varying between 5.5 and 6.5 mm, were selected from the Liapor F8 4–8 mm fraction. The

Table 2
Composition of studied composites

Component (in g)	Composite A (reference)	Composite B	Composite C
CEM III/B 42.5 LH HS (CEMIJ)	825.0	825.0	825.0
CEM I 52.5 R (ENCI)	825.0	825.0	825.0
Water	505.8	505.8	505.8
Silica fume (slurry, 50% solid)	173.7	173.7	173.7
Lignosulphonate	1.7	1.2	0.9
Naphthalene sulphonate	13.2	9.6	7.2
Cement paste volume (%)	66.7	66.7	66.7
NWA volume (%)	33.3	25.0	–
LWA volume (%)	–	8.3	33.3

Liapor grains were immersed in water for 1 day prior to mixing. The Young's modulus of the LWAs was about 20 GPa. The cement paste compositions were the same as those used in the LWAC experiments (see Table 1).

The composites were cast in prismatic moulds ($40 \times 40 \times 160$ mm^3) and demoulded after 1 day. For one set of specimens (A1, B1, and C1) drying started directly after demoulding. For the other set of specimens (A2, B2, and C2) drying started at an age of 7 days, after 6 days of sealed curing at 30 °C. The specimens were dried in an environmental chamber ventilated with air at 30 °C and 30% RH. Only one side of the specimens, i.e. the bottom side in the mould, was exposed to drying to create one-dimensional drying conditions. Drying continued for 13 days for specimens A1, B1, and C1 and 14 days for A2, B2, and C2. During the drying experiment the weight of the specimens was measured at regular intervals. After drying, the drying shrinkage microcrack-pattern was impregnated with fluorescent epoxy and prepared for microscopy examination. From four longitudinal cross-sections of each specimen, crack-maps were obtained by manual crack mapping on digital micrographs (as the one shown in Fig. 4). No bond cracks or cracks inside Liapor grains were reported in the crack-maps. From the crack-maps the following crack-parameters were extracted: the total crack length (TCL) and the maximum penetration depth of cracking (MPD). Radar diagrams showing the overall orientation of cracking were constructed. The aspect ratio of the radar diagram is defined as the 0/180 axis divided by the 90/270 axis. More details about sample preparation and crack quantification can be found in [14].

2.4. Elastic modulus of the cement paste during hardening

The elastic modulus in compression was tested after 1, 3 and 7 days of sealed hardening on cement paste prisms, $50 \times 50 \times 200$ mm^3. The prisms were cast into temperature-controlled steel moulds and cured at 30 °C. The mix composition of the cement paste was the same used for the autogenous deformation measurements and for the microcrack-detection experiments (see Sections 2.1 and 2.3).

3. Results

3.1. Autogenous deformation in LWAC

The free deformations of the studied LWAC mixtures are shown in Fig. 1. The two mixes with the finer LWAs expanded from the beginning of the measurements until one or two weeks after casting. The mix with fraction 8–16 mm LWAs showed some shrinkage from 48 to 144 hours after casting, followed by further expansion.

3.2. Drying shrinkage of LWA particles

In Fig. 2 the average result of the three parallel shrinkage measurements and the weight loss are shown. It is noticed that the water content of the LWA particle

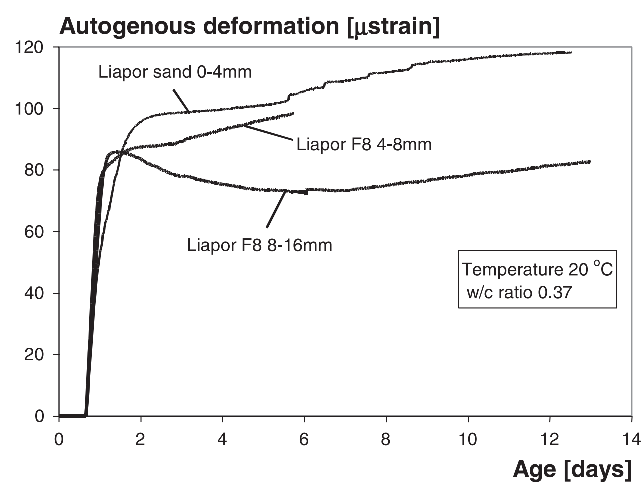

Fig. 1. Autogenous deformation of mixtures with saturated LWAs.

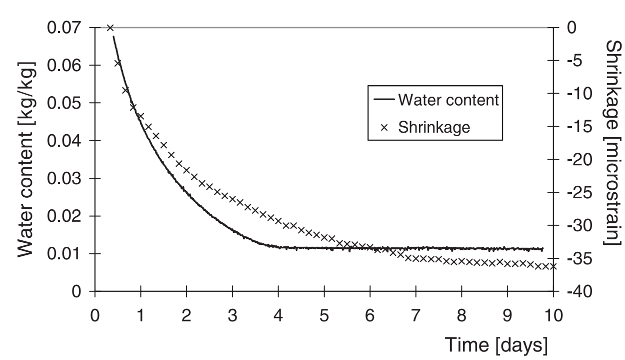

Fig. 2. Weight loss and shrinkage of saturated LWA subjected to drying at 50% RH.

is in equilibrium with the ambient RH at a value lower than 0.01 kg/kg. This in accordance with desorption isotherms measured on the LWAs [13]. The LWAs showed substantial shrinkage.

3.3. Drying shrinkage microcracking

The moisture loss of the composites is shown in Fig. 3. The specimens dried after 1 day sealed hydration (A1, B1, and C1) lost more moisture than the ones dried after 7 days (A2, B2, and C2), especially in the first hours of drying. The composites with 100% Liapor grains (C1 and C2) lost substantially more moisture than the other composites under the same drying conditions.

Fig. 4 shows a micrograph of an impregnated drying shrinkage microcrack-pattern on one of the cross-sections in specimen B1. The bright lines are the impregnated microcracks plus a small rim of impregnated cement paste. Closer to the drying surface (i.e. the top side in Fig. 4) the impregnated rims are broader, since the cement paste is more extensively dried there. The crack width varies between 5 and 40 μm. It can be seen that some of the Liapor grains (marked L in Fig. 4) are also impregnated, due to their porosity. Sometimes microcracks propagate right through Liapor grains as illustrated in Fig. 5.

Figs. 6 and 7 show the effect of Liapor grains on drying shrinkage microcracking. In the crack-maps the crack-patterns of four cross-sections are combined to show trends in cracking more clearly. The total length (TCL) and penetration depth (MPD) of cracking is lower in the 100% Liapor grain composite compared to the other composites for both 1-day and 7-days of curing under sealed conditions. The degree of orientation increased with a larger amount of Liapor grains as shown by the aspect ratio of the radar diagrams. This effect seems to be less evident for the 1-day sealed cured specimens.

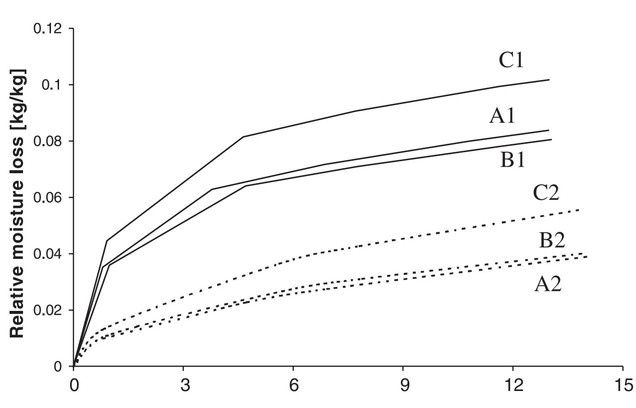

Fig. 3. Relative moisture loss of studied composites. Drying at 30 °C and 30% RH.

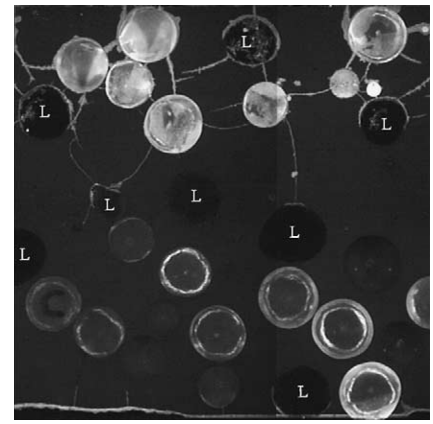

Fig. 4. Micrograph of impregnated drying shrinkage microcrack-pattern in specimen B1 (25% Liapor grains, 1 day sealed curing and 13 days drying). Image size is 40 × 40 mm. L = Liapor grains, other grains are glass spheres. The specimen was drying from the top.

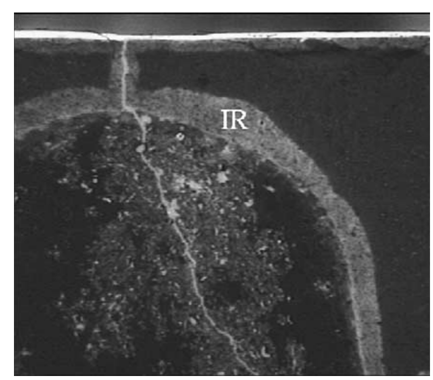

Fig. 5. Micrograph of impregnated drying shrinkage microcrack propagating through a Liapor particle. Image size is 3.6×4.1 mm^2. IR = impregnated cement paste rim.

3.4. Elastic modulus of the cement paste during hardening

Results of the elastic modulus of cement paste are reported in Fig. 8. The elastic modulus increases from 13.5 GPa at 1 day to 21.5 GPa at 7 days of hydration.

4. Discussion

4.1. Early-age behaviour

4.1.1. Autogenous expansion of the cement paste and shrinkage of the LWA

LWAC realized with saturated LWAs expanded at early-age in sealed conditions (see Fig. 1). The bulk expansion is due to the expansion of the cement paste, which is cured under almost saturated conditions, ensured by water from the LWA. This behaviour is similar to the expansion that occurs in pastes cured under

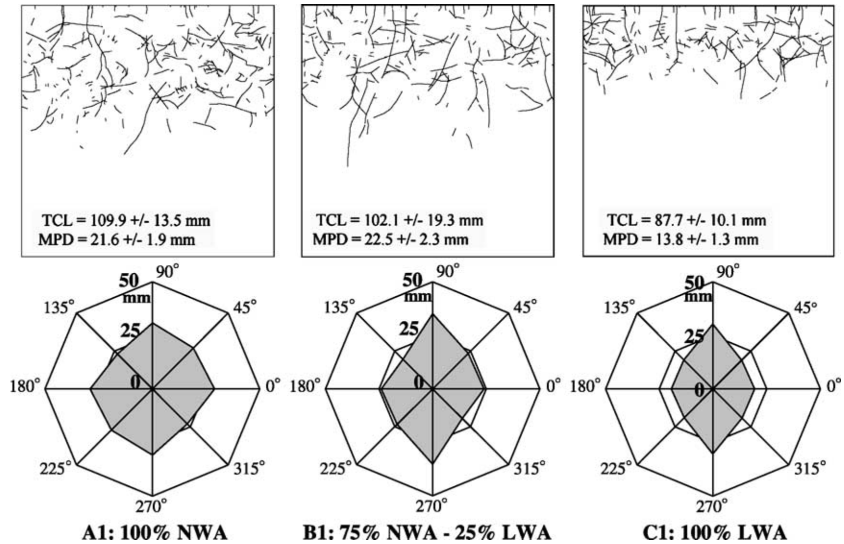

Fig. 6. Effect of Liapor grains on drying shrinkage microcracking in 1-day sealed cured specimens A1, B1, and C1 after 13 days of drying. Upper row: crack-maps constructed by superposition of four cross-sections (40×40 mm^2). Lower row: radar diagrams showing the overall orientation of cracking. The aspect ratio of the diagrams is 0.92, 0.70, and 0.63, respectively.

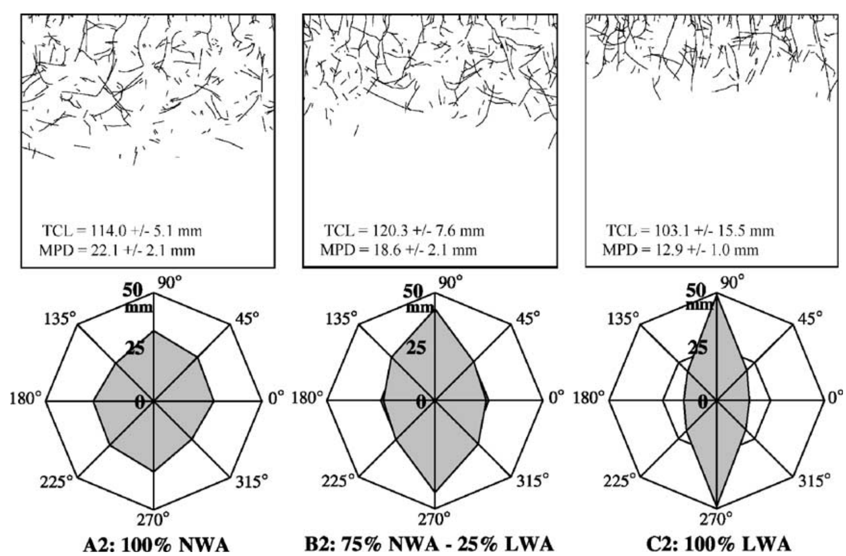

Fig. 7. Effect of Liapor grains on drying shrinkage microcracking in 7-days sealed cured specimens A2, B2, and C2 after 14 days of drying. Upper row: crack-maps constructed by superposition of four cross-sections (40×40 mm^2). Lower row: radar diagrams showing the overall orientation of cracking. The aspect ratio of the diagrams is 0.86, 0.56, and 0.31, respectively.

water, which might amount to about 1000–2000 μstrain [15]. Jensen and Hansen [16] measured an expansion of about 1000 μstrain for a w/c ratio 0.30 cement paste with 20% silica fume addition internally cured with saturated superabsorbent polymers. Possible explanations of the early-age expansion have been discussed elsewhere [13,17].

Water loss from the LWAs also results in shrinkage of the particles themselves (see Fig. 2). However, it must be pointed out that the shrinkage shown in Fig. 2 was measured in the case of almost complete drying of the LWAs, down to 50% RH. In the case of a LWAC at early ages, the RH in the concrete is expected to remain high [5]. For high RH levels, the LWAs might be considered almost as non-shrinking if compared to the volume changes of the concrete. However, if drying behaviour of LWAC is considered, where the RH may drop substantially, also the deformation of the LWAs may be of importance.

4.1.2. Meso-level stresses in the sealed composite

Consider a linear elastic solution for a system with a spherical aggregate embedded in a matrix, with perfect bond between the two phases. In this case, expansion of

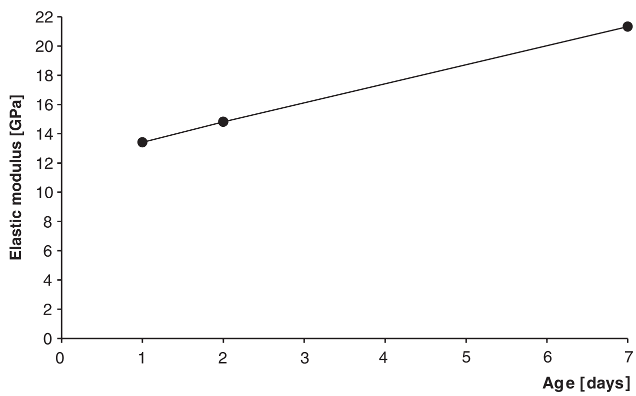

Fig. 8. Elastic modulus in compression of cement paste cured at 30 °C.

the matrix and shrinkage of the aggregate will result in uniform tensile stresses in the aggregates and tensile radial stresses and compressive tangential stresses in the matrix [7].

The most important requirement for the applicability of this model to autogenous expansion in LWAC is a perfect bond between the cement paste and the LWAs. It has been observed [18,19], that cement paste penetrates in the outer porous layer of the LWA particles and therefore the bond in LWAC is stronger than in NWC. Fig. 5 shows another evidence of the existence of good bond between LWA and cement paste: under severe drying, a crack propagated through an aggregate instead of along the rim. If the bond between matrix and aggregates is not strong enough, according to the linear elastic solution the aggregates break away from the matrix, leaving a gap proportional to their diameter [20]. This behaviour has been previously observed in LWAC [8], but no evidence of de-bonding was present in the composites studied in this paper.

The model described in [7] can be used to calculate the stresses in the cement paste and the LWA. The model, however, describes an ideal situation (one spherical particle in an infinite matrix) while LWAC is a complex composite, for example due to shape and grading of the particles. The internal stresses, due to the differential deformations between the cement paste and the aggregates, are proportional to the elastic modulus of the restraining particles and the cement paste [7]. LWAs have a low elastic modulus, about 20 GPa. Besides, the elastic modulus of the cement paste is very low at early-ages. The relaxation of the stresses caused by creep of the cement paste (which is very rapid and significant at early-ages) further reduces the eigenstresses in the lapse of time [21]. In the composites with NWAs examined in this paper, eigenstresses due to autogenous shrinkage of the cement paste are higher, because of higher elastic modulus of the aggregates (77 GPa), but not high enough to cause microcracking by aggregate-restraint [22].

4.1.3. Bulk deformation

Because of the low elastic modulus of the LWA particles, deformations of the matrix are less restrained in LWAC than in NWC. Therefore, the bulk deformation of the composite is in general higher in LWAC than in NWC if the deformation of the cement paste is the same [10].

4.2. Drying behaviour

4.2.1. Moisture loss

Fig. 3 shows that the drying behaviour of the Liapor mixtures is different from the one of the glass spheres mixtures. The mixtures with 100% LWA showed a much higher moisture loss, while the ones with only 25% LWA were almost equivalent to the reference.

The increased moisture loss of the Liapor mixtures may be due to the loss of the water entrained in the LWAs. Actually, the Liapor grains possess an open porous structure, evident from the fact that some of them result impregnated by epoxy (see Fig. 5). The Liapor grains in the mixtures with only LWAs might therefore provide a shortcut for moisture transport. An additional reason is that the steeper RH gradient between the saturated composite and the environment results in quicker moisture loss. The initial internal RH at the start of drying in the mixture with saturated LWAs is higher than in the mixture with glass spheres, where the cement paste is exposed to self-desiccation. For the cement paste a value of 90% RH was measured after one week of hydration in sealed conditions [17], whereas in the literature a value of 95% RH is found for mixtures with saturated LWAs after several weeks of hydration [5].

4.2.2. Meso-level internal stresses due to aggregate-restraint

When LWAC is subjected to drying, both the cement paste and the LWA particles shrink (see Fig. 2 and Section 4.1.1). Therefore, the differential shrinkage between LWAs and cement paste is less than in the case of NWC, where the aggregates are inert. This will result in lower internal stresses between the cement paste and the aggregates. Another factor that reduces the eigenstresses in drying LWAC is the lower elastic modulus of the LWAs when compared to NWAs.

According to the linear elastic solution [7], the LWAs will be under hydrostatic compression (instead of tension, which is the case in autogenous expansion) and the paste in radial compression and in tangential tension at the interface.

4.2.3. Global shrinkage and self-restraint

Since both cement paste and aggregates shrink and the LWAs have lower elastic modulus than the NWAs, the total shrinkage of the composite will be greater for LWAC than for NWC [10].

Moreover, since drying proceeds from one side, only the cross-sections that have been reached by the drying front shrink, while the inner ones are still expanding due to expansion of the saturated cement paste. On the other hand, in NWC with a low water/binder ratio, also the cross-sections far from the drying front shrink due to self-desiccation of the cement paste as hydration proceeds.

As a consequence of larger bulk shrinkage of the drying cross-sections and of autogenous expansion at a distance from the drying surface, in LWAC the shrinkage gradient between the drying surface and the core of the specimen is greater than in NWC. This fact produces a higher degree of self-restraint of the sample in LWAC if compared to NWC. The presence of stresses caused by shrinkage gradients may affect macroscopic drying shrinkage measurements on LWAC [12]; for example, it has been observed that the drying LWAC shows a very pronounced size effect [9].

4.2.4. Cracking

In the studied composites two types of restraint were responsible for the drying shrinkage microcracking. These are aggregate-restraint, the restraint aggregates display against the shrinkage of the cement paste, and self-restraint, a result of non-uniform shrinkage caused by a developing moisture gradient [14]. The stresses caused by both types of restraints are always superimposed.

It was observed in this study that the degree of drying shrinkage microcracking (i.e. length and depth) was less in the 100% LWA composites than in the composites with 100% or 75% NWAs for both 1 day and 7 days curing (Figs. 6 and 7). Moreover, the degree of orientation increased with the amount of LWAs. This cracking behaviour of the composites can be explained by the differences in elastic modulus of the LWAs and NWAs and by the difference in non-uniform shrinkage (self-restraint) between the composites. Firstly, the elastic modulus of the LWAs is much lower and the LWAs shrink: therefore the degree of aggregate-restraint is lower than for the NWAs. Secondly, as discussed before, self-restraint of LWA concrete or composites may be larger due to a steeper moisture gradient and due to the lower elastic modulus of LWAs. As a result of these two factors, the impact of self-restraint stresses in the formation of microcracks is larger in LWA composites. The shrinkage gradient responsible for self-restraint causes tensile stresses directed mainly parallel to the drying surface, while aggregate restraint causes tensile stresses randomly oriented around aggregates. Thus, a higher proportion of self-restraint will result in higher degree of crack-orientation in directions perpendicular to the drying surface. Also, the formation of tensile stresses by self-restraint is limited until a certain depth from the drying surface [23]. Therefore, a higher relative contribution of self-restraint in causing cracking also resulted in the lower crack depth in the LWA composite.

It should be mentioned though, that the lower depth and length of microcracking in the LWA composite might also partly be a result of the better bond of the LWAs with the cement paste compared to bond of NWAs. In fact there are indications that the bond of the cement paste with the NWAs (i.e. smooth glass spheres) is very weak [14], while the bond of the LWAs was shown in this paper to be sometimes as strong as the LWAs themselves (see Fig. 5). In experiments on composites with smooth glass spheres and composites with rough (i.e. sand-blasted) glass spheres, the latter composites (with assumingly a better bond) showed a strong decrease in drying shrinkage microcracking [24]. Thus, the better bond in the LWA composites may have also resulted in a lowering of the aggregate-restraint stress contribution compared to the NWA composites.

A second important observation is the difference in aspect ratio between the radar diagrams for the same composites with different curing durations (Figs. 6 and 7). For all three types of composites it was observed that the aspect ratio of radar diagram of the 7-days cured composites is lower. This can probably be explained by the difference in elastic modulus of the cement paste for the 1-day and 7-days cured composites. The evolution of the elastic modulus of the cement paste during the drying experiments is not known, but on the basis of Fig. 8 it can be concluded that the elastic modulus of the cement paste in the 1-day cured composites was lower during the drying experiments. Therefore, the relative influence of aggregate-restraint in the 1-day cured composites was probably greater, which caused cracking to be more isotropic.

It was also observed that LWAs sometimes do not act as crack arrestors. In Fig. 5 a crack originating at the drying surface propagated through a Liapor grain, instead of along the interface. This behaviour, which is due to the good bond of LWAs with the cement paste and to the low elastic modulus and strength of the LWAs, could result in increased brittleness of LWAC when compared to NWC [25].

Finally, it needs to be mentioned that the cement paste in LWAC mixtures, due to internal curing, reach higher degree of hydration than corresponding NWC [3]. As a consequence, both the strength and the elastic modulus of the cement paste might be higher in the LWA composites. Also this factor might contribute to a higher crack orientation in the studied LWA composites.

5. Conclusions

The most relevant findings about the interaction of LWA and cement paste in early-age and drying LWAC are the following:

- LWAC realised with saturated LWAs expands at early-age due to expansion of the cement paste. According to a linear elastic solution, expansion of the paste and shrinkage of the LWAs upon moisture loss might lead to separation of the aggregate from the matrix. However, no evidence of de-bonding of the aggregates was observed in the composites studied in this paper. This favourable behaviour might be attributed to the low stiffness of the cement paste at early-ages, which produces low stresses that are further reduced by creep. Another reason is the good bond between the porous aggregates and the cement paste, which is a characteristic of LWAC.
- In drying shrinkage cracking of composites containing LWAs, the internal restraint due to the aggregates was less important than the self-restraint due to the presence of a shrinkage gradient. A possible explanation of this fact might be that eigenstresses in drying LWAC are lower than in NWC due to lower elastic modulus of the LWAs and shrinkage of the LWAs upon drying. On the other hand, since LWAs have a lower elastic modulus than NWAs, deformations of the cement paste are less effectively restrained by the aggregates. Therefore drying LWAC has greater bulk shrinkage when compared to NWC. In combination with non-uniform drying, this results in higher self-stresses in the cross-section of drying specimens.
- The lower elastic modulus and strength of the LWAs and the good bond with the cement paste result in cracks that propagate through the LWAs instead of along the interface, as happens in NWC. This fact might contribute to making LWAC a more brittle material than NWC.

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References

[1] Jensen OM, Hansen PF. Autogenous deformation and change of the relative humidity in silica fume-modified cement paste. ACI Mater J 1996;93(6):539–43.

[2] van Breugel K, de Vries J. Mixture optimization of HPC in view of autogenous shrinkage. In: Proc 5th Int Symp on Utilization of High Strength/High Performance Concrete, Sandefjord, Norway, 1999. vol. 2, p. 1041–50.

[3] Weber S, Reinhardt HW. A new generation of high performance concrete: concrete with autogenous curing. Adv Cement Based Mater 1997;6(2):59–68.

[4] Takada K, van Breugel K, Koenders EAB, Kaptijn N. Experimental evaluation of autogenous shrinkage of lightweight aggregate concrete. In: Proc Autoshrink 1998, Int Workshop on Autogenous Shrinkage of Concrete, Hiroshima, Japan, 1998. p. 221–30.

[5] Bentz DP, Geiker M, Jensen OM. On the mitigation of early age cracking. In: Int Sem on Self-desiccation and Its Importance in Concrete Technology, Lund, Sweden, 2002:195–203.

[6] Sickert G, Schwesinger P, von Haza-Radlitz G. Creep, shrinkage and creep recovery of HPLWA-concrete. In: Proc Int Symposium on Utilization of High Strength/High Performance Concrete, Sandefjord, Norway, 1999. vol. 2, p. 1301–10.

[7] Goltermann P. Mechanical predictions on concrete deterioration. Part 1: eigenstresses in concrete. ACI Mater J 1994;91(6):543–50.

[8] Saito M, Kawamura M, Arakawa S. Role of aggregate in the shrinkage of ordinary Portland and expansive cement concrete. Cem Concr Compos 1991;13:115–21.

[9] 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: Proc RILEM Int Conf on Early Age Cracking in Cementitious Systems (EAC'01), 2001. p. 337–44.

[10] Hobbs DW. Influence of aggregate restraint on the shrinkage of concrete. ACI Mater J 1974;71:445–50.

[11] Bisschop J, Pel L, van Mier JGM. Effect of aggregate size and paste volume on drying shrinkage microcracking in cement-based composites. In: Proc 6th Int Conf on Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-brittle Materials (ConCreep6), Boston, 2001. p. 75–80.

[12] Wittmann FH. Mechanisms and mechanics of shrinkage. In: Proc. 6th Int Conf on Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-brittle Materials (ConCreep6), Boston, 2001. p. 3–12.

[13] Lura P, Autogenous deformation and internal curing of concrete. PhD thesis. Delft University of Technology. Delft, The Netherlands, 2003.

[14] Bisschop J, van Mier JGM. Effect of aggregates on drying shrinkage microcracking in cement-based materials. In: Proc UEF Conf Advances in Concrete and Cement, Mt-Tremblant, Canada, 2000, Concr Sci Eng, in press.

[15] Neville AM. Properties of concrete. 4th ed. New York: John Wiley & Sons; 1995.

[16] Jensen OM, Hansen PF. Water-entrained cement-based materials. I. Principles and theoretical background. Cem Concr Res 2001;31(5):647–54.

[17] Lura P, Jensen OM, van Breugel K. Autogenous deformation and RH-change in Portland and blast furnace slag cement pastes. In: Proc Int Sem on Self-Desiccation and its Importance in Concrete Technology, Lund, Sweden, 2002. p. 127–37.

[18] Zhang MH, Gjørv OE. Microstructure of the interfacial zone between lightweight aggregate and cement paste. Cem Concr Res 1990;20(4):610–8.

[19] Wasserman R, Bentur A. Interfacial interactions in lightweight aggregate concretes and their influence on the concrete strength. Cem Concr Compos 1996;18:67–76.

[20] Garboczi EJ. Stress, displacement, and expansive cracking around a single spherical aggregate under different expansive conditions. Cem Concr Res 1997;27(4):495–500.

[21] Dela BF. Eigenstresses in hardening concrete. PhD thesis. Department of Structural Engineering and Materials, The Technical University of Denmark, Lyngby, Denmark, 2000.

[22] Bisschop J, Lura P, van Mier JGM. Shrinkage microcracking in cement-based materials with low water–cement ratio. Concr Sci Eng 2001;3:151–6.

[23] Hwang CL, Young JF. Drying shrinkage of Portland cement pastes. I. Microcracking during drying. Cem Concr Res 1984;14:585–94.

[24] Bisschop J. Drying shrinkage microcracking in cement-based materials. PhD thesis. Delft University of Technology, Delft, The Netherlands, 2002.

[25] van Mier JGM. Fracture processes of concrete. Boca Raton, FL: CRC Press; 1997.