EFFECT OF MIXTURE COMPOSITION AND SIZE EFFECT ON SHRINKAGE OF HIGH STRENGTH CONCRETE

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Abstract

Experiments with low water/binder ratio mixtures for concretes with a nominal characteristic cube compressive strength of 65 MPa have revealed that these mixtures may exhibit significant autogenous shrinkage. This autogenous shrinkage is considered to be the result of self-desiccation. The decrease of the relative humidity due to self-desiccation will affect the subsequent deformations due to drying shrinkage. The question is to what extent the early self-desiccation violates current predictive formula for drying shrinkage. Another question concerns the size effect on drying shrinkage of low water/binder ratio concretes. In this contribution the results of an experimental research project on autogenous and drying shrinkage of different concrete mixtures with the indicated nominal compressive strength is presented. Since the interaction between the hydration-induced autogenous shrinkage and drying shrinkage was the major issue, the duration of the tests was limited to 90 days. Research parameters are the mixture composition, type of aggregate, the size of the specimen and the time at which the specimens were subjected to drying. The tests last In the discussion of the results attention will be paid to the role of the relative humidity of the concrete. The question to what extent the effect of changes in the relative humidity caused by self-desiccation differs from those caused by drying shrinkage will be mentioned briefly. The experimental data is compared with shrinkage predictions obtained with the current code MC’90, which code intends to cover concrete grade C65. The aim of this comparison was to check the limits of applicability of this code if applied to low water/binder ratio mixtures.

1. Introduction

Recently a number of bridges have been built in The Netherlands with concrete grade C55/65, i.e. a characteristic cube compressive strength of 65 MPa. The practical advantage of using concrete in this strength class is that designers can still use the current Dutch design code VBC’95. This code intends to cover strength classes up to grade C55/65 and designers do not need to consult additional documents for designing those bridges as long as they stick to this strength class. As regards shrinkage, however, the current codes only consider drying shrinkage. Recent studies of the deformational
behaviour of concretes with a characteristic cube compressive strength of about 65 MPa have revealed substantial autogenous shrinkage. Knowing that both autogenous shrinkage and drying shrinkage are caused by, or are at least correlated with a decrease of the relative humidity of the concrete, the question from the engineering practice was whether the occurrence of autogenous shrinkage could be considered as an early form of drying shrinkage. In that case the code values for drying shrinkage could be reduced, since a certain part of the shrinkage had occurred already in the concrete’s early life. An argument against this reasoning would be that, although the current codes only mention drying shrinkage, the experiment-based shrinkage formulae do contain already some autogenous shrinkage, but that for the sake of simplicity this has never been made explicit.

From the theoretical point of view a simple addition of autogenous shrinkage and drying shrinkage is not justified, as the drop of relative humidity due to self-desiccation occurs in a relatively short period of time when compared to the decrease of the relative humidity as caused by drying shrinkage. The decrease of the relative humidity goes along with an increase of capillary forces, which puts the microstructure in a state of stress and causes the deformation of the system. In the period that the autogenous shrinkage occurs, the stiffness of the concrete is, on average, still lower than in the period that drying shrinkage occurs. Hence the capillary forces caused by self-desiccation will exert larger deformations than those caused by drying shrinkage. Creep effects, which are inherently connected with the exerted stresses in the microstructure, will further complicate a quantitative judgement of the contribution of self-desiccation and drying shrinkage to the resulting macroscopic deformations of the concrete. Finally, if drying shrinkage starts early, i.e. when the hydration process is still going on, the hydration process will be retarded or will stop completely. As a result of this less autogenous shrinkage will occur. Only little information is available on the interference of autogenous and drying shrinkage. Interesting contributions to the subject are those of Miyazawa et al. [1], Ishida et al. [2], Persson [3] and Aïtcin [4]. With the aim to generate additional quantitative data about the interference between autogenous shrinkage and drying shrinkage, an experimental study was performed. The study focuses on the performance of concrete with a characteristic cube compressive strength of 65 MPa, since it was particularly for mixtures in this strength class that designers experienced the need for more data. In view of the practical applicability of experimental results also the size of the test specimen was considered an important research parameter.

2. Experiments

2.1 Details of the mixtures
An experimental study was carried out focusing on autogenous and drying shrinkage of six different concrete mixtures, target characteristic cube compressive strength 65 MPa. A characteristic cube compressive strength of 65 MPa corresponds with a mean cube compressive strength of 73 MPa. It was the designers wish to know which concrete mixture could yield the required strength with the most favourable deformational performance in the early stage of hardening. The composition of the six mixtures is shown in Table 1. Main differences between the mixtures concern the amount of cement, type of aggregate and type and amount of fillers. In all mixtures a blend of Portland cement (CEM I) and blast slag cement (CEM III) was used. In mixture IV 25% of the dense aggregate is replaced by saturated lightweight aggregate, Liapor F10. In mixture V
Table 1 Mixture compositions of concrete

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>kg/m³</td>
<td>133</td>
<td>153</td>
<td>156</td>
<td>156</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>CEM III/B 42.5 LH HS</td>
<td>kg/m³</td>
<td>248</td>
<td>340</td>
<td>300</td>
<td>300</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>CEM I 52.5 R</td>
<td>kg/m³</td>
<td>112</td>
<td>110</td>
<td>100</td>
<td>100</td>
<td>225</td>
<td>225</td>
</tr>
</tbody>
</table>
| Limestone powder
  3)                          | kg/m³    | 60  |     |      |      |     |     |
| Silicol SL (50/50 slurry)      | kg/m³    |     | 50  | 50   |      |     |     |
| Water/cement ratio             |          | 0.37| 0.34| 0.39 | 0.39 | 0.34| 0.34|
| Sand 0 – 4 mm                  | kg/m³    | 942 | 860 | 830  | 830  | 773 | 773 |
| Crushed aggregate 4–16 mm      | kg/m³    | 997 | 980 | 975  | 730  |     |     |
| Liapor F10, 4-8 mm             | kg/m³    | 156 | 614 | 576  | 156  | 614| 576 |
| HR Superplast, CON 35          | kg/m³    | 5.0 |     |      |      |     |     |
| Cretoplast CON 35              | kg/m³    | 1.8 |     |      |      |     |     |
| Cretoplast SL01 CON 35         | kg/m³    | 7.2 |     |      |      |     |     |
| Addiment BV1                   | kg/m³    | 1.6 | 1.6 | 0.9  | 0.9  |     |     |
| Addiment FM 951                | kg/m³    | 4.8 | 4.8 | 9.0  | 9.0  |     |     |

1) Lightweight aggregate, 100% saturated (24 hours in water)
2) Lightweight aggregate, 50% saturated
3) Fineness 530 m²/kg

all coarse aggregate consists of saturated lightweight aggregate Liapor F10, whereas mixture VI was made with Liapor F10, 50% saturated. Tests with lightweight aggregate were considered in view of the internal curing capacity of the lightweight aggregate as proposed by, e.g., Weber et al. [7]. In this study 100% saturation was considered realised by storing air-dry aggregates for 24 hours in water. By added half of this absorbed amount to air-dry aggregate, 50% saturation was obtained. For this study this was considered accurate enough, even though it is known that after 24 hours storing in water the individual particles may still have to potential of absorb more water. In order to reach the required strength with the lightweight aggregate mixtures, the cement content was higher than in the mixtures with dense crushed aggregate, while also silica fume was added. Mixtures with saturated lightweight aggregate were investigated with the aim to quantify the ability of the water-containing particles to neutralise the self-desiccation process and to minimise the autogenous shrinkage of the concrete. Mixture III, with 400 kg cement and a w/c ratio of 0.39, is considered as the reference mixture.

2.2 Specimens, curing conditions and measurements

The concrete compressive strength was measured on concrete cubes, 150x150x150 mm³. The cubes were cured at a relative humidity of 99% and a temperature of 20°C. Deformations were measured on prisms. Measurements started 1 day after casting and were stored afterwards in a climate room at 20±2°C. Most of the measurements were performed on prisms 100x100x400 mm³. For the mixtures III and V measurements were also performed on prisms 50x50x200 mm³ and 150x150x600 mm³. Measurements on autogenous shrinkage can be performed vertically [8] or horizontally placed specimen. In this study the autogenous shrinkage was measured on sealed
specimens, 100x100x400 mm³, placed vertically. For each mixture two prisms were used. The measurements started 1 day after casting of the concrete. During a short time, when the measurement equipment was attached to the concrete, the specimens had been exposed to ambient in-door climatic conditions. For studying the effect of drying, the sealing of initially sealed prisms was removed after 7 and 28 days and were placed in a climate room with RH = 50% and a temperature of 20°C. For all the mixtures drying was measured on prisms 100x100x400 mm³. For the reference mixture III (normal weight concrete) and mixture V (lightweight aggregate mixture), drying shrinkage was also measured on specimens 50x50x200 mm³ and 150x150x600 mm³. All shrinkage measurements were performed in two-fold. The shrinkage curves to be presented represent the average of two prisms.

3. Results of experimental study

3.1 General
The results of the experimental study are presented in the sections 3, 4 and 5. In section 3 the compressive strength is presented of all the mixtures (I to VI), as well as the measured deformations of the mixtures I, II, III and IV is presented.

In section 4 the deformingal behaviour of the reference mixture III (Normal weight concrete: NWC) is compared with that of the lightweight aggregate concrete (LWAC) mixtures V and VI. Section 5 deals with the size effect on drying shrinkage for the mixtures III and V. In these sections a first evaluation of the results is made by comparing the measurements with shrinkage curves of the Model Code MC’90.

3.2 Compressive strength
The mean cube compressive strength after 7, 14 and 28 days is presented in Table 2. The highest strength was observed for mixture I with 60 kg/m³ limestone filler. Strength values beyond the target strength of 73 MPa (mean value) were also obtained with the lightweight aggregate concrete mixture V, where a high cement content was used and 25 kg/m³ silica fume was added to compensate (partly) for the lower strength of the aggregate. The strength of mixture VI, the LWAC-mixture with a degree of saturation of the aggregate of 50%, was even higher than that of mixture V (100% saturated). A plausible reason for this is that in the early stage of hardening the effective water/cement ratio in mixture VI is lower than in mixture V, resulting in a stronger paste. The reference mixture III, with a cement content of 400 kg/m³ and a w/c ratio of 0.39, did not reach the required 28 day mean cube compressive strength of 73 MPa.

<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></td>
<td>7 days</td>
</tr>
<tr>
<td>I</td>
<td>350</td>
<td>60 kg limestone</td>
<td>0.37</td>
<td>72.5</td>
</tr>
<tr>
<td>II</td>
<td>450</td>
<td>----</td>
<td>0.34</td>
<td>61.2</td>
</tr>
<tr>
<td>III</td>
<td>400</td>
<td>----</td>
<td>0.39</td>
<td>62.7</td>
</tr>
<tr>
<td>IV</td>
<td>400</td>
<td>----</td>
<td>0.39</td>
<td>44.2</td>
</tr>
<tr>
<td>V</td>
<td>450</td>
<td>50 kg SF-slurry</td>
<td>0.34</td>
<td>62.7</td>
</tr>
<tr>
<td>VI</td>
<td>450</td>
<td>50 kg SF-slurry</td>
<td>0.34</td>
<td>33.6</td>
</tr>
</tbody>
</table>

Table 2 Strength of concrete mixtures, grade B65, after 7, 14 and 28 days
3.2 Autogenous deformation (sealed condition)
The autogenous deformation of the mixtures I to IV is presented in Fig. 1. The measurements started after 1 day. This implies that part of the autogenous deformation is not included in the measurements. The aim of the test series was, however, to quantify how autogenous deformation would affect the drying shrinkage. In the practice drying shrinkage will generally not start in the first day after casting. For the purpose of this study it was sufficient, therefore, to measure only the autogenous deformation after 1 day. Autogenous shrinkage was highest for mixture II, the mixture with the lowest water/cement ratio and a high cement content. Unlike the mixtures I, II and III, the mixture with 25% replacement of crushed aggregate by saturated lightweight aggregate particles hardly exhibited any autogenous deformation.

![Autogenous deformation of mixture I to IV. Sealed curing at 20ºC. Measurements starting after 1 day.](image)

At first the autogenous shrinkage of the mixtures I, II and III was considered relatively high. A possible reason for this could have been that the sealing was not tight enough. However, a comparison of the data with measurements on a sample sealed with a sandwich of a plastic foil and a steel plate yielded similar shrinkage values [6].

3.3 Drying shrinkage (unsealed condition)
Shrinkage deformations of the mixtures I, II, III and IV under unsealed condition is presented in Fig. 2 and 5. When drying starts after 7 days mixture IV, with 25% Liapor, exhibited the highest shrinkage strains (Fig. 2). However, when drying starts at 28 days the difference between the four mixtures is much less, particularly in the first period of the drying process (Fig. 5). The trend shown in Fig. 5 is that shrinkage of the mixture with the 25% Liapor starts slower than for the other mixtures, but that at the age of 90 days the drying shrinkage is a bit higher. Looking at the rate of the shrinkage processes of the four mixtures, the shrinkage strains of mixture IV will exceed those of the other mixtures.

The Fig. 3 and 6 show the shrinkage curves according to the Model Code MC’90. In these theoretical curves the concrete compressive strength is an important parameter. By using the measured compressive strength values from Table 2, the shrinkage curves show...
Figure 2  Measured shrinkage of mixtures I to IV after removal of sealing at t = 7 days. RH = 50%. Specimen 100x100x400 mm³.

Figure 3 Calculated shrinkage according to ModelCode’90. Mixtures I to IV. RH = 50%. Specimen 100x100x400 mm³.

Figure 4  Measured shrinkage. Specimen sealed up to 7 days, then unsealed and exposed to RH = 50%. Specimen 100x100x400 mm³.
Figure 5  Measured shrinkage mixtures I to IV after removal of sealing at 28 days. RH = 50%. Specimen size 100x100x400 mm$^3$.

Figure 6  Calculated shrinkage according to ModelCode'90 for mixtures I to IV. RH = 50%. Specimen 100x100x400 mm$^3$.

Figure 7  Measured deformation. Specimen sealed up to 28 days, then unsealed and exposed to RH = 50%. Mixtures I to IV. Samples 100x100x400 mm$^3$.
a significant scatter. For reason of comparison also the nominal shrinkage curve for a concrete grade B65 is shown. A comparison of the Fig. 2 and 3 shows that on average the measured shrinkage is higher than the predicted shrinkage. The trend that a higher strength is accompanied by less shrinkage is found back in both figures. A comparison of the Fig. 5 and 6 shows that in case drying starts after 28 days, the measured strain at 90 days is, on average, in good agreement with predicted values. The systematic strength-related relative difference between the theoretical shrinkage curves is not seen any more in the measured curves. The mixture with 25% Liapor performed quite differently.

3.4 Total shrinkage
In the Fig. 4 and 7 the total measured deformation of the mixtures I to IV is shown in case drying starts after 7 and 28 days, respectively. The deformations up to 7 and 28 days are caused exclusively by self-desiccation. Subsequent deformations are due to the combined effect of continuing self-desiccation and drying.

In Table 3 a more detailed analysis of the measurements is presented for the drying experiments starting after 28 days. Assuming that for the total strain caused by autogenous shrinkage and drying shrinkage the superposition principle would hold, the total increase in strain from 28 to 90 days would be: \( \Delta \varepsilon_{\text{aush}}(28d-90d) + \varepsilon_{ds}(28d-90d) \). The measured drying shrinkage \( \varepsilon_{ds} \) from 28 to 90 days, however, includes some autogenous shrinkage already. The autogenous shrinkage of the drying specimens will be less than in the sealed specimen, since in the drying specimen hydration will be hampered by the loss of water to the environment. In case the effect of autogenous shrinkage in the drying specimen is ignored and the measured autogenous shrinkage is simply added to the measured drying strain, the sum of these two would overestimate the measured strains by 50, 40, 33 and 4% for the mixtures I to IV, respectively (see Table 3).

A comparison of the shrinkage curves of MC’90 of Fig. 3 (drying after 7 days) with the total shrinkage of Fig. 4 clearly shows that the code values underestimate the actual total deformation. At \( t = 90 \) days the measured drying shrinkage ranges between 0.19 \( 10^{-3} \) to 0.31\( 10^{-3} \) (Fig. 3), whereas the total strain, which includes autogenous shrinkage, ranges

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Comparison of autogenous shrinkage and drying shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured shrinkage [(*0.001)</td>
<td>Mix I</td>
</tr>
<tr>
<td>( \varepsilon_{\text{aush}}(90d) ) (Fig. 1)</td>
<td>0.30</td>
</tr>
<tr>
<td>( \varepsilon_{\text{aush}}(28d) ) (Fig. 1)</td>
<td>0.21</td>
</tr>
<tr>
<td>( \Delta \varepsilon_{\text{aush}}(28d – 90d) )</td>
<td>0.09</td>
</tr>
<tr>
<td>( \Delta \varepsilon_{\text{aush}}(28d – 90d) ) * 100%</td>
<td>30%</td>
</tr>
<tr>
<td>( \varepsilon_{ds}(28d – 90d) ) (Fig. 5)</td>
<td>0.18</td>
</tr>
<tr>
<td>( \Delta \varepsilon_{\text{aush}}(28d - 90d) ) / ( \varepsilon_{ds}(28d - 90d) ) * 100%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Remark:
1. Measured drying shrinkage \( \varepsilon_{ds} \) includes some autogenous shrinkage
2. Autogenous shrinkage will be affected by drying of a specimen.

Because of the interaction between autogenous shrinkage and drying shrinkage mentioned under point 1 and 2, dividing the autogenous shrinkage by the measured drying shrinkage is, from the materials science point of view, not allowed.
between 0.38x10^{-3} to 0.55x10^{-3} (Fig. 4). A similar comparison of the figures 6 and 7, which figures refer to the tests where drying started after 28 days, shows again an underestimation of the total deformation by MC’90, except for the mixture IV with 25% Liapor. The predicted shrinkage after 90 days ranged between 0.17x10^{-3} to 0.28x10^{-3}, whereas the total shrinkage deformation of the mixtures I, II and III ranged between 0.39 10^{-3} to 0.51x10^{-3}.

4. Effect of type of aggregate on shrinkage deformation

4.1 General

Autogenous shrinkage is strongly related to the hydration process as long as this process controls the changes in the relative humidity of the concrete. In case of sealed curing of concretes, which contain water-saturated aggregate particles, the relative humidity in the concrete will be strongly influenced by water transport from the aggregates to the paste. In case the relative humidity of the concrete is not only determined by the relative humidity of the environment but also by internal sources, it is to be expected that the size effect as considered in design codes is no longer applicable. Most of these size effect factors are based on analysis of shrinkage data on concretes made with dense aggregate. In order to investigate the size effect of normal weight concrete (NWC) and lightweight aggregate concrete (LWAC), a small experimental test series was performed. In section 3 it was shown already that 25% replacement of dense aggregate by saturated lightweight aggregate influenced the shrinkage behaviour significantly. In the following the deformational behaviour of two mixtures with only lightweight aggregate will be compared with the behaviour of the reference mixture III.

4.2 Autogenous shrinkage of NWC and LWAC (sealed condition)

With the aim to quantify the effect of water-containing aggregate particles on the autogenous shrinkage of different concrete mixtures, grade B65, measurements were performed on concrete samples 100x100x400 mm. The results of the measurement of the
autogenous deformations of the mixtures III, V and VI are presented in Fig. 8. Measurements started 24 hours after casting. Mixture III, made with dense crushed aggregate, served as the reference. The lightweight aggregate concrete with 100% saturated lightweight aggregate exhibited swelling, up to 0.07‰ at $t = 90$ days. The mixture with 100% saturated aggregate exceeds the swelling of the mixture with 50% saturated aggregates substantially. A comparison of this result with the swelling of mixture VI, with a degree of saturation of the aggregate of 50%, was even bigger than that of mixture V. This, at first sight, strange result finds its explanation in the fact the measurement started after 24 hours. During this first 24 hours the swelling of the mixture with 100% saturated aggregate exceeded that of the mixture in which the aggregates were saturated by 50% [6]. If the shrinkage observed in the first 24 hours would have been added to the shrinkage measured after 1 day we would see that the swelling of the 100% saturated aggregate is bigger than that of the mixture with 50% saturated aggregate.

4.3 Shrinkage of NWC and LWAC (unsealed condition)
The age of the concrete at which the sealing was removed and the drying process started, was 7 and 28 days. For the three mixtures the strain curves are presented in the figures 9 and 10. The highest shrinkage strains after 90 days were measured for the reference mixture III. The shrinkage of the two LWAC mixtures was much less. The lowest shrinkage was observed for mixture V with a degree of saturation of the aggregate of 50%. At an age of 90 days the drying shrinkage of mixtures V and VI was about 70% and 30% of the shrinkage of reference mixture III.

Figure 9  Measured shrinkage of mixtures III, V and VI after removal of sealing at 7 days. RH = 50%. Specimen size 100x100x400 mm$^3$. 
Figure 10  Measured shrinkage of mixtures III, V and VI after removal of sealing at 28 days. RH = 50%. Prisms 100x100x400 mm$^3$.

4.4 Shrinkage according to Model Code MC’90

Figure 11 shows the shrinkage curves for the mixtures III, V and VI according to MC’90. The measured compressive strength at 28 days was used as input in the shrinkage calculations and is responsible for the deviation between the three shrinkage curves. A comparison of the measured and calculated shrinkage curves of Fig. 10 and 11, respectively, shows that MC’90 overestimates the measured shrinkage of the mixtures V and VI significantly.

Figure 11  Calculated shrinkage according Model Code '90. Drying started after 28 days. RH = 50%. Specimen 100x100x400 mm$^3$.

It is noticed that the code MC’90 deals with normal weight concrete and not with lightweight aggregate concrete. A comparison of measured shrinkage strains of LWAC with theoretical shrinkage curves of MC’90 are, therefore, to be considered as a demonstration of the deviating behaviour of lightweight aggregate concrete when compared to normal weight concrete.
4.5 Total shrinkage – NWC versus LWAC

The total deformation of the mixtures III, V and VI is presented in Fig. 12. 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 VI with 50% saturated aggregate, exhibits no shrinkage at all after 90 days. For mixture V the total shrinkage after 90 days is \(0.13 \times 10^{-3}\). This is about half the calculated drying shrinkage according to MC‘90 as shown in Fig. 11. The behaviour of the mixtures V and VI clearly demonstrates that the presence of water-containing aggregate particles in the concrete completely violates the shrinkage formulae derived for normal weight concrete. A major reason for the discrepancies between observations and predictions and the differences between the individual mixtures goes back to the role of the relative humidity on the deformational behaviour of the mixtures.

![Figure 12](image-url)  Total deformation of reference mixture III and lightweight aggregate concrete mixtures V and VI. Sealed curing up to 28 days, then exposed to RH = 50%. Sample size 100x100x400 mm³.

5. Effect of element size on shrinkage of NWC and LWAC

5.1 Measured size effects

The effect of the size of the shrinkage specimen has been investigated for the reference mixture III and the LWAC V made with 100% saturated Liapor F10. The size of the specimens was 50x50x200 mm³, 100x100x400 mm³ and 150x150x600 mm³. The shrinkage measurement started after 7 and 28 days. The results for the reference mixture III are presented in Fig. 13 and 14 and for the LWAC mixture V in Fig. 15 and 16.

As expected, drying shrinkage will develop faster the smaller the specimens. The shrinkage of the specimen 50x50x200 mm³ develops faster indeed, particularly when drying starts early. In all cases the shrinkage of the specimen 150x150x600 mm³ is lowest.

A comparison of the drying shrinkage curves of the LWAC exhibits some, at first sight, unexpected features. Normally shrinkage strains are higher if drying starts at an earlier age. The younger the concrete at the moment drying starts, the more free capillary water is present that can be withdrawn from the concrete and can cause shrinkage of the
Figure 13  Measured shrinkage as a function of time for different specimen sizes. Reference mixture III. Start of measurement after 7 days. RH = 50%.
(Note: Raw data of sample 150x150x600mm³ has been corrected for measurement error)

Figure 14  Measured shrinkage stains as function of time for different specimen size. Reference mixture III. Start of measurement after 28 days. RH = 50%.

Figure 15  Measured shrinkage strains as function of time for different specimen size. Lightweight aggregate concrete V. Measurements started after 7 days. RH = 50%.
5.2 Effect of element size according to Model Code MC’90

In Fig. 17 the effect of the specimen size is shown as predicted with MC’90. The shape of the shrinkage curves of the reference mixture III, shown in Fig. 14, correlates quite well
with the curves in Fig. 17 predicted with MC’90. However, the shape of the shrinkage curves of the lightweight concrete mixture V, as well as the absolute values of the shrinkage strains presented in Fig. 16, deviate significantly from the predictions by the MC’90. This holds for all the specimens made of LWAC. A general trend is that at first the shrinkage rate of LWAC is lower than that of NWC, i.e. of the values predicted by the MC’90. At later ages, however, there is a tendency that the rate of shrinkage of LWAC remains higher than that of NWC. For the small specimens, 50x50x200 mm, this tendency is very clear. For the bigger specimen the testing period was too short to be convincing in this respect. From the relatively high shrinkage rates of LWAC at later ages it might be inferred, that the final shrinkage of LWAC will be higher than that of NWC. This would be in agreement with experimental results of Sickert et al. [5].

6. Conclusions

The shrinkage due to self-desiccation and drying in an environment with a RH of 50% was investigated experimentally for different concrete mixtures with a target characteristic cube compressive strength of 65 MPa. Investigated parameters were the type of aggregate, moment of start of the drying process and specimen size. Measured shrinkage strains were compared with predictions according to MC’90. This comparison was made in order to check whether this code could still be used in case strength grades were considered slightly beyond the range covered by the code.

6.1 Autogenous deformation (sealed specimen)

Autogenous shrinkage of normal weight concrete (NWC), w/b = 0.34 to 0.39, reached values between 0.30x10⁻³ to 0.40x10⁻³ after 90 days (measurements starting at an age of the concrete of 1 day). Similar measurements on a mixture with blended aggregate, i.e. a blend with 25% saturated Liapor, hardly exhibited autogenous shrinkage. Autogenous deformations of 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. It is noticed the measured autogenous shrinkage might have been affected by some moisture loss through the plastic sealing. The autogenous shrinkage found this study might be slightly higher than would have been found in “full” sealing [9].

6.2 Shrinkage deformation of unsealed specimen

Depending on the age at which drying of the concrete started, the observed shrinkage strains were influenced by autogenous shrinkage. Measurements on normal weight concrete, 100x100x400 mm³, whereby drying started after 7 and 28 days, revealed that the shrinkage was higher than predicted by the MC’90.

The drying shrinkage up to 90 days after casting of LWAC mixtures was much lower than predicted with the MC’90. Furthermore, the shape of the shrinkage curves differed from those for NWC. At first shrinkage of the LWAC proceeds slower than that of NWC. At later ages the rate of shrinkage remained relatively high. This might result in a higher final shrinkage of the LWAC.
6.3 Total shrinkage
In case drying of the concrete started 7 days after casting, the total shrinkage of the mixtures I, II and III at an age of 90 days ranged between $0.43 \times 10^{-3}$ and $0.55 \times 10^{-3}$ (Fig. 4). In case drying started 28 days after casting, the total strain was slightly lower and ranged between $0.40 \times 10^{-3}$ and $0.52 \times 10^{-3}$. The fact that the moment at which drying started does not significantly affect the total strain is in agreement with work of Miyazawa et al. [1]. It is noticed, however, that this finding does not hold in case of lightweight aggregate concrete. Also in case drying starts at very early ages other results can not be excluded.

In the MC’90 no explicit allowance is made for autogenous shrinkage. The total shrinkage of the specimen consists of the measured drying shrinkage plus the autogenous shrinkage prior to the start of the drying process. If the total shrinkage of NWC is compared with the shrinkage calculated according to MC’90, it appears that the MC’90 underestimates the total shrinkage, at least in the first 90 days after the start of the drying process. In case of LWAC, where autogenous swelling was observed, the swelling almost completely compensated the drying shrinkage. In that case the MC’90 overestimates the total deformation that occurred in the period of the test, i.e. 90 days.

6.4 Size effect on shrinkage
In a sealed specimen with a homogeneous temperature during hydration (which implies a small specimen), the autogenous deformation has the same magnitude throughout the cross section of the specimen. Drying of concrete is a slow process, causing moisture gradients in the cross section of the specimen. The moisture gradients depend on the pore structure of the concrete and the size and shape of the specimen. Measured drying shrinkage strains, therefore, exhibit a size effect. In case drying of the concrete starts at an early stage of the hydration process, the withdrawal of water from the concrete will affect the progress of the hydration process and of the autogenous shrinkage. In case of normal weight concrete this size effect has been quantified mainly on the basis of an evaluation of experimental data. The presence of water-saturated lightweight aggregate particles in the concrete affects the relative humidity in the concrete. This violates the size effect rules based on experiments with normal weight concrete. It was found that in case of LWAC the size effect is more pronounced than in case of NWC. Small LWAC samples, $50 \times 50 \times 200 \text{ mm}^3$, exhibited higher shrinkage than NWC. In the case larger specimens are considered, size $100 \times 100 \times 400 \text{ mm}^3$ and $150 \times 150 \times 600 \text{ mm}^3$, the opposite was found.

For NWC the measured size effect was less pronounced than predicted with MC’90 (compare Fig. 14 and 17). In case of LWAC, however, the measured size effect was greater than predicted with MC’90. That code values do not apply in case of LWAC was expected. It must be attributed to the fact that currently used codes describe shrinkage as a macroscopic phenomenon. The mechanisms, which cause the shrinkage strains, are not dealt with explicitly. This makes extrapolation beyond the range of concretes and/or environmental (curing) conditions for which codes are written unjustified.

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References