Behavior of Foam Particles Lightweight Concrete with Time

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Abstract

Lightweight Concrete with polystyrene foam particles (LWC) was obtained through the use of polystyrene foam as a partial aggregate’s replacement to reduce the concrete dry unit weight from 23 KN/m³ to 18.50 KN/m³. This research presents an experimental and theoretical investigation in the long-term behavior of LWC in compression and flexure. Two experimental programs were conducted; namely, creep and shrinkage of LWC under compressive loading test, and the time-dependent flexural behavior of reinforced LWC beams. The main variable in the first experimental program was the percentage of sustained load, while the main variables in the second experimental program were the percentage of sustained load and the percentage of compression reinforcement. Experimental results showed that LWC exhibits a significantly higher time-dependent strain (shrinkage plus creep) than normal weight concrete (NWC) under sustained compressive load and at the same compressive strength, with an increasing percentage about 9%. The creep strains of LWC seemed to be proportional to the stress to strength ratio. The time-dependent deflections of the LWC beams were higher than those of NWC beams with increasing percentage about 25%. Addition of compression steel reinforcement (As') to LWC beams reduced time-dependent deflections. Sustained load level and LWC time-dependent deflection were directly proportional. Finally, models and equations proposed by different codes were used to evaluate the obtained experimental results. From the theoretical study, it was found that Bazant-Baweja B3 Model gave superior shrinkage strains prediction for LWC. The ACI 209R-92 presented preferable predictions of creep strain and time-dependent deflection of LWC.

Keywords: LWC behavior, Concrete type, Creep, Shrinkage, Long-term behavior, Stress level, Compression reinforcement ratio.

1. Introduction

In the light of the LWC with polystyrene foam particles advantages, the safety and serviceability of the structure cannot be known without a comprehensive knowledge of the concrete properties which determine its deformational characteristics under sustained load. Among these properties, the behavior of concrete element under sustained stress for a period (i.e., creep of concrete). This phenomenon is very important in concrete design and cannot be ignored. Numerous researches were conducted to study the time-dependent behavior of LWC with different lightweight aggregate (LWA) (Gudmundsson, J.G., 2013), (Haranki, B., 2009), (Hosny, A.I., 2010). In comparison with NWC, results have shown that the creep behavior might vary differently depending on the LWA used in the LWC mix. Since very limited creep testing has been performed to study LWC with polystyrene foam particles, and therefore empirical data is scarce, this research presented herein was aimed to investigate the effect of the polystyrene foam particles on the long-term behavior of concrete in compression and flexure.

2. Concrete Mixtures Evaluated

Two concrete mixes were used for the specimens, the first mix was for the LWC specimens and the second mix was for the NWC specimens. To achieve LWC mixture; polystyrene foam was added to the mix which consisted of natural sand as fine aggregates, the fine crushed stone of nominal maximum size of 10 mm as coarse aggregate, fresh ordinary Portland cement, and tap water. To achieve two concrete mixtures having the same compressive strength; silica fume and a lower w/c ratio, than the reference NWC, was added to the LWC mixture. As a consequence of using silica fume and low w/c ratio, superplasticizer was used to produce self-leveling concrete. The two mixes proportions/m³ by weight are shown in Table 1.
Table 1 Design of LWC and NWC Mix Proportions

<table>
<thead>
<tr>
<th>Concrete mix</th>
<th>LWC</th>
<th>NWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m²)</td>
<td>450</td>
<td>350</td>
</tr>
<tr>
<td>Silica fume (kg/m³)</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Coarse Aggregate (kg/m³)</td>
<td>630</td>
<td>1260</td>
</tr>
<tr>
<td>Sand (kg/m³)</td>
<td>630</td>
<td>630</td>
</tr>
<tr>
<td>Polystyrene Foam (liter/m³)</td>
<td>330</td>
<td>-</td>
</tr>
<tr>
<td>Super Plasticizer (liter/m³)</td>
<td>13.5</td>
<td>-</td>
</tr>
<tr>
<td>W/C ratio</td>
<td>0.308</td>
<td>0.40</td>
</tr>
</tbody>
</table>

3. Experimental Program

3.1 Creep & Shrinkage of LWC under Compressive Loading Test

3.1.1 Creep Test

3.1.1.1 Test Specimens

This part presents the two experimental programs carried out. The first program was executed to evaluate creep of molded LWC in compression according to the methods proposed by ASTM C512/C512M, and determination of companion unloaded shrinkage specimens according to the method proposed by ASTM C157. The second program was carried out to study the time-dependent flexural behavior of reinforced LWC beams.

3.1.1.2 Test Apparatus

The design of the creep test apparatus is shown in Fig.1. Three apparatuses are manufactured and used in this test. In each test frame, four 15×30 cm cylindrical specimens are placed on top of one another and cemented together by epoxy and tested under the same load.

3.1.2 Shrinkage Test

Fig.3. shows the test set-up of the free shrinkage test. The free shrinkage measurements were made using three 75×300 mm concrete prisms specimens for each concrete mixture. Two pairs of gauge studs were placed at both ends of the specimens. The specimens were removed from the molds at the age of 23 h and then placed in water for a minimum of 30 minutes.
At the age of 24 h, the specimens were removed from water storage and wiped with a damp cloth. An initial reading was immediately taken with a length comparator. The specimens were then stored in the drying room and strain measurements on both the loaded (creep) and the unloaded (shrinkage) specimens, made with the strain gauge at appropriate intervals up to an age of 9 months, and are reported.

3.2 Time-Dependent Flexural Behavior of Reinforced LWC Beams

This experimental program used for investigation of the flexural behavior of reinforced LWC beams under sustained load with time, since the creep test in the first part was carried out on unreinforced LWC specimens.

3.2.1 Test Specimens

Two groups of beams with different stress levels were used in this investigation. These stress levels are (1) 25% of the ultimate load and, (2) 50% of the ultimate load. Each of the preceding groups consists of four beams divided into three beams made of LWC mixture and one beam made of NWC mixture to compare its creep behavior with each other. Beams in each of the previous groups of different stress levels were having three different percentage of additional compression reinforcement (As’) to tension reinforcement (As) as follows; As’/As = 0%, As’/As = 60% and, As’/As = 100%, the subgroups were named (A, B, C) respectively. Table 2 shows the experimental test program profile and Fig.4 shows details of the tested beams.

3.2.2 Test Apparatus

The same creep test apparatus used in the previous test would be used in this one.

3.2.3 Instrumentation

The mid-span deflection was measured using dial gauge. In the first two weeks, deflections were recorded daily, and the load was checked. Then, the records were taken every three to four days for a month time; finally, the readings were taken once per week until the time of removal of the applied load.

3.2.3 Test Procedure

The beams in both groups were tested at the age of 28 days. The load was applied as explained before. The deflection was noted immediately after applying the full sustained load and was recorded as the immediate, initial or short-term deflection. The sustained load was applied for 120 days, and during this period deflection readings were recorded at regular intervals. Fig.5 shows the test setup.

Fig.4 Concrete dimensions and details of tested beams

Fig.5 4-point bending creep test
4. Experimental Results and Discussions

4.1 Mechanical Properties of Concrete

The mechanical characteristics of the two concrete mixtures were determined before testing. The compressive strength ($f_{cu}$), the tensile strength ($f_{ct}$) and elastic modulus ($E_c$) were measured according to ASTM Standards C39, C496 and C469, respectively at 28 days. All tests were carried out on three samples from each mixture, and mean values of mechanical properties are given in Table 3.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Stress Level%</th>
<th>Concrete Mix</th>
<th>Specimen Dimensions (Tension)</th>
<th>Tension (RFT.)</th>
<th>Compression (RFT.)</th>
<th>$A_s$ / $A_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1A</td>
<td>25%</td>
<td>LWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ6</td>
<td>0</td>
<td>(A)</td>
</tr>
<tr>
<td>L-1B</td>
<td></td>
<td>NWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ8</td>
<td>60</td>
<td>(B)</td>
</tr>
<tr>
<td>L-1C</td>
<td></td>
<td>LWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ10</td>
<td>100</td>
<td>(C)</td>
</tr>
<tr>
<td>L-2A</td>
<td>50%</td>
<td>LWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ6</td>
<td>0</td>
<td>(A)</td>
</tr>
<tr>
<td>L-2B</td>
<td></td>
<td>LWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ8</td>
<td>60</td>
<td>(B)</td>
</tr>
<tr>
<td>L-2C</td>
<td></td>
<td>LWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ10</td>
<td>100</td>
<td>(C)</td>
</tr>
<tr>
<td>N-1B</td>
<td></td>
<td>NWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ8</td>
<td>60</td>
<td>(B)</td>
</tr>
<tr>
<td>N-2B</td>
<td></td>
<td>NWC</td>
<td>10 20 2ɸ10</td>
<td>2ɸ10</td>
<td>100</td>
<td>(C)</td>
</tr>
</tbody>
</table>

4.2 Creep and Shrinkage of LWC under Compressive Loading Test Results

4.2.1 Comparison between LWC and NWC mixtures

4.2.1.1 Shrinkage Test Results

Fig. 6 shows the plots of shrinkage strains against time for the LWC and the NWC. The drying shrinkage of concretes increased gradually with decreasing rate, due to the reduction in the drying rate with time. It can be observed that LWC appear to have relatively higher shrinkage than NWC with increasing percentage of 31%. A higher increasing percentage of LWC shrinkage strain was predicted, however, this increasing percentage was decreased because of using a lower water/cement ratio in LWC mixture than the ratio in the NWC mixture.

4.2.1.2 Creep Test Results

4.2.1.2.1 Creep Strain

Figs. 7 to 9 present plots of creep strain of LWC and NWC against time since loading. It can be noticed that the creep strains of LWC were equal to or lower than the creep strains of the NWC, in spite of the fact that concretes made of lightweight aggregates are expected to exhibit higher creep than those made with hard aggregates. On the other hand, when concretes of the same strength are compared, essentially the same creep is observed. The strength of the LWC is lower than the strength of NWC of the same w/c ratio and, to obtain the same strength, the former concrete must be prepared with a lower w/c ratio than the latter one. The lower w/c ratio reduces the creep of the cement paste, and this reduction counteracts the increased creep which is brought about by the use of the lightweight aggregate.
4.2.1.2.2 Creep Coefficient

Figs. 10 through 12 show the plots of creep coefficient versus loading time for the LWC and NWC for the three load levels. It can be observed that the creep coefficients of LWC are substantially lower than those of NWC. Creep coefficient of LWC is about 36% lower than creep coefficient of NWC.

4.2.1.2.3 Specific Creep

Figs. 13 to 15 show that the specific creep of the LWC is slightly lower than the specific creep of NWC throughout the test period. The cement paste matrix affects the creep of concrete. Higher volume and lower strength of cement paste increases creep. While the quantity of paste content and strength are similar in the LWC and NWC in the current study, their quality differed. The LWC with silica fume and lower w/c ratio had a denser paste with lower porosity compared with the NWC. In spite of the lower elastic modulus of the LWC in comparison to the NWC, the LWC had lower 280-day specific creep compared with the NWC. This implies that quality of the paste, in terms of the porosity and strength which is influenced by water-to-cementitious material ratio and use of silica fume, is a more dominant factor than the stiffness of the aggregate comparing these two concretes.
4.2.1.3 Time-Dependent Strain

The time-dependent strain (shrinkage plus creep) of LWC specimens were higher than those of NWC specimens with increasing percentage about 9%. Fig. 16 shows time dependent strains (shrinkage plus creep) of LWC and NWC after 280 days of sustained load. The magnitudes of the elastic strain, shrinkage plus creep strain, shrinkage strain, creep strain, and total strain of the LWC at 280 days are summarized in Table 4 as percentages of the magnitudes for the NWC.

Table 4 Relative magnitudes of deformations after 280 days of sustained load

<table>
<thead>
<tr>
<th>Load Level</th>
<th>Mixture Type</th>
<th>Elastic Strain (%)</th>
<th>Shrinkage+creep</th>
<th>Shrinkage (%)</th>
<th>Creep (%)</th>
<th>Total Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>LWC</td>
<td>154</td>
<td>113</td>
<td>131</td>
<td>99</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>NWC</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>40%</td>
<td>LWC</td>
<td>154</td>
<td>108</td>
<td>131</td>
<td>100</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>NWC</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>60%</td>
<td>LWC</td>
<td>154</td>
<td>107</td>
<td>131</td>
<td>100</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>NWC</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
4.2.2 Effect of Stress to Strength Ratio on Creep Strain

Measured creep strain of LWC mix at 280 days was 0.000365 and 0.000815 for stress to strength ratio equal to 0.2 and 0.4 respectively. At 280 days, the ratio between creep at stress to strength ratio 0.4 to 0.2 was 2.2, which is close to the actual ratio between stresses to strength ratio (2). Similarly, the ratio between creep at 0.6 to 0.4 was approximately 1.2, and the actual ratio between stresses to strength ratio was (1.5). From Fig.17, it can be seen that a linear relation between creep and stress to strength ratio exists up to the ratio of 0.6 so that the following simple linear function was used to develop the relationship:

$$\varepsilon_{c280} = \alpha.(\text{Stress/Strength ratio}) + \beta \tag{1}$$

Where $\varepsilon_{c280}$ is the creep strain at 280 days. By using this relationship, the creep strain of LWC with polystyrene foam particles under different stress levels could be approximated by just testing the concrete under compressive strength.

![Fig.17 The relation between stress level and creep strain at 280 days for LWC specimens](image)

4.2.3 Effect of Stress Level on LWC Creep Coefficient

Fig.18 shows the comparison of creep coefficients of the LWC concrete mix at the three stress levels at 280 days.

![Fig. 18 Effects of different stress level on LWC creep coefficient](image)

It can be observed from the previous table, a linear relationship between the immediate deflection ($\Delta i$) and time-dependent deflection ($\Delta 120 - \Delta i$) at day 120, end of loading period. Fig.19 presents a graph; every point on it represents a pair of values ($[\Delta 120 - \Delta i, \Delta i]$) of mid-span deflection for all the beams in both stress levels. It can be seen that all the points lie practically on a straight line no matter to which compression reinforcement ratio and loading level the points belong, which means that the immediate and time-dependent deflections of LWC beams can be assumed to be dependent. Thus, the following function was used to develop the relationship:

$$y = 0.0015x + 0.0001 \quad R^2 = 0.9138$$

From this figure, it can be observed that the three different stress levels had nearly no effect on the creep coefficient of LWC mix. In some cases, the creep coefficient was considerably higher at 60% stress level, while in others, it was considerably higher at 20% stress level.

4.3 Dependent Flexural Behavior of Reinforced LWC Beams Test Results

An increase in the deflection of beams subjected to the sustained load is influenced mainly by the creep of concrete; time-dependent changes in tension stiffening; deterioration of bond between the concrete and reinforcement; the shrinkage of concrete; increasing crack widths and formation of new primary cracks. Since creep in bending was harder to separate from the total deflection, the time-dependent deflection due to previous influences together ($\Delta t - \Delta i$) was calculated by subtracting the immediate deflection after loading ($\Delta i$) from the total mid-span deflection ($\Delta T$). Table 5 shows the values of immediate deflection, time-dependent deflection, and time-dependent deflection ratio for LWC beams.

<table>
<thead>
<tr>
<th>Beam name</th>
<th>Applied sustained load (%)</th>
<th>Immediate deflection ($\Delta i$) (m)</th>
<th>Time-dependent deflection ($\Delta 120 - \Delta i$) (mm)</th>
<th>Time-dependent/Immediate deflection ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1A</td>
<td>25%</td>
<td>0.125</td>
<td>0.059</td>
<td>0.472</td>
</tr>
<tr>
<td>L-1B</td>
<td>25%</td>
<td>0.117</td>
<td>0.045</td>
<td>0.385</td>
</tr>
<tr>
<td>L-1C</td>
<td>25%</td>
<td>0.113</td>
<td>0.042</td>
<td>0.372</td>
</tr>
<tr>
<td>L-2A</td>
<td>50%</td>
<td>0.362</td>
<td>0.115</td>
<td>0.318</td>
</tr>
<tr>
<td>L-2B</td>
<td>50%</td>
<td>0.337</td>
<td>0.095</td>
<td>0.282</td>
</tr>
<tr>
<td>L-2C</td>
<td>50%</td>
<td>0.318</td>
<td>0.085</td>
<td>0.267</td>
</tr>
</tbody>
</table>
\[ \Delta_{120} = \alpha \Delta_i + \beta \]  

(2)

Where \( \Delta_{120} \) is the time-dependent deflection at day 120 and \( \Delta_i \) is the immediate deflection.

In reinforced LWC beams, as the concrete shrink, it compressed the steel reinforcement which imposed an equal and opposite tensile force on the concrete at the level of the steel. This tensile force led to time-dependent cracking (in previously uncracked regions), increase in deflection, a widening of existing cracks and subsequently high time-dependent deflections in LWC beams than that of NWC beams. LWC beams were also recorded rather high immediate deflection values as compared with NWC immediate deflection values. This demonstrates the negative effect of the porous texture of the LWC on its mechanical properties; particularly, lower elastic modulus than NWC, which led to relatively high deflection at early ages, after that a much more high deflection at late ages no matter loading level the beams were loaded.

### 4.2.5 Effect of As'/As Ratio on The Time-Dependent Deflection

It can be observed from Figs. 22 and 23 that the compression steel has the effect of significantly reducing the time-dependent deflections. The addition of compression reinforcement reduced the long-term deflections, almost after one week since loading, and the beneficial effect of compression reinforcement in reducing long-term deflections increased with increase in the ratio As'/As.

### 4.2.4 Comparison between LWC and NWC Beams

LWC beams were recorded substantially higher time-dependent deflection than that of NWC beams with an increasing percentage about 23% as shown in Fig. 20, as in LWC time-dependent compressive deformations which discussed before.

![Fig. 19 Immediate deflections versus time-dependent deflections at day 120, all beams](image1)

![Fig. 20 Time dependent deflections of LWC and NWC beams after 120 days of sustained load](image2)

![Fig. 22 Time-dependent deflections for different additional compression reinforcement, load-level 25%](image3)

![Fig. 23 Time-dependent deflections for different additional compression reinforcement, load-level 50%](image4)

![Fig. 24 presents the time-dependent deflection ratio (\( \lambda \)) of LWC beams with different compression reinforcement ratios (As'/As). It shows that for the beams in both load levels, increase in the ratio As'/As from 0 to 0.6 reduced the time-dependent deflection ratio (\( \lambda \)). However, no further improvement in the effectiveness of compression reinforcement in controlling the time-dependent deflection ratio (\( \lambda \)). It was noted when As'/As was increased to 1.](image5)
Fig. 24 Time-dependent deflection ratios for different additional compression reinforcement

4.2.6 Effect of Load Level on the Time-Dependent Deflection

Fig.25 shows the effect of load level applied on the time-dependent deflection at day 120 (Δ120 - Δi). Time-dependent deflection (Δ120 - Δi) has been affected by the percentage of the applied load. The greater the applied sustained load-level, the higher time-dependent deflection (Δt - Δi). For instance, in beams, L-1A and L-2A, which have the same compression reinforcement ratio, time-dependent deflection (Δ120 - Δi) values, were 0.059 mm and 0.115 mm for applied load 25% and 50% from the ultimate load, respectively, with an increase of 49%. However, the time-dependent deflection ratio (λ) decreases with the increase of load level applied to the tested beams.

Fig. 25. Time-dependent deflection at day 120 for different applied load level

5. Code Prediction

5.1 Comparison between Experimental Results and Codes Predictions

In this section, shrinkage strains and creep strains of cylindrical LWC specimens at the age of 280 days are computed according to five methods and models, where the actual compressive strength and elastic modulus of the LWC from the control specimens were used in the code predictions. These methods and models are ACI 209R-92, Bazant-Baweja B3 model; CEB MC90-99 model, GL2000 model, and the Egyptian code of practice ECP 203-2007.

5.1.1 Prediction of Shrinkage Strain

Fig.26 shows the plots of experimental shrinkage strains at 280 days against predicted shrinkage strains using the different five methods and models for the LWC mixture in this study. As shown in following data, the Bazant-Baweja B3 model gives a better prediction for LWC shrinkage strain in comparison with the other four models and methods.

Fig.26 Shrinkage strains prediction of the five methods compared to measured values

5.1.2 Prediction of Creep Strain

The five models mentioned before were used to estimate strains due to creep in the concrete specimen and compared to measured creep strains. It was observed that ACI 209R-92 model presents preferable creep strains prediction for LWC than other models and methods, especially at high-stress levels (stress-level 40% and 60%). Figs.27 to 29 show the measured creep strains against predicted creep strain from the ACI 209R-92 model.

Fig.27. Experimental versus predicted creep strains (stress level 20%)
Fig. 28. Experimental versus predicted creep strains (stress level 40%)

Fig. 29. Experimental versus predicted creep strains (stress level 60%)

5.2 Comparison between Measured and Calculated Time-Dependent Deflections

Fig. 30 compares the experimental values of time-dependent deflections to predicted values using the ACI equation and the ECP equation.

From the above figure, it can be observed that ACI method gives a better prediction of time-dependent deflections of LWC than ECP method and this because that the multiplier factor ($\lambda$) in ACI method depends on the additional steel reinforcement and time of applying the sustained load on the concrete element, while the multiplier factor ($\alpha$) in ECP method depends on the additional steel reinforcement only.

Conclusions

For the tested LWC specimens, it can be concluded that:

1) The LWC with polystyrene foam particles has a significantly higher drying shrinkage than the NWC with increasing percentage of 31%.
2) The creep strain of LWC with polystyrene foam particles is equal to that of NWC during the test period.
3) The time-dependent strain (shrinkage plus creep) the LWC with polystyrene foam particles significantly higher than that of NWC with increasing percentage of 8%.
4) The creep strains of LWC with polystyrene foam particles seem to be proportional to the stress to strength ratio. As the stress to strength ratio increases, the creep strains of LWC with polystyrene foam particles increases.
5) ACI 209R-92 presents preferable creep and shrinkage strains prediction for LWC with polystyrene foam particles than other models and methods.
6) The reported investigations show that the initial and long-term deflection of the LWC with polystyrene foam particles can be assumed to be dependent.
7) The time-dependent deflections of the LWC with polystyrene foam particles beams are higher than those of NWC beams with increasing percentage of 25%. Hence, the time-dependent behavior of the LWC with polystyrene foam particles in compression and flexure are almost the same as compared with the time-dependent behavior of the NWC.
8) The effect of the additional compression steel reinforcement $A_s'$ on a time-dependent deflection of the LWC with polystyrene foam particles beams is a decrease with the increase of the ratio $A_s'/A_s$. However, no further improvement in the effectiveness of compression reinforcement in controlling the time-dependent deflection of the LWC with polystyrene foam particles beams is noted when $A_s'/A_s$ was exceeded 0.6.
9) Effect of load level on time-dependent deflections value of the LWC with polystyrene foam particles beams, the higher the sustained load level, the bigger the time-dependent deflection value.
10) ACI 209R-92 presents preferable time-dependent deflection prediction for LWC with polystyrene foam particles beams than ECP.
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