AUTOGENOUS AND DRYING SHRINKAGE OF HIGH STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE AT EARLY AGES – THE EFFECT OF SPECIMEN SIZE

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Abstract
Concrete with a nominal characteristic cube compressive strength of 65 MPa is made with a low water/binder ratio. In order to avoid self-desiccation of the cement paste, it is possible to add saturated lightweight aggregates (LWA) in the fresh mix. This addition modifies the deformational behaviour of the concrete.
In this contribution the results of an experimental program about autogenous and drying shrinkage of high-strength concrete mixtures. Variables were aggregate type (crushed aggregate or LWA), degree of saturation of the LWA (100% and 50%), specimen size (prisms 50x50x200 mm³, 100x100x400 mm³, 150x150x600 mm³) and age at start of drying (7 and 28 days). The experimental data are presented and evaluated. Drying shrinkage results are compared with predictions according to currently used formulae (Model Code '90). Conclusions are drawn regarding the applicability of current codes to allow for the size effect in case of lightweight aggregate concrete (LWAC).

1. Introduction
A low water/binder ratio makes concrete sensitive to self-desiccation of the cement paste, which leads to autogenous shrinkage. Partial substitution of the coarse aggregates with saturated LWA reduces the autogenous shrinkage [1]. As proposed by, e.g., Weber et al. [2], water contained in the LWA neutralises the self-desiccation process, reducing or entirely avoiding the autogenous shrinkage. If all the coarse aggregates are replaced with water-saturated LWA, from the first hours after casting swelling, in place of shrinkage, is observed [3]. This swelling increases steadily for months [4]. Not only the total amount of water contained in the LWA, but also its spatial distribution (concentrated in few coarse particles or homogeneously distributed in finer ones) affects the process of internal water curing. In [5] it is shown that mixtures with fine LWA swell more than mixtures with the same volume of coarser aggregates, provided that the amount of water stored in the LWA is the same. Relative humidity in concrete is important not only at
early age, but also when later drying shrinkage is considered. About the interaction of autogenous and drying shrinkage in low w/c ratio normal weight concrete (NWC), reference is made to [6-9].

In a sealed specimen with homogeneous temperature distribution during hydration, the autogenous deformation in the cross section is constant. Drying of the concrete is a slow process (especially for low w/c ratio mixtures, with tight microstructure) and causes moisture gradients in the cross section of the specimen, depending both on the pore structure of the material and on size and shape of the specimen. If the internal relative humidity is not only determined by the external conditions, but also by internal processes of water transport (from the LWA to the drying paste), it is expected that size effects, as considered in the codes, are no longer applicable. Most of these size effect factors are in fact based on analysis of shrinkage data on NWC. LWAC specimens exposed to drying conditions will shrink at the outer faces, while the inner core will not be influenced, at first, by the environmental relative humidity, and continue to swell. Depending on the size of the specimen, the total deformation might result in shrinkage (for smaller specimens) or in swelling (in larger specimens, where the behaviour of the core prevails). It is also expected that the final shrinkage, when the specimen has reached equilibrium with the environment (process that will be completed in years, see [4]), will be higher for LWAC than for NWC, since the water content is higher in the first mixtures. This fact might affect the risk of cracking of LWAC at later ages.

A series of experiments was performed to investigate autogenous and drying shrinkage in LWAC and the effect of specimen size. The results are compared with tests performed on a NWC mixture and with predictions according to Mode Code '90.

2. Materials and experimental set-up

2.1 Mixture compositions

The tested LWAC mixtures had a target characteristic cube compressive strength of 65 MPa (i.e. to mean strength 73 MPa). Mixture compositions are shown in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>kg/m³</td>
<td>156</td>
<td>139</td>
<td>139</td>
<td>146</td>
<td>146</td>
</tr>
<tr>
<td>CEM III/B 42.5 LH HS</td>
<td>kg/m³</td>
<td>300</td>
<td>230</td>
<td>230</td>
<td>237</td>
<td>237</td>
</tr>
<tr>
<td>CEM I 52.5 R</td>
<td>kg/m³</td>
<td>100</td>
<td>230</td>
<td>230</td>
<td>238</td>
<td>238</td>
</tr>
<tr>
<td>Silicol SL (50/50 slurry)</td>
<td>kg/m³</td>
<td>51</td>
<td>51</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td></td>
<td>0.39</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Sand 0 – 4 mm</td>
<td>kg/m³</td>
<td>830</td>
<td>790</td>
<td>790</td>
<td>773</td>
<td>773</td>
</tr>
<tr>
<td>Crushed aggregate 4–16 mm</td>
<td>kg/m³</td>
<td>975</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liapor F10, 4-8 mm</td>
<td>kg/m³</td>
<td>628</td>
<td>589</td>
<td>614</td>
<td>584</td>
<td>584</td>
</tr>
<tr>
<td>Addiment BV1</td>
<td>kg/m³</td>
<td>1.6</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Addiment FM 951</td>
<td>kg/m³</td>
<td>4.8</td>
<td>9.2</td>
<td>9.2</td>
<td>7.1</td>
<td>9.5</td>
</tr>
</tbody>
</table>

1) LWA, 100% saturated   2) LWA, 50% saturated   3) LWA, 60% saturated
In all mixtures a blend of Portland cement (CEM I) and blast furnace slag cement (CEM III) was used. Mixture I, with crushed coarse aggregates, 400 kg cement and a w/c ratio of 0.39, is considered as the reference mixture. In the other mixtures, all coarse aggregate is replaced by LWA Liapor F10. Mixtures II and IV (differing for the total cement amount) are realised with saturated LWA. Mixture III is identical to II but the Liapor F10 is 50% saturated. Mixture V is like IV but the degree of saturation is 60%. In this study, 100% saturation was considered realised by storing air-dry aggregates for 24 hours in water, which corresponds to a normal practice. In fact it is known that after 24 hours of water storing the aggregates still have the potential to absorb more water [4]. Spraying half of the absorbed water amount on air-dry aggregate, 50% saturation was obtained; the same principle was applied for 60% saturated aggregate.

2.2 Specimens, curing conditions and measurements
The concrete compressive strength was measured on concrete cubes, 150x150x150 mm³, cured at a relative humidity of 99% and a temperature of 20°C.
For mixes I, II and III, autogenous shrinkage was measured on sealed prisms, 100x100x400 mm³, placed vertically. Measurements started 1 day after casting and the specimens were stored in a climate room at 20±2°C. Drying shrinkage was measured on prisms where the sealing was removed after 7 or 28 days. The specimens were placed in a climate room with RH = 50% and T = 20°C. For all the mixtures drying shrinkage was measured on prisms 100x100x400 mm³; for the reference mixture I and for mixture II also on 50x50x200 mm³ and 150x150x600 mm³ specimens. All shrinkage measurements were performed in two-fold; the shrinkage curves represent the average of two prisms.
On mixes IV and V, only autogenous shrinkage was measured. Measurements were performed with an autogenous deformation testing machine (ADTM), with which also the very early age deformations, just after concrete setting, could be recorded. The autogenous shrinkage up to one week after casting was recorded. For a description of the experimental equipment and details of the testing methods, reference is made to [3].

3. Results of experimental study

3.1 Compressive strength
The mean cube compressive strengths after 7, 14 and 28 days are presented in Table 2.

<table>
<thead>
<tr>
<th>Mixture nr.</th>
<th>Cement [kg/m³]</th>
<th>Filler and other binder</th>
<th>W/c ratio</th>
<th>Mean cube compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 days</td>
<td>14 days</td>
</tr>
<tr>
<td>I</td>
<td>400</td>
<td>----</td>
<td>0.39</td>
<td>62.7</td>
</tr>
<tr>
<td>II</td>
<td>460</td>
<td>50 kg SF-slurry</td>
<td>0.37</td>
<td>62.7</td>
</tr>
<tr>
<td>III</td>
<td>460</td>
<td>50 kg SF-slurry</td>
<td>0.37</td>
<td>33.6</td>
</tr>
<tr>
<td>IV</td>
<td>475</td>
<td>50 kg SF-slurry</td>
<td>0.37</td>
<td>58.2</td>
</tr>
<tr>
<td>V</td>
<td>475</td>
<td>50 kg SF-slurry</td>
<td>0.37</td>
<td>69.9</td>
</tr>
</tbody>
</table>
Strength values beyond the target strength of 73 MPa (mean value) were obtained with all the LWAC mixtures, with a high cement content and the addition of silica fume to compensate for the lower strength of the aggregate. The strengths of mixtures III and V, with a degree of saturation of the aggregate of 50% and 60%, were higher than for mixtures II and IV (100% saturated). A plausible reason is that, in the early stage of hardening, the effective w/c ratio in mixtures III and V is lower than in mixtures II and IV, resulting in a stronger paste. The reference mixture I did not reach the required 28 day mean cube compressive strength of 73 MPa.

3.2 Autogenous shrinkage of NWC and LWAC (sealed condition)

Autogenous deformation was measured on concrete samples 100x100x400 mm³ for mixtures I, II and III. The results of the measurements are presented in Fig. 1.

![Autogenous deformation graph](image_url)

Figure 1 Effect of type of aggregate and degree of saturation on autogenous deformation of mixtures I, II and III. Measurements started after 24 hours. Isothermal curing (20°C).

Measurements started 24 hours after casting. On reference mixture I shrinkage was measured. The LWAC with 100% saturated LWA showed swelling, up to 70 μstrain. The swelling of mixture III, with LWA 50% saturated, was even higher. An explanation is that, since the measurement started after 24 hours, the very early-age deformations have not been recorded. In fact, mixtures IV and V (comparable to mixtures II and III respectively) in the first day after casting (see Fig. 2, data obtained with an ADTM), show a higher swelling in the first hours for the mixture with 100% saturated LWA. In particular, mixture IV swelled from 6 hours after casting. The expansion reached a maximum of 115 μstrain after 24 hours and then remained almost constant for more than 5 days. Mixture V showed minor shrinkage in the very early stage of hardening. After 10 hours expansion was observed. The maximum expansion was about 80 μstrain, reached after 72 hours. Thus, by comparison with mixes IV and V, it could be assumed that also the swelling of mixture II, in the first 24 hours after casting, exceeded that of mixture III.
Figure 2  Autogenous deformation of LWAC mixtures with saturation degrees of the aggregates 100% (Mix IV) and 60% (Mix V). Isothermal curing (20°C).

3.3 Shrinkage of NWC and LWAC (unsealed condition)
The sealing was removed 7 or 28 days after casting, starting the drying process. For the three mixtures, the strain curves are presented in Fig. 3.

Figure 3  Measured shrinkage of mixtures I, II and III after removal of sealing after 7 days (full lines) and after 28 days (dotted lines). Drying at RH = 50%, T = 20°C. Specimen size 100x100x400 mm³.

The highest shrinkage strains after 90 days were measured for the reference mixture I. Shrinkage of the two LWAC mixtures was much less, the lowest being observed for mixture II, with a degree of saturation of the aggregate of 50%. The shrinkage of mixtures II and III was about 70% and 30% of the shrinkage of reference mixture I.
As reported in [6], the age of start of drying does not sensibly influence the drying shrinkage. For the NWC the difference is small and in the case of the LWAC the values of shrinkage at 90 days are the same, regardless of the age when drying starts.

### 3.4 Total shrinkage – NWC versus LWAC

The total deformation of the mixtures I, II and III is presented in Fig. 4.

Up to 28 days only autogenous strains occur. The deformations measured after 28 days are due to both drying and self-desiccation. The LWAC mixture III with 50% saturated aggregate, exhibits no shrinkage at all after 90 days. For mixture II the total shrinkage after 90 days is 130 μstrain. For reference mixture I the final shrinkage is 470 μstrain. The behaviour of the mixtures II and III is thus totally different from the behaviour of NWC, showing the effect of the presence of water-containing aggregate particles in the concrete. A major reason for the deviations between LWAC and NWC goes back to the role of the relative humidity on the deformatonal behaviour of the mixtures [5].

![Graph showing total strain vs. time for mixtures I, II, and III](image)

**Figure 4** Total deformation of mixtures I, II and III. Sealed curing up to 28 days, then exposed to RH = 50% and T = 20°C. Sample size 100x100x400 mm³.

### 3.5 Measured size effects on LWAC and predictions according to MC'90

The effect of specimen size on the shrinkage has been studied for the LWAC mixture II. Specimens’ sizes were 50x50x200 mm³, 100x100x400 mm³ and 150x150x600 mm³. Measurement started after 7 and 28 days. For other experimental results, including tests on the reference mixture I, reference is made to [9]. Experimental results for drying after 28 days and calculations according to MC'90 are presented in Fig. 5.

The shapes of the shrinkage curves of mixture II, as well as the absolute values of the shrinkage strains, differ significantly from predictions by the MC'90. At first the shrinkage rate of LWAC is lower than predicted by the MC'90, but at later ages it is higher, a fact that is shown by the smallest specimens. For the bigger specimens the testing period was too short to confirm this assumption. From the higher shrinkage rates
of LWAC at later ages it might be deduced that the final drying shrinkage of LWAC would be higher than that of NWC. This is confirmed by other experimental results [4]. It should be noticed that the MC’90 deals with NWC and not LWAC. Therefore, comparison of measured shrinkage strains of LWAC with theoretical shrinkage curves of MC’90 must be considered as a demonstration of the deviating behaviour of LWAC when compared to NWC. In order to predict size effect in shrinkage of LWAC, a microstructure-based approach to the problem is needed, taking into account the relative humidity and the moisture transport within the concrete.

Figure 5 Measured shrinkage and calculations according to MC’90 for different specimen size. LWAC (mix II). Drying started after 28 days. RH = 50%, T = 20°C.

4. Conclusions

The shrinkage due to self-desiccation and drying in an environment with 50% RH was investigated experimentally for lightweight concrete mixtures with a target characteristic cube compressive strength of 65 MPa. Investigated parameters were the saturation of the aggregates, moment of start of the drying process and specimen size. Measured shrinkage strains were compared with those of NWC and with predictions according to MC’90. LWAC with a degree of saturation of the aggregate (Liapor F10) of 100% and 50% exhibited autogenous swelling up to an age of 90 days, whereas for the reference NWC mixture shrinkage (up to 470 μstrain) was measured. Drying shrinkage of LWAC up to 90 days was much lower than predicted with the MC’90. Furthermore, comparison with other experimental results [9] reveals that the shape of the shrinkage curves differs from those of NWC. At first, shrinkage of LWAC proceeded slower. At later ages the rate of shrinkage remained relatively high. This might result in a higher final shrinkage of the LWAC (compare also with [4]). If the total deformation is taken into consideration, LWAC mixtures exhibited very low shrinkage or even slight swelling up to 90 days from casting.
The size effect of drying shrinkage on NWC has been quantified mainly on the basis of experimental data. The presence of water-saturated LWA particles affects the relative humidity in the concrete, violating the size effect rules of MC’90, based on experiments on NWC. It was found that in case of LWAC the size effect is more pronounced than in case of NWC [9]. Small LWAC samples exhibited higher shrinkage than predicted with the MC’90. For larger specimens the opposite was found. In order to obtain accurate predictions of drying shrinkage in LWAC specimens of different sizes, the actual humidity distribution in the cross-section should be considered in the calculations.

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References