Prestress loss of high-strength calcium silicate element masonry with thin-layer mortar

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ABSTRACT
At Eindhoven University of Technology, the behaviour of post-tensioned shear walls of high-strength calcium silicate element (CASIEL) masonry with thin-layer mortar (TLM) is investigated. As a part of this research, prestress losses due to creep and shrinkage of such masonry were monitored for 250 days. Experiments were conducted in a climate-controlled environment and all specimens were conditioned to the same moisture content. The specimens measured 175 x 175 x 1100 mm³ and contained one bed joint of TLM. High-strength CASIELs from two manufacturers were used, having similar compressive strength, but different dry density and Young’s modulus. Test setups for creep and prestress loss were developed and shrinkage was measured on unloaded control specimens. It is concluded that time-dependent deformations and prestress loss of high-strength CASIEL-TLM masonry are low compared to other kinds of masonry. Therefore, this type of masonry is very suitable for post-tensioning.

Keywords: Calcium silicate element masonry, post-tensioned, creep, shrinkage, prestress loss

1 INTRODUCTION
At Eindhoven University of Technology a research project has been set up to investigate the mechanical behaviour of post-tensioned shear walls of calcium silicate element (CASIEL) masonry with thin-layer mortar (TLM). An introduction to this research project is given elsewhere [1]. This paper addresses one aspect of the project, namely prestress loss of high-strength CASIEL-TLM masonry. Neglecting prestress loss in the design of a post-tensioned shear wall leads to an overestimation of its capacity. Therefore, it is important to accurately assess prestress loss.

Prestress loss, according to [2], may result from elastic, shrinkage and creep deformations of the masonry, anchorage slip, frictional effects, relaxation of the tendons and in some situations ambient temperature variations. In this paper, only prestress loss due to creep and shrinkage deformations of high-strength CASIEL-TLM masonry under uniaxial compression is considered. Creep is the time-dependent deformation due to stress. Shrinkage is the time-dependent deformation without stress. For CASIEL masonry, drying shrinkage and carbonation shrinkage can be distinguished. Drying shrinkage is related to loss of water from the masonry and is partly irreversible. Carbonation shrinkage is caused by a chemical reaction of calcium hydroxide with carbon dioxide, which produces calcium carbonate and water. Carbonation shrinkage is completely irreversible. According to the manufacturer, both types of shrinkage are of the same order of magnitude for normal strength CASIEL masonry.

Concrete creep has been investigated extensively since the early twentieth century. Reference books, such as [3], deal with the influence of concrete composition and environmental parameters on...
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cement creep, based on decades of experimental research. In experiments, creep deformations are measured over time and the influence of different parameters is investigated by varying one parameter at a time. Though these experiments are time-consuming and costly, they are necessary to obtain reliable creep data for building practice and to validate analytical and numerical models that predict creep or prestress loss. Attempts to predict creep from physicochemical and environmental properties has led to complex models that are not useful from an engineering point of view.

Masonry creep has been investigated in the same manner as creep of concrete, but to a lesser extent. The combination of units and mortar leads to an even larger number of parameters to be investigated. Experimental research has focused mainly on clay brick masonry and concrete block masonry, but some investigations also paid attention to calcium silicate brick or block masonry with general purpose mortar (GPM), e.g., [4]. Creep of normal-strength CASIEL-TLM masonry has been reported in [5, 6]. Creep of high-strength CASIEL-TLM masonry has not been investigated, since it has only become available on the market recently.

Masonry prestress loss has been investigated for clay masonry, concrete masonry, and normal-strength calcium silicate masonry with GPM, e.g., [7]. Creep and prestress loss of CASIEL-TLM masonry have not been investigated yet. While creep and shrinkage are long-term material properties of the masonry, prestress loss is also related to material properties of the prestressing steel and to the axial load ratios of the prestressing steel and the masonry. Thus, predictions of prestress loss should be based on short-term and long-term material properties of the masonry and the prestressing steel. Therefore, creep experiments, with constant stress, and prestress loss experiments, with decreasing stress, were conducted simultaneously. Results of these experiments can be used to verify various methods of calculation to predict prestress loss based on creep data. In this paper, prestress loss is predicted based on a simple formula, which neglects the reduction of creep due to decreasing stress.

2 TEST METHODS

Considerations concerning specimen dimensions and the test setup are described in [1] and are summarized here. CASIELs from two different manufacturers, denoted C and S, were used to construct specimens of size 175 x 175 x 1100 mm containing one bed joint of TLM. Test setups for creep and prestress loss were developed, based on [8], designed for a maximum compressive stress of 9 MPa. From one CASIEL of approximately 1000 x 175 x 600 mm, four prisms, 175 x 175 x 550 mm were cut (A - D), see Figure 1(a). Parts A and D of successively produced CASIELs were combined to form specimens for the long-term tests, as shown in Figure 1(b). Parts B and C were used for short-term testing.

![Figure 1](image.png)

(a) Dimensions, and (b) specimen selection: Code C1A = Series C, 1st element, part A.

The test scheme for the long-term experiments is shown in Table 1. Creep experiments were conducted at two prestress levels, 8.5 MPa and 4.25 MPa respectively. Prestress loss experiments
were only conducted at the highest prestress level. For every creep or prestress loss experiment, shrinkage was measured on an unloaded control specimen. In this paper, approximately 250 days of experimentation are included in the results.

Specimens were constructed by joining two prisms of 175 x 175 x 550 mm with a bed joint of TLM, see Figure 2(a). The mortar was allowed to set for at least one week. Next, two long sides of the specimens were sealed with paraffin, see Figure 2(b), and stainless steel measurement discs were attached on the other two long sides using X60 two-component adhesive. After that, specimens were immersed in water until a moisture content of 6.5 ± 0.5 % (m/m) was reached; see Figure 2(c). For series C the moisture content averaged 6.44 % (m/m) (Coefficient of Variation = CV = 5.3 %), and for series S the average was 6.09 % (m/m) (CV = 3.9 %). The conditioned specimens were wrapped in plastic foil and at least one week was allowed for moisture distribution within the specimen. The plastic foil was removed immediately before testing and the moisture content was determined once more by weighing the specimens.

The experiments were carried out in a climate-controlled (CC) room. The target temperature and relative humidity (RH) of the CC room were 20°C and 60 %, respectively. Temperature and RH were logged, and averaged at 20.9°C (Standard Deviation = SD = 0.3°C) and 59.3 % RH (SD = 2.9 %), respectively over the period from March to November 2009.

Table 1. Test scheme for long-term experiments in climate-controlled environment.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material</th>
<th>Creep</th>
<th>Prestress loss</th>
<th>Shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>4.25 MPa</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>8.5 MPa</td>
<td>8.5 MPa</td>
<td></td>
</tr>
</tbody>
</table>

A technical drawing of the test setup is given in [1]. A photo of the test setups for creep, prestress loss and shrinkage is shown in Figure 3(a). Four Dywidag Threadbars® were tested to determine Young’s modulus, 0.1 % proof strength and ultimate tensile strength. The ultimate tensile strength averaged 1166 MPa, which means that the Dywidag bars were initially loaded to respectively 33 % and 16 % of their ultimate strength in the experiments. The compressive springs were test-loaded to their
maximum design load twice. The average spring constant was 1424 N/mm (CV = 2.2 %). Sets of four springs were selected based on equal spring constant and equal height. The prestress was applied by a hydraulic jack below the steel plate carrying the specimen, see Figure 3(b) and (c). Care was taken in centring the specimen and the hydraulic jack in the test setup. After prestressing, the hydraulic jack was removed from the test setup.

During and after prestressing, measurement data was gathered in several ways. Two electrical strain gauges were attached on opposite sides of each Dywidag bar. These were used to derive the axial strain in the bar during prestressing and afterwards. For the creep experiments, Digimatic Indicators (DIs) were used to measure the deformation of the steel plate between the specimen and the compressive springs during the prestressing operation. After prestressing, the DIs were removed and used for the next test setup. The relative movement of the plates above and below the compressive springs was still regularly measured with an extended micrometer, see Figure 3(d). The deformation of the specimens was measured with a demountable mechanical (DeMec) strain gauge with a length of 300 mm, see Figure 3(e). The electrical strain gauges on the Dywidag bars were regularly reconnected to a strain gauge amplifier to measure the axial deformation of the bars. A steel plate with dummy strain gauges was used to initialize the channels of the strain gauge amplifier with the correct offset, before each measurement.

Figure 3 Test setup and measurements: (a) Creep, prestress loss, and shrinkage tests (from left to right), (b) applying prestress by hydraulic jack, (c) position of hydraulic jack, (d) measurements of spring deformation by extended micrometer, and (e) taking measurements with the DeMec strain gauge.

3 RESULTS

The short-term compressive strength and Young’s modulus were determined for specimens in hygral equilibrium with the CC-room conditions. The compressive strength was determined for small prisms
of 100 × 175 × 100 mm and large prisms of 175 × 175 × 550 mm. Small oven-dry prisms were also weighed to estimate the dry density of the material. Results are shown in Table 2.

Shrinkage was measured on unloaded control specimens. For both materials, shrinkage was measured on three specimens. The TLM bed joint of specimen S4D-3A cracked during transport from the laboratory to the CC room. Hence these measurements are excluded from the results, which are shown in Figure 4. Shrinkage results were averaged over three regions: the top element, the bottom element and the interface, including a TLM joint. The interface region clearly exhibited more shrinkage for both series. The differences between the top and bottom element results are attributed to the contact between the bottom element and the CC-room floor, and unequal moisture distribution over the height of the specimen. When shrinkage results of the two series are compared, the influence of the different porosity of the materials on shrinkage becomes clear.

In the creep tests, the compressive springs were designed to allow a maximum prestress loss of 2 %. Measurement of the movement of the compressive springs indicated that the maximum prestress loss was 1.0-1.7 %, which satisfies this requirement. Therefore, the designed test setup is suitable to measure creep and the results can be interpreted as creep under constant stress.

Table 2. Short-term material properties of specimens stored in CC room.

<table>
<thead>
<tr>
<th>Series</th>
<th>Dry density of units</th>
<th>Mean compressive strength of units</th>
<th>Young's modulus of units and specimen Long-term test specimen†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size →</td>
<td>Small*</td>
<td>Small*</td>
<td>Large*</td>
</tr>
<tr>
<td>Units →</td>
<td>[ kg / m³ ]</td>
<td>[ MPa ]</td>
<td>[ MPa ]</td>
</tr>
<tr>
<td>C</td>
<td>2130</td>
<td>46.1</td>
<td>33.7</td>
</tr>
<tr>
<td>S</td>
<td>1960</td>
<td>40.4</td>
<td>34.0</td>
</tr>
</tbody>
</table>

*Small specimens are 100 × 175 × 100 mm; Large specimens are 175 × 175 × 550 mm.
†Young's modulus of long-term test specimen derived from DeMec measurements.

Typical creep results are shown in Figure 5. In part (a) of this figure, the total strain is shown as measured. The specific creep as shown in Figure 5(b) is obtained by subtracting the elastic strain and the average shrinkage strain of Figure 4(b), and dividing by the prestress (8.5 MPa for this specimen).
It was found that the specific creep results could best be described by a simple power function. For series C, the specific creep results for the elements (top and bottom) and interface, were of equal magnitude, and no attempt was made to separate the results. A power function was fitted to the data on log-log scale. By assuming a lognormal distribution of the data around the fitted power function, a 90% confidence interval was determined. For accurate long-term prediction, data of approximately the first two weeks were not taken into account. Peak values outside the range of the bulk data were neglected. Experimental results and the 90%-confidence interval are shown in Figure 6.

For series S, the difference between elements and interface was significant, as can be seen in Figure 5, and therefore the results were separated. To accurately estimate the specific creep of CASIEL walls, the 90% upper limits of elements and interfaces were averaged. The gauge length was 300 mm. In building practice, one TLM joint is present per 600 mm element, which is equivalent to two gauge lengths, one of which includes a TLM joint. Measurements over elements and interfaces, 90% confidence intervals, and the overall average of series S, are shown in Figure 7.

![Figure 5](image_url) Creep results for S5D-6A at 8.5 MPa. (a) Total (elastic, creep and shrinkage) strain as measured, and (b) specific creep derived from total strain, excluding shrinkage.

![Figure 6](image_url) Specific creep of series C. Data and 90%-confidence interval on (a) log-log scale, and (b) linear scale. The power function shown is the 90% upper limit.

In the prestress loss experiments, an initial prestress loss after load transfer of 15-16% occurred. This initial loss is not included in the results, because it can be overcome by overstressing. The prestress loss, measured on the Dywidag bars, has to comply with creep and shrinkage measured on the specimen. Average creep and shrinkage over a height of 900 mm are shown in Figure 8(a), and prestress loss of the Dywidag bars is shown in Figure 8(b). The latter includes estimates of prestress...
loss, based on the average creep and shrinkage measurements. The time-dependent behaviour of the load-introduction areas between the steel plates and the specimen was not measured, although these areas also contribute to the prestress loss. In series S, these areas behaved similarly to the rest of the specimen, and hence the estimated and measured prestress loss in Figure 8(b) agree well. In series C, a gap of approximately 9% between the estimated and measured prestress loss was found. The only difference in the load introduction areas of series S and C, was a thin layer of paraffin (< 1 mm) in series C, between the top of the specimen and the steel plate of the test setup. This layer was applied to seal the top side of the prestress loss specimen, similar to the shrinkage specimens, and was considered irrelevant to the prestress loss. However, a time-dependent deformation of 154 µm within the paraffin layer would explain the additional 9% of prestress loss. It was also observed that the paraffin was squeezed out of the contact area in the course of time. The paraffin layer exhibited no significant time-dependent behaviour after approximately 40 days, and after this time, the measured and estimated prestress loss of series C run parallel.

Figure 7 Specific creep of series S. Data and 90%-confidence interval on (a) log-log scale, and (b) linear scale.

Figure 8 (a) Creep and shrinkage of specimen under decreasing stress, and (b) prestress loss of Dywidag bars as measured and as estimated from creep and shrinkage results.
4 DISCUSSION

While creep and shrinkage are material properties of the masonry, prestress loss is a system property, because it is also influenced by material properties of the prestressing steel, and the axial load ratios of the masonry and the prestressing steel. Therefore, it is more useful to predict prestress loss from creep and shrinkage of the masonry, than to measure prestress loss directly. In Table 3, the shrinkage and creep results after 250 days are shown. The prestress loss of series C and S after 250 days, as derived from the strain in the Dywidag bars, was 12 % and 16 % respectively, neglecting the 9 % of prestress loss due to the paraffin layer in series C. The following formula from [9] can be used to predict prestress loss from creep and shrinkage:

\[
\delta(%) = 100 \left( \varepsilon_{shr} + \chi k_c \sigma_{m;0} \left( \frac{E_p A_p}{\sigma_{m;0} A_m} \right) \right)
\]  

(1)

In this equation, \( \delta(\%) \) is the percentage of prestress loss, \( \varepsilon_{shr} \) is the shrinkage strain, \( k_c \) is the specific creep, \( \sigma_{m;0} \) is the initial prestress of the masonry, \( E_p \) is the Young's modulus of the prestressing steel, \( A_p \) and \( A_m \) are the cross-sectional areas of prestressing steel and masonry respectively. If the average specific creep from Table 3 is used, the prestress loss is overestimated, because constant stress is assumed instead of decreasing stress. Therefore, the prestress loss correction factor \( \chi \) is introduced. Using equation (1) and the average specific creep from Table 3, the predicted prestress loss of series C and S with \( \chi = 1 \) is 17.6 % and 25.6 % respectively. To predict the actual prestress loss as measured, the prestress loss correction factor should be \( \chi = 0.54 \) for both series. It is expected that the prestress loss correction factor is not a constant, but a function of time. Therefore, equation (1) with \( \chi = 1 \) should be used as an upper limit, if no further information about \( \chi \) is available. In literature, several methods of calculation, which can predict prestress loss from creep and shrinkage, are available. However, a demonstration of these methods falls outside the scope of this paper.

In Table 4, estimates of shrinkage and predictions of specific creep after 50 years are given. Using the average values to predict prestress loss yields 35.3 % and 43.2 % respectively. These predictions overestimate actual prestress loss, as explained above. Moreover, the experiments overestimate prestress loss in building practice, due to the high axial load ratio (70 % of the design strength) of the masonry and the low axial load ratio (35 % of the design strength) of the prestressing steel in the experiments. For axial load ratios of 40 % and 70 % for the masonry and prestressing bars respectively, the predicted prestress loss for building practice is in the order of 10-12 %, which is modest. The prestress loss is lowest when the initial axial load ratio of the masonry is low, and the initial axial load ratio of the prestressing steel is high. In the experiments, this ratio was only 35 %, to prevent relaxation of the prestressing steel. In the predictions, loss due to steel relaxation is not included, but this loss will be low compared to loss due to creep and shrinkage of the masonry, especially when low-relaxation steel is used.

Table 3. Shrinkage and creep results summary for \( t = 250 \) days.

<table>
<thead>
<tr>
<th>Series</th>
<th>Shrinkage</th>
<th>Specific Creep</th>
<th>Young's Modulus</th>
<th>Creep coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[µm / m ]</td>
<td>[µm / m / MPa ]</td>
<td>[MPa]</td>
<td>[-]</td>
</tr>
<tr>
<td>C</td>
<td>87.6</td>
<td>average</td>
<td>25.1</td>
<td>average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90% upper</td>
<td>33.8</td>
<td>maximum</td>
</tr>
<tr>
<td>S</td>
<td>75.4</td>
<td>average</td>
<td>44.6</td>
<td>average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90% upper</td>
<td>50.5</td>
<td>maximum</td>
</tr>
</tbody>
</table>
In [10], a creep coefficient for calcium silicate masonry of 1.5 is given, and a shrinkage strain of 200 µm/m. Previous research on normal-strength calcium silicate masonry [6], yielded creep coefficients of 1.05 and 0.75 for calcium silicate masonry with general purpose mortar (GPM) and TLM respectively, and shrinkage strains between 280-370 µm/m. These values can be compared to the results of this investigation, shown in Table 3. It should be noted however, that although the specimens in [6] had the same initial moisture content (6.5 % m/m), the relative humidity was 50% instead of 60%. Therefore, it is to be expected that the creep and shrinkage results, presented in this paper, are lower.

5 CONCLUSIONS

Short-term and long-term material properties of two series of CASIEL-TLM masonry were determined. Although these series had a similar compressive strength, other material properties such as the dry density, Young’s modulus, specific creep and shrinkage differed significantly. Therefore, the compressive strength of CASIEL-TLM masonry is not a useful property for long-term predictions. A first investigation into the long-term behaviour and prestress loss of high-strength CASIEL-TLM masonry has been presented in this paper. The measurements lasted 250 days. Shrinkage for this period averaged 88 µm/m and 75 µm/m for series C and S, for which the CASIELs were provided by two different manufacturers. The 90% upper limit of specific creep from the experiments was 34 µm/m/MPa and 51 µm/m/MPa for series C and S. The creep coefficients are 0.58 for series C and 0.52 for series S. The apparent discrepancy between specific creep and creep coefficient is caused by the Young’s modulus of the specimens, which averaged 15,800 MPa and 9,300 MPa for series C and S respectively.

To extrapolate the results, predictions were made for a period of 50 years. No model could be found that can adequately predict the measured shrinkage. Shrinkage of series S had almost levelled off after 250 days, while shrinkage of series C was still increasing. A 90% upper limit of specific creep is predicted of 78 µm/m/MPa and 86 µm/m/MPa, and creep coefficients of 1.34 and 0.89 for series C and S respectively.

Prestress loss predictions for the experiments for a period of 50 years, gave values of 35 % and 43 % for series C and S. Translated to building practice, this yields prestress losses due to creep and shrinkage of 10-12 %, which is modest compared to prestress loss of concrete masonry, which can be in the range of 20-30 % in building practice [11]. This first series of long-term experiments with high-strength CASIEL-TLM masonry is promising and has shown that this type of masonry is suitable for post-tensioning.

<table>
<thead>
<tr>
<th>Series</th>
<th>Shrinkage (estimate)</th>
<th>Specific Creep (prediction)</th>
<th>Young’s Modulus</th>
<th>Creep coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ µm / m ]</td>
<td>[ µm / m / MPa ]</td>
<td>[MPa]</td>
<td>[-]</td>
</tr>
<tr>
<td>C</td>
<td>120</td>
<td>average</td>
<td>57.9</td>
<td>average</td>
</tr>
<tr>
<td></td>
<td>90% upper</td>
<td>78.1</td>
<td>maximum</td>
<td>17,200</td>
</tr>
<tr>
<td>S</td>
<td>120</td>
<td>average</td>
<td>76.2</td>
<td>average</td>
</tr>
<tr>
<td></td>
<td>90% upper</td>
<td>85.6</td>
<td>maximum</td>
<td>10,400</td>
</tr>
</tbody>
</table>

Table 4. Shrinkage and creep predictions for $t = 50$ years.
6 FURTHER RESEARCH

A gap exists between creep, shrinkage and prestress loss determined in a laboratory under conditions of controlled temperature and RH on the one hand, and the actual long-term behaviour exposed to changing weather conditions on the other hand. To bridge this gap, two prestress loss and two shrinkage experiments were conducted outdoors, simultaneously with the experiments described in this paper. The results of these outdoor experiments will be published elsewhere.

The long-term experiments are part of a larger research program, investigating the behaviour of post-tensioned CASIEL-TLM masonry shear walls. In this research program, it is intended to post-tension several stories at once. Therefore, wall-floor connections will be post-tensioned as well. Between the concrete floor and CASIEL-TLM masonry wall, a kicker course mortar joint of 20-40 mm is required in current construction practice. The long-term behaviour of wall-floor connections including these joints will be tested in the same test-setups and conditions.

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