Internal water curing with Liapor aggregates

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ABSTRACT. Internal water curing is a very efficient way to counteract self-desiccation and autogenous shrinkage in high performance concrete, thereby reducing the likelihood of early-age cracking. This paper deals with early-age volume changes and moisture transport in lightweight aggregate concrete realized with wet lightweight aggregates. Lightweight aggregate concrete mixtures with different degree of saturation and different particle size of the lightweight aggregates were studied and compared to normal weight concrete. Autogenous deformations, self-induced stresses in fully restrained conditions, elastic modulus and compressive strength were measured. Early-age expansion of the mixtures was greater the higher the degree of the saturation of the lightweight aggregates and the finer their particle size. The elastic properties and the early-age expansion of the lightweight aggregate concrete were calculated with simple composite models, showing good agreement with the experimental findings.

keywords: Lightweight Aggregates, Autogenous deformation, Self-induced stresses, Internal water curing.

1. Introduction

High-Performance Concrete is generally made with a low water/cement ratio, which makes it susceptible to self-desiccation. Addition of silica fume to reduce porosity and increase the strength further reduces the internal relative humidity (RH) of the concrete [1]. This self-desiccation process is directly related to autogenous shrinkage. Autogenous shrinkage results in tensile stresses in the cement paste, due to the internal restraint of the aggregates [2], and in bulk deformation of the concrete itself [3]. Both these phenomena should be controlled as they may induce micro- or macro-cracking and impair the performance and the durability of the concrete.

Conventional curing procedures of water ponding, as used for drying shrinkage, are not effective in the case of autogenous shrinkage. They may eliminate the autogenous shrinkage in small cross-sections only, because the penetration of water from the external surface is limited. Moreover, external curing might be difficult to apply to some surfaces. In view of this limitation, different strategies have been developed, based on the use of internal water reservoirs. One strategy is based on the use of lightweight aggregates (LWA) [4], while the other is based on the use of water absorbing polymers [5]. Both water-saturated porous aggregates and water-saturated polymers are able to act as internal reservoirs, providing a source of curing water to the paste volume in their vicinity. This process of internal curing is aimed at offsetting self-desiccation and avoiding self-desiccation shrinkage.

The potentiality of water-entrainment by LWA to offset self-desiccation of low water/binder ratio concrete and turn early-age shrinkage into expansion has been observed for many years. However, some fundamental questions regarding the actual mechanisms of internal curing remain unanswered. The mechanisms of water transport from the LWA to the self-desiccating paste have received only scant attention [6] and no attempt was made to quantify how much of the water remains in the pores of the LWA when the internal RH of the concrete is high. The origin of early-age expansion of lightweight aggregate concrete (LWAC) was mostly ignored and no attempt was made to relate it to volume changes of cement paste during hardening. Also, systematic studies are missing about the effect of the degree of saturation of the LWA and their dimension on the early-age deformation of LWAC.

This article addresses the issues outlined above both with experiments and with calculations. Autogenous deformation of LWAC realized with pre-wetted expanded shale (Liapor) aggregates was measured. LWAC showed early-age expansion instead of shrinkage, which was measured on the corresponding normal weight concrete (NWC) mix [7]. The expansion depended both on the degree of saturation of the LWA and on their dimension. To understand the internal curing process, properties of the LWA (Liapor 8) were also investigated.

2. Properties of LWA

2.1. *Density, porosity, and pore structure*

The density of Liapor 8 varies between 1450 and 1550 kg/m^3. With helium pycnometry, water absorption and mercury intrusion porosimetry (MIP), Zhang & Gjørv [8] calculated densities and porosity of Liapor 8. Table 1 shows their results.

Table 1. Porosity and density of Liapor 8, from [8]

	Liapor 8	
Particle size	**4-8 mm**	**8-16 mm**
Open porosity [%]	40.3	34.8
Closed porosity [%]	5.3	4.1
Total porosity [%]	45.6	38.9
Solid density [kg/m^3]	2520	2520
Particle density [kg/m^3]	1370	1540

In MIP tests [8], the intruded volume was 0.29 cm^3/g for the 4-8 mm fraction and 0.215 cm^3/g for the 8-16 mm fraction. Most of the pore volume was intruded when the pressure corresponded to pore necks with diameter between 350 and 70 nm. Weber & Reinhardt [6] report MIP results on the 4-8 mm fraction where the peak diameter of the pore size distribution was found at 400 nm. Zhang & Gjørv [8] observed the pore structure of the LWA with scanning electron microscopy, noticing a dense outer shell 0.1-0.3 mm thick and a more porous interior. Shapes of the pores were irregular, some spherical and isolated and others elongated and interconnected.

2.2. *Absorption under water*

Measurements of water absorption were performed on Liapor 8, fractions 4-8 mm and 8-16 mm. The LWA were first oven dried at 105 °C to determine the dry weight and then immersed in water at 20 °C. Results are plotted in Figure 1 together with data from [8]. The two fractions show different absorption: the coarser fraction absorbed about 17% by weight in the first day and then the weight remained almost unchanged; the finer fraction absorbed only slightly more water in the first day, but the absorption proceeded until 2 weeks after immersion, reaching a value of 25% by weight. The absorption after 6 h was about 80% of the 1-day value. In the finer fraction of the Liapor 8 aggregates more water can be absorbed. This is confirmed by the lower density of the finer fraction and by its higher porosity (Table 1). This fact might be beneficial if one wants to minimize the LWA content and maximize the water content of the mixture. On the other hand, it is unpractical to immerse the LWA in water for such a long time before concrete mixing. In another experiment, performed only on the 4-8 mm fraction, the LWA were vacuum-saturated with water. The absorption was in this case 26% by weight, very similar to the long-term absorption under water.

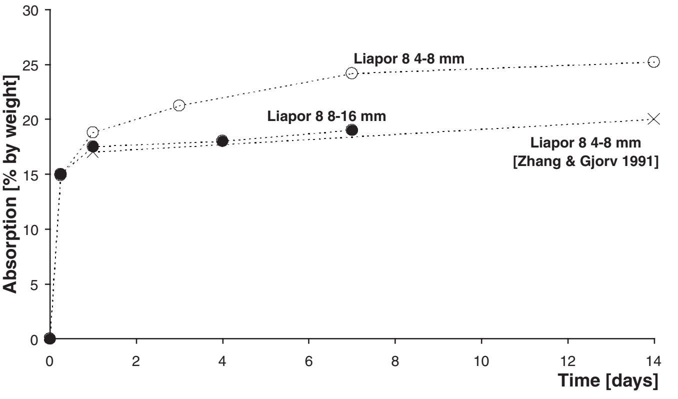

Figure 1: Percent water absorption by weight of Liapor 8, 4-8 mm and 8-16 mm fractions, stored in water at 20 °C

2.3. ***Desorption***

The LWA, Liapor 8 4-8 mm, were first immersed in water for 6 h and then exposed to decreasing RH levels in a desiccator, kept at 20 ± 1 °C, until moisture equilibrium was reached. The different RH levels were obtained by storage above saturated salt solutions, with known equilibrium RH at 20 °C. Three saturated salt solutions were used: KNO_3 (94.6% RH), KCl (85.1% RH), and NaCl (75.5% RH). The LWA followed a decreasing RH ramp, remaining about 2 weeks at every RH level. After the 2-week period, the LWA were weighed and moved to another desiccator. After the last step, they were dried in the oven at 105 °C to determine the dry weight.

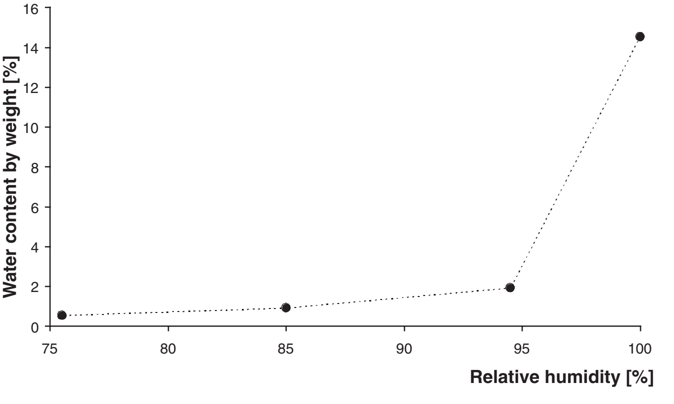

Figure 2. Desorption of Liapor 8 4-8 mm at 20 ± 1 °C

Results are shown in Figure 2. At 94.6% RH a significant fraction of the water content, about

13% by weight, was lost. This amount of absorbed water is thus readily available for transport to the paste while it self desiccates, since it is weakly bound by capillary forces to the pores of the LWA. In fact the pores of the LWA are relatively large compared to the pores in a cement paste, having an average radius of 0.05-0.2 µm [8]. This pore neck size corresponds to an equilibrium RH of 98 to 99.5%, calculated with Kelvin's equation [9].

3. Experiments on LWAC

3.1. *Materials*

Mixtures with w/c ratio 0.37 and 5% silica fume addition were studied. The mixtures contained both Portland cement (CEM I 52.5 R) and BFS cement (CEM III/B 42.5 LH HS) and were identical to Mixture C in [7], except for the LWA. Aggregate volume ratio of the mixes was 0.66. Only the coarse aggregate fraction of the NWC mix, with volume ratio of about 0.36, was substituted with LWA. Table 2 shows the mixtures with different degrees of saturation of the LWA.

Table 2. Mixture compositions of LWAC with different saturation of the LWA

Saturation of the LWA	**97.7%**	**69.3%**	**31.2%**
w/b ratio (without entrained water)	0.35	0.35	0.35
w/b ratio (with entrained water)	0.49	0.45	0.40
	[kg/m^3]	[kg/m^3]	[kg/m^3]
CEM I 52.5 R (Portland)	238.0	238.0	238.0
CEM III/B 42.5 LH HS (BFS)	237.0	237.0	237.0
Water (including admixtures)	175.8	175.8	175.8
LWA (Liapor 9.5, 4-8 mm)	538.4	538.4	538.4
Quartz sand, 0-4 mm	772.5	772.5	772.5
Lignosulphonate	0.9	0.9	0.9
Naphtalene sulphonate	7.1	7.1	7.1
Silica fume slurry (50% water)	50.0	50.0	50.0
Water in the LWA	71.0	50.4	22.7

The LWA were Liapor 9.5, 4-8 mm fraction. The grain density of the LWA was approximately 1650 kg/m^3. Three different target degrees of saturation of the LWA were employed. The required degree of saturation was obtained by spraying the LWA with the corresponding fraction of the 1-day absorption. To check how much of the sprayed water was actually absorbed by the LWA, wet weight and dry weight (after 24 h in the oven at 105 °C) were

measured on 3-kg samples taken from the aggregates just prior to mixing. The measured degree of saturation of the three mixtures is indicated in Table 2.
The absorption capacity of the aggregates was assumed as the amount of water absorbed after 24 hours under water at 20 °C. This is only a convention, since the LWA were probably not saturated at that time, as discussed previously. As a matter of fact, storage of the LWA for 1 d under water before concrete mixing is an established practice in LWAC production technology. For Liapor 9.5, 4-8 mm fraction, the 1-day absorption was 13.5% by weight of dry LWA.

In the case of mixtures with different particle size, the LWA used was Liapor 8 in two of the mixes and Liapor sand in the third mix. The grain density of the LWA was 1400-1500 kg/m^3 for Liapor 8 and 1100 kg/m^3 for Liapor sand. Details about the composition of the mixtures are reported in Table 3.
The water absorbed by the aggregates corresponded to the 1-day underwater absorption of the aggregate with the lowest absorption capacity, Liapor 8 8-16 mm. This quantity was about 15% by weight of dry aggregates. In fact the weight of the LWA was different in the three mixes, due to the different densities; thus the quantity of absorbed water also differed. The difference was quite relevant in the case of Liapor sand (51 kg/m^3 of water in the LWA) while the other two mixes were almost equivalent in this respect (72 and 77 kg/m^3 of water in the LWA).

Table 3. Mixture compositions of LWAC with different particle size of the LWA

	LWAC with Liapor 8 and Liapor sand		
Type of Liapor	Sand 0-4 mm	8 4-8mm	8 8-16 mm
w/b ratio (without entrained water)	0.35	0.35	0.35
w/b ratio (with entrained water)	0.45	0.50	0.51
	[kg/m^3]	[kg/m^3]	[kg/m^3]
CEM I 52.5 R (Portland)	238.0	238.0	238.0
CEM III/B 42.5 LH HS (BFS)	237.0	237.0	237.0
Water (including water in admixtures)	175.8	175.8	175.8
LWA (Liapor)	334.2	473.9	509.1
Quartz sand, 0-4 mm	772.5	772.5	772.5
Lignosulphonate	0.9	0.9	0.9
Naphtalene sulphonate	7.1	7.1	7.1
Silica fume slurry (50% water)	50.0	50.0	50.0
Water in the LWA	50.8	72.0	77.4

3.2. ***Methods***

3.2.1. Compressive strength and elastic modulus

Compressive strength and elastic modulus at different ages were measured on sealed specimens. Compressive strength was measured on concrete cubes with edge 150 mm. Elastic modulus in compression was tested on prisms, 100×100×400 mm^3. Cubes and prisms were cast in temperature-controlled steel molds.

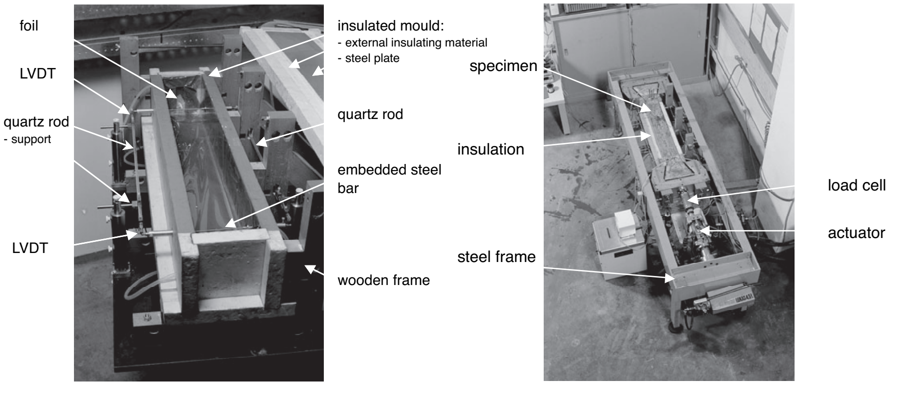

Figure 3. Left, experimental setup for the measurement of the free deformations of hardening concrete (ADTM). Right, experimental setup for the determination of stress development in hardening concrete (TSTM).

3.2.2. Free deformations and self-induced stresses

Measurements of free deformations were performed with the Autogenous Deformation Testing Machine (ADTM) and measurements of self-induced stresses in fully restrained conditions were performed with the Temperature-Stress Testing Machine (TSTM), shown in Figure 3. Both test devices were built and developed at the Concrete Structures Laboratory at Delft University of Technology [10]. For a detailed description, see [9].

3.3 ***Results***

3.3.1. Compressive strength

Figure 4 shows the cube compressive strength of the LWAC with variable degree of saturation. The compressive strength of the corresponding NWC [7] is also reported. All mixtures reached strength between 75 and 85 MPa at 28 days. The mixture with 69.3% saturated aggregates shows the highest strength at all ages, even higher than the NWC. The mixture with 31.2% saturated LWA shows an early development of strength close to the mix with 69.3% saturation, but the value at 28 days is the lowest. The mix with saturated aggregates had the lowest strength at early ages, but the 28-days value was close to the NWC.

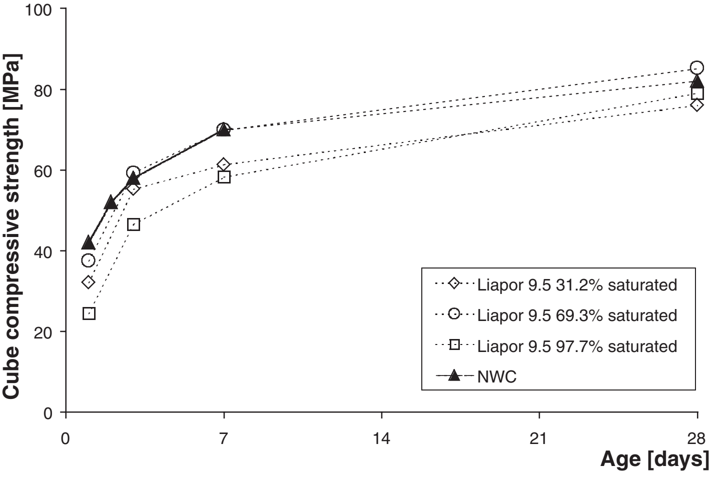

Figure 4. Cube compressive strength of LWAC with different degrees of saturation of the LWA compared with the corresponding NWC

In Figure 5 the compressive strength of mixtures with LWA of different dimensions (Liapor 8 and Liapor sand) is presented. The 28-days strength of the mixtures with Liapor 8 was considerably higher than the strength of the mixture with Liapor sand, 80 MPa versus 65 MPa. However, the two mixes with Liapor 8 4-8 mm and 8-16 mm had rather similar strength both at 3 and 28 days. LWAC realized with Liapor 8 reached 28-days strength similar to NWC with the same matrix.

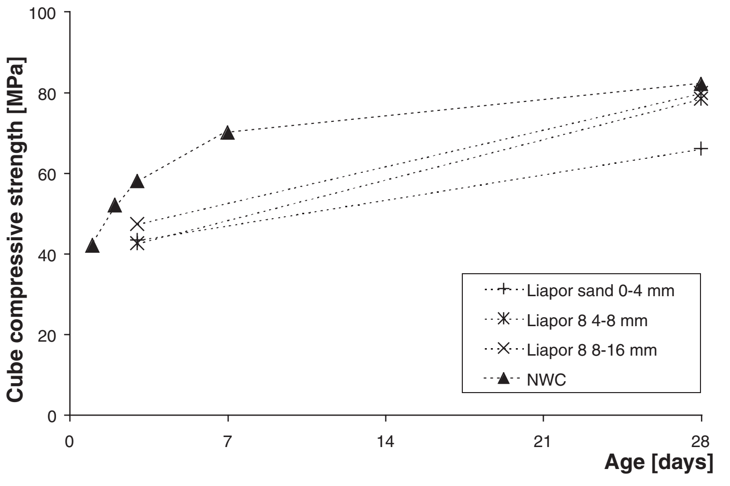

Figure 5. Cube compressive strength of LWAC with different particle size of the LWA compared with the corresponding NWC

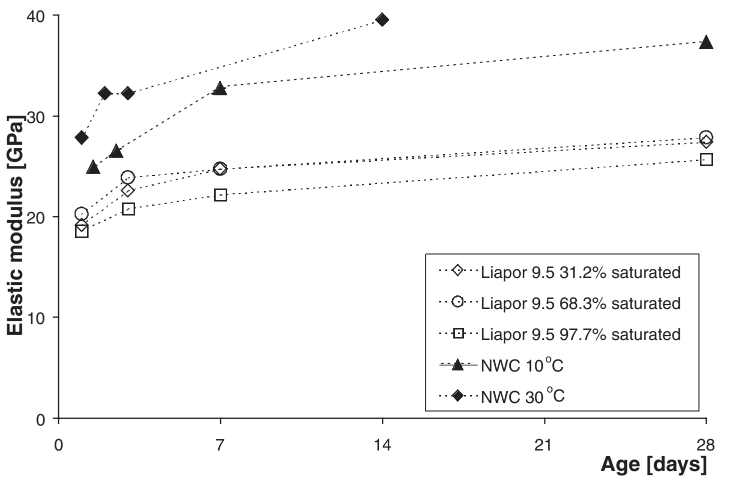

Figure 6. Elastic modulus of LWAC with different degrees of saturation of the LWA compared with the corresponding NWC

3.3.2 Elastic modulus

The development of the elastic modulus is shown in Figure 6. Only the mixtures with variable degree of saturation of the LWA were tested. Values between 25 and 28 GPa are reached at 28 days. The two mixes with 69.3% and with 31.2% saturated LWA show the highest values. For the reference mix, the results for curing at 10 and 30°C are shown, since the elastic modulus at 20°C was not measured [7].

3.3.3. Autogenous deformation and self-induced stress

In Figure 7, autogenous deformation of LWAC with different degrees of saturation of the LWA is presented. LWAC made with saturated LWA expanded from the start of the measurements, 6 h after casting. The expansion reached a maximum of 115 µstrain at 1ed LWA showed minor shrinkage in the very early stage of hardening. After 10 h, expansion occurred and reached 80 ?strain at 3 d. The mixture with 31.2% saturated LWA started with intensive shrinkage until 13 8 h and moderate expansion in the next 5 d. The resulting deformation 6 d after casting corresponded to shrinkage.

The effect of the degree of saturation of the aggregate on the stress development is shown in Figure 8. For the Liapor mixtures with degree of saturation 97.7% and 69.3%, which exhibited expansion, compressive stresses were measured. The maximum stresses were between 0.6 and 0.8 MPa. After the peak, a small decrease of the stress occurred, probably due to relaxation. For the mixture with 31.2% saturated LWA, the shrinkage registered in the first hours, when the elastic modulus of the concrete was still very low, did not induce any significant stress in the TSTM. The subsequent expansion, however, resulted in compressive stresses with maximum about 0.45 MPa after 2 d of hardening.

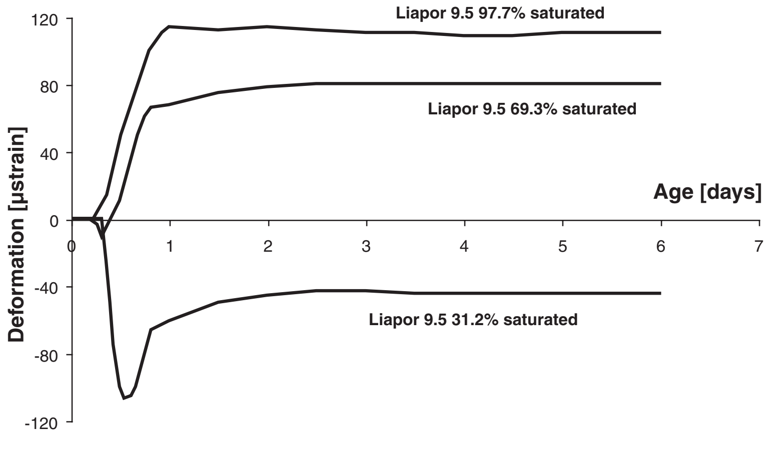

Figure 7. Autogenous deformation of LWAC with different degrees of saturation of the LWA

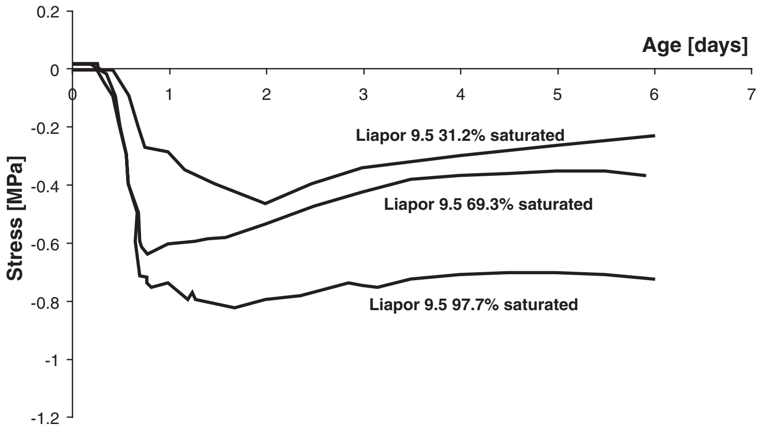

Figure 8. Self-induced stress of LWAC with different degrees of saturation of the LWA

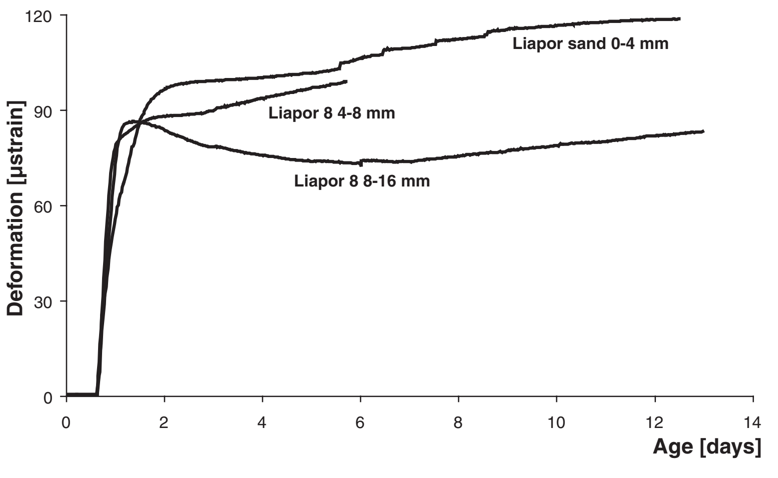

Figure 9. Autogenous deformation of LWAC with different particle size of the LWA

In Figure 9 the autogenous deformation of LWAC mixtures with LWA of different particle size is shown. The three mixes expanded from the beginning of the measurements. The mix with Liapor sand 0-4 mm expanded rapidly until 2 d, reaching 95 µstrain. Afterwards expansion proceeded steadily but at a lower rate until a value of 120 µstrain. The expansion of the mix with Liapor 8 4-8 mm was continuous, reaching a value of 100 µstrain at 6 reached a peak of 85 µstrain at 30 h. Then some shrinkage occurred until 6 d, followed by further expansion. At 13 d the expansion was about 80 µstrain.

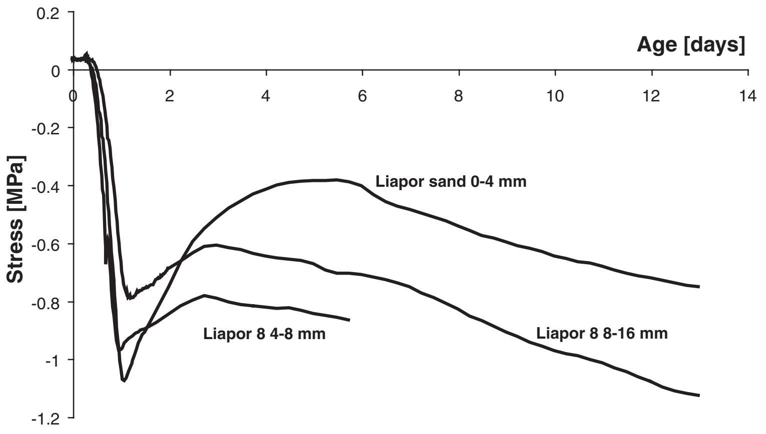

Figure 10. Self-induced stress of LWAC with different particle size of the LWA

Stress development in LWAC with aggregates of different particle size is shown in Figure 10. The stress of the mix with Liapor sand shows a maximum in compression, about 1.1 MPa, higher than the one observed for the mixture with 4-8 mm Liapor 8, 1.0 MPa, and for the mixture with 8-16 mm Liapor 8, 0.8 MPa. For all the mixes, the peaks are reached within 24-30 h from casting. The relaxation of the compressive stress after the peak is more relevant for the mixture with Liapor sand, where the stress is reduced to 0.4 MPa, than for the other two mixtures. The stress development of the two mixtures with Liapor 8 is similar, showing slight relaxation until 3 d and then an increase of the compressive stress. In the case of the mix with 8-16 mm LWA, the experiment was prolonged to 13 d showing continuous increase of the compressive stress, up to a value of more than 1.1 MPa. Also the mixture with Liapor sand, after relaxation of the stresses up to 6 d, shows an increase of the compressive stresses until the end of the experiment.

3.4. *Discussion*

3.4.1. Compressive strength

LWAC generally reached 28-days strength similar to NWC with the same matrix. In particular, the mixture with 69.3% saturated Liapor 9.5 (Figure 4) had the highest strength at all ages, even higher than the NWC. Possibly it combines the beneficial effects of the internal curing with a relatively low w/c ratio. A fast development of strength is shown also by the mixture with 31.2% saturated Liapor 9.5 (Figure 4), but the strength at 28 days is the lowest, possibly due to less internal curing. The opposite is shown by the mixes with saturated Liapor 9.5 (Figure 4) and Liapor 8 (Figure 5), where the strength at early ages was low, but the 28-days value was close to the NWC. Finally, the mixture with Liapor sand (Figure 5) showed that the use of a LWA with lower density, and hence poorer mechanical properties, limits the strength of the LWAC.

A number of factors influence the compressive strength of LWAC:

1) The strength of concrete is severely influenced by the weakest component. Since the mechanical properties of the LWA are generally inferior to the ones of NWA, the strength of the aggregates tends to provide a ceiling strength for the strength of the concrete [11]. The strength of a particular LWA is the result of its porosity and of its pore size distribution as well as of the strength of the pore-free vitreous material surrounding the pores [11]. According to these considerations, one would expect the highest compressive strength for the mixtures with NWA, followed by Liapor 9.5, Liapor 8, and Liapor sand. In practice, Liapor 9.5 and 8 performed as well as NWA and a strength decrease was noticed only for Liapor sand.
2) Moist concrete shows lower strength than partially dried concrete [5]. When cured in sealed conditions, LWAC has internal RH higher than NWC due to water supply from the LWA. Accordingly, the mixes with saturated LWA should have lower strength, a fact that was not observed for the mixtures studied.
3) An improved quality of the interfacial transition zone and of the bond between LWA and matrix may contribute to the strength of LWAC. It has been observed [12], that cement paste penetrates in the outer porous layer of the LWA particles, strengthening the bond.
4) Stress homogeneity in loaded LWAC, due to limited elastic mismatch between aggregates and cement paste [11], might reduce the occurrence of internal microcracking, thus increasing the strength. This fact produces also increased brittleness of LWAC, whose stress-strain curves are normally almost elastic until failure [11].
5) Continuous hydration of the mixture at later ages, promoted by the extra water stored in the LWA, might also contribute to the strength increase.
6) Finally, since the cement paste in the LWAC does not shrink but expands at early age (see the following sections), micro-cracks or eigenstresses in the paste [2], due to aggregate restraint, are avoided. This fact might also contribute to increased strength at later ages of LWAC compared to NWC.

3.4.2. Elastic modulus

The elastic modulus of NWC was much higher than the one of LWAC, essentially due to the higher elastic modulus of the NWA, about 50-75 GPa vs. 17-20 GPa of the LWA [13].

Using the following equation developed by Hobbs [14], it is possible to calculate the elastic modulus of a concrete based on the elastic modulus of matrix and aggregates:

$$E_C = \frac{(E_A - E_M).\phi_A + E_A + E_M}{E_A + E_M + \phi_A.(E_M - E_A)}.E_M \quad (1)$$

where E_A [MPa] is the elastic modulus of the aggregates, E_M [MPa] the elastic modulus of the matrix, and ϕ_A [m^3/m^3] the volume fraction of the aggregates.

To calculate the elastic modulus of the reference NWC mix [7], the following assumptions are made:

1) $E_M = E_P = 20$ GPa, as measured in [15] on the same cement paste.
2) $E_A = 60$ GPa for NWA.
3) $\phi_A = 0.66$.

Using these assumptions, $E_C = 39.7$ GPa is obtained, whereas the measured elastic modulus varied from 37.3 to 39.5 GPa, depending on the curing temperature [7].

To calculate the elastic modulus of a LWAC mix, a different procedure needs to be applied, since two types of aggregates with different stiffness are present. First, the elastic modulus of the mortar fraction is calculated with Eq.1. Then, the obtained elastic modulus of the mortar is used as modulus of the matrix in the calculation of the elastic modulus of LWAC.

For the calculation of the elastic modulus of the mortar, the inputs are the following:

1) $E_P = 20$ GPa [15].
2) $E_A = 60$ GPa for the sand in the mortar fraction.
3) $\phi_A = 0.30/(0.30+0.34) = 0.469$ for the sand in the mortar fraction.

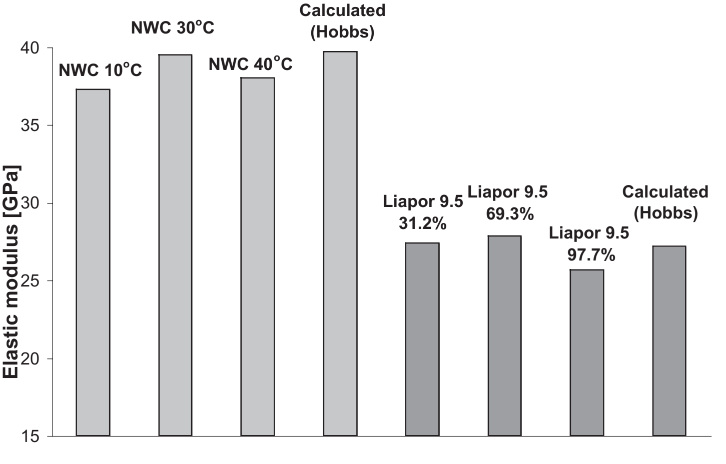

Figure 11. Measured and calculated 28-days elastic modulus of NWC (left, Mix C in reference [7], curing temperature 10, 30 and 40°C) and LWAC (right, mixes in Table 2, curing temperature 20°C)

Using these values, $E_{MOR} = 32.2$ GPa is obtained for the mortar. Eq.1, with $E_M = E_{MOR}$, $E_A = E_{LWA} = 20$ GPa for Liapor 9.5, and $\phi_A = \phi_{LWA} = 0.36$ yields $E_C = E_{LWAC} = 27.2$ GPa. The

measured elastic modulus varied from 25.7 to 27.8 GPa, depending on the saturation of the LWA (Figure 6).
Measured and calculated elastic moduli, both for NWC and for LWAC, are reported in Figure 11. Eq.1 gives a good fit of experimental results and may be used both for NWC and for LWAC. The differences between the measured elastic moduli of the different LWAC mixtures might have been caused by differences in the elastic modulus of the paste, due to internal curing, and by different moisture status [11].

3.4.3. Early-age expansion of LWAC

Early-age expansion of LWAC is an intriguing phenomenon. Cement paste in sealed High Performance Concrete made with regular aggregates generally shrinks due to self-desiccation. Water transport from the saturated LWA in LWAC is supposed to reduce or eliminate the shrinkage by counteracting self-desiccation, but this does not explain the origin of the expansion. In the following section, it will be shown that expansion of LWAC can be directly calculated supposing that the cement paste expands as it does when it is cured in saturated conditions.

Early-age expansion in LWAC was measured by a number of researchers [4, 16-19]. Sickert et al. [17] measured continuous expansion for more than 1 year, most of it occurring in the first days. The bulk expansion is due to the expansion of the cement paste, which is cured in almost saturated conditions, ensured by water from the LWA. This behavior is similar to the expansion that occurs in thin cement paste samples cured under water, which may amount to 1000-2000 μstrain [20]. Jensen & Hansen [21] measured an expansion of about 800 μstrain, most of it in the first day of hydration, on a w/c ratio 0.30 cement paste with 20% silica fume addition internally cured with superabsorbent polymers.

Here, an approximate calculation of early-age expansion of LWAC as a function of expansion of the cement paste is presented. The expansion of the mix with saturated Liapor 9.5 (Figure 7) is used as an example. The scope of this calculation is to verify whether the literature values of expansion of saturated cement pastes are compatible with the expansion measured on LWAC. Most of the expansion of the LWAC occurs in the first day. To calculate expansion of LWAC with the following approach, its mechanical properties need to be known. Comparing the free deformation measured with the ADTM (Figure 7) and the self-induced stress measured in the TSTM (Figure 8), the early-age effective stiffness of the mixture may be calculated. The peak of the self-induced stress of the mix with saturated Liapor 9.5 corresponds to the peak of expansion. If the peak stress, σ_{PEAK} [MPa], is divided by the corresponding strain, ε_{PEAK} [m/m], an effective stiffness of the LWAC during expansion is obtained:

$$E_{LWAC,EF} = \left| \frac{\sigma_{PEAK}}{\varepsilon_{PEAK}} \right| \tag{2}$$

This effective stiffness probably includes also some creep and plastic deformation. According to this calculation, the average stiffness of the LWAC in the first day is 6.3 GPa. As a reference, the elastic modulus measured at 1 d was 18.6 GPa (Figure 6). Knowing the stiffness of the LWAC during the expansion phase, it is possible to calculate the stiffness of the mortar phase by inverting Eq.1: $E_{MOR} = 3.83$ MPa. With the stiffness of the mortar phase, the volume fraction of the sand in the mortar, $\phi_S = 0.469$, and the stiffness of the sand, $E_S = 60$ GPa, we may apply Pickett's model [22] to calculate the ratio between the expansion of the paste and the expansion of the mortar phase.

Pickett [22] derived an expression for the effects of aggregates on concrete shrinkage. The formula is derived by considering the restraining effect of one small spherical aggregate particle embedded in a large body of shrinking concrete. The concrete surrounding the aggregate particle is considered as a homogeneous material and both the particle and the concrete are assumed to be elastic. As further particles are added, the elastic properties and the shrinkage are recalculated, while the body is still considered to remain homogenous. Integration and a number of assumptions lead to the expression:

$$\varepsilon_C = \varepsilon_P \cdot (1-\phi_A)^{\alpha_P} \tag{3}$$

where ε_C [m/m] is the shrinkage of concrete, ε_P [m/m] the shrinkage of the paste, ϕ_A [m^3/m^3] the volume fraction of the aggregates and α_P [-] is a parameter defined as:

$$\alpha_P = \frac{3 \cdot (1-\nu_C)}{1+\nu_C+2 \cdot (1-2\nu_A) \cdot E_C / E_A} \tag{4}$$

where ν_C and ν_A [-] are the Poisson's ratio of the concrete and of the aggregates, respectively, and E_C and E_A [MPa] are the elastic moduli of the concrete and of the aggregates, respectively.

Applying Eq.3 to calculate the ratio between the expansion of the paste and the expansion of the mortar phase, $\varepsilon_{MOR}/\varepsilon_P = 0.35$ is obtained. Expansion of the mortar is restrained by the LWA. The LWA in this calculation are supposed to be volumetrically stable since the internal RH remains high in the first hours after casting [9]. Applying once again Eq.3 with $E_{LWAC} = 6.3$ GPa (as calculated with Eq.2), $E_{LWA} = 20$ GPa, and $\phi_{LWA} = 0.36$, we finally obtain $\varepsilon_{LWAC}/\varepsilon_{MOR} = 0.56$. The ratio of the deformation of the LWAC to the deformation of the paste results by multiplication of the two ratios: $\varepsilon_{LWAC}/\varepsilon_P = 0.19$. Since the expansion of the LWAC at 1 day is 120 µstrain, the expansion of the paste results 620 µstrain. This result, given the uncertainties of the calculation, is in fairly good agreement with the 800 µstrain measured on saturated cement paste in the first day of hydration [21].

3.4.4. Self-induced stresses

The self-induced stress of all LWAC mixtures tested was always compressive in the first week of hydration. The corresponding NWC, on the other hand, developed a tensile stress of up to 2 MPa. These reduced stresses in LWAC might be an important contribution to mitigate early-age cracking risk in field conditions when external restraint is present. More in detail, the self-induced stress and the autogenous deformation of mixtures with Liapor 9.5 were functions of the degree of saturation of the LWA. The mixtures with more entrained water expanded more and the compressive stresses were higher. It should be noticed, however, that also the mixture with 31.2% saturated aggregates showed a good performance, since the shrinkage in the first hours of hydration apparently occurred while the concrete was still plastic and did not correspond to any appreciable build up of tensile stresses. The mixtures with small and homogenously distributed saturated LWA (Liapor 8 4-8 mm and Liapor sand 0-4 mm) showed more expansion in the first 2 weeks after casting and higher self-induced compressive stresses than the mixture with coarser aggregates (Liapor 8 8-16 mm). This behavior may be due to a better distribution of the water-reservoirs in the mixtures with finer LWA.

4. Conclusions

LWAC realized with expanded shale (Liapor) aggregates generally reached 28-days compressive strength similar to NWC with the same matrix. Explanations of this fact should take into consideration strength and elastic modulus of LWA, moisture conditions of the concrete, the improved interfacial transition zone in LWAC, the internal curing process, and the reduction of the eigenstresses due to absence of self-desiccation shrinkage. The elastic modulus of the LWAC mixtures was lower than for the corresponding NWC, due to the lower stiffness of the LWA compared to NWA. Both elastic moduli of NWC and of LWAC could be calculated with good approximation using a simple composite model [14].

In LWAC, incorporation of wet LWA in the mix produced early-age expansion in place of shrinkage. The cause of the bulk expansion was the expansion of the cement paste, hardening in saturated conditions due to internal curing, as was confirmed applying Pickett's model [22]. Early-age expansion was strongly dependent on the degree of saturation of the LWA and to a lesser extent on their particle size, being larger for smaller LWA. These facts showed the impact on the internal curing process of the quantity of entrained water and of the distance of water penetration into the hardening cement paste. Properties of the LWA favorable for internal curing, such as a high porosity and an open pore structure, were pointed out and measured.

5. References

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