USING TIME-TEMPERATURE SUPERPOSITION TO PREDICT LONG-TERM CREEP OF NUCLEAR CONCRETE

Aishwarya Baranikumar1, Christa E. Torrence2 and Zachary Grasley3

1Graduate Research Student, Civil Engineering, Texas A&M University (aish04@tamu.edu)
2Graduate Research Student, Materials Science and Engineering, Texas A&M University.
3Professor, Zachry Department of Civil Engineering, Texas A&M University.

ABSTRACT

The prestressed concrete containment structure serves as a prime member in nuclear structures shielding the nuclear reactor from the environment. Containment structures undergo harsh service conditions involving steep temperature and pressure gradients during their lifetime. With the containment facilities nearing the end of their design life, the effect of time dependent deformation on these structures is significant. At room temperature creep can be 2-3 times the initial deformation in the first year and at elevated temperatures, creep effects are further amplified and cannot be ignored. The purpose of this study is to predict, using the time-temperature superposition principle, the long-term creep induced strain in the containment structure from the results obtained during short periods of testing.

INTRODUCTION

A vast majority of the nuclear power plants in the U.S. are nearing the end of their original design life and yet there is interest in continuing their use. It is hence critical to identify the risk associated with the long-term use of these facilities and in turn understand the impact of the time-dependent changes on their structural performance. Since these structures are typically post-tensioned concrete containment vessels, one of the main concerns is the phenomenon known as concrete creep. Concrete creep is a long-term deformation that results in stress redistributions, pre-stress losses and potentially concrete cracking.

Concrete creep is a long-term phenomenon that proceeds for decades and is difficult to predict from short-term tests. Furthermore, concrete creep is temperature and moisture dependent and is influenced by concrete age and stress reversals. The duration and temperature dependence of concrete creep can be addressed utilizing the time-temperature superposition (TTS) principle first noted by Schwarzl et al. (1952). Schwarzl et al. (1952) suggested that a small increase in temperature generally increases the kinetics of most processes. In thermo-rheologically simple materials, it implies that during similar deformation processes at different temperatures, the same sequence of molecular events occur with different speed and can be correlated using temperature dependent shift factors. That being said, it is not necessary that the shift factor is a linear function of temperature, i.e., the rate at which events occur between 20°C and 40°C need not be the same as the rate between 40°C and 60°C. Hannant (1967) found that the slope of creep strain against temperature is not linear between 27°C and 100°C because the rate of increase of creep accelerates as the temperature increases. Nasser et al. (1965) studied the behavior of creep in concrete at different temperatures ranging from 21°C to 96°C. For a stress-strength ratio of 35% loaded at 14 days of age and 15 months under load, the creep at 72°C was 1.75 times higher than that at 21°C and the creep at 96°C was 1.95 times higher than that at 21°C. In comparison, McDonald (1977) showed that at a stress-strength ratio of 31% loaded at 90 days of age and 12 months under load, the compressive creep at 66°C was 1.79 times that at 23°C. Bazant et al. (2004) summarized the temperature effect on concrete creep from various
literatures, which indicates concrete behaves like a thermo-rheologically simple material. More recently, Ladaoui et al. (2011) and Vidal et al. (2015) analyzed the effect of temperature ranging between \(20^\circ C\) and \(80^\circ C\) on the basic creep of High Performance Concrete (HPC). It was concluded that the basic creep of HPC increased by a factor of 2 (stress-strength ratio of 30\% and 10 months under load), with a temperature rise from \(20^\circ C\) to \(50^\circ C\).

In the current study, the authors propose creep tests on cement mortar at different temperatures using smaller sized specimens making the tests easier and cheaper to conduct than traditional concrete creep tests. As concrete creep occurs entirely due to creep within the cement paste phase (Bažant 1975), the sensitivity of concrete creep to various parameters including mixture design, stress, environment, etc. can be captured by cement mortar experiments. A unique, miniature version of conventional creep frames that are much more amenable to placing in climate chambers are used in this study. The creep measurements from mortar are upscaled to predict concrete creep behavior using a computational algorithm (Torrence et al. 2019). To measure the effects of high temperatures on mortar creep, tests were performed at elevated temperatures (up to \(80^\circ C\)). The results from the creep tests at different temperatures were shifted to fit along the axis of logarithmic time scale to obtain a creep master curve.

EXPERIMENTAL METHOD

Materials

Électricité de France (EDF) Vercors mortar mix (EDF 2014) was chosen as the mix design for this study as it closely represents the mixture used in most US prestressed concrete reactor vessels. Type I cement was used and River sand passing No.8 sieve (< 2.38 mm) was used as fine aggregate. All aggregates were dried for 24 hours before mixing. The water to cement mass ratio for the mix was 0.52 and the sand to cement mass ratio was 2.12. The admixture Pozzolith 80 with a dosage of 422.5 ml per 100kg of cementitious materials was used. The mixture proportions are shown in Table 1 and referenced in EDF (2014).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Unit</th>
<th>Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (Type I/II)</td>
<td>kg/m(^3)</td>
<td>601</td>
</tr>
<tr>
<td></td>
<td>lb/yd(^3)</td>
<td>1013</td>
</tr>
<tr>
<td>River Sand</td>
<td>kg/m(^3)</td>
<td>1263</td>
</tr>
<tr>
<td></td>
<td>lb/yd(^3)</td>
<td>2129</td>
</tr>
<tr>
<td>Water</td>
<td>kg/m(^3)</td>
<td>323</td>
</tr>
<tr>
<td></td>
<td>lb/yd(^3)</td>
<td>544.4</td>
</tr>
<tr>
<td>Admixture Pozzolith 80</td>
<td>l/m(^3)</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>oz/yd(^3)</td>
<td>66</td>
</tr>
</tbody>
</table>

Sample Preparation

The cement mortar was mixed according to ASTM C305-99 and immediately cast into 50 mm x 100 mm cylindrical molds with embedded vibrating wire gages (50 mm gage length) from Geokon. Fishing line was used to suspend the gage axially at the center of each mold. To prevent moisture loss, the sample was kept in the mold until the time of testing i.e., 28 days. Prior to testing, the samples were demolded and sealed with adhesive-backed aluminium foil to minimize drying. Concrete plugs of 25 mm height were attached
to both ends of the sample to ensure uniform compressive stress throughout the cross-section. Sulfur capping compound was used to ensure the ends of the sample were smooth for loading.

**Fabrication of Creep Frame**

Unlike the standard ASTM C512 creep frames, a unique miniature version of the creep frame was fabricated for the mortar samples as shown in Figure 1. The advantage of the scaled down version of the frame is that they are much more amenable to placing in climate chambers, ovens, etc., which is key to performing thermally accelerated creep tests. The creep frame has a spring at the bottom to help maintain the load. A ball bearing at the center of one of the plates ensures that there is no eccentricity in loading. An inline load cell was used to record the load levels in the frame. Although stress levels are kept close to constant during the creep test, the actual stress level was recorded periodically to account for the load loss. A 5 ton mini hydraulic jack was used to apply axial force to the samples.

![Diagram of Miniaturized Mortar Creep Test Frame](image)

**Figure 1. Miniaturized mortar creep test frame**

**Uniaxial creep test**

The fabricated miniaturized creep frames were used to run the uniaxial creep test. At 28 days, samples were loaded using a hydraulic jack to a constant load of 816 kg (or 1800 lbs, which is approximately 10% of compressive strength of the mortar). Since the load was applied in a short period of time compared to the duration of the creep test, it can be approximated as a step wise load application. The axial strain from the vibrating wire gage as well as the load readings from the load cell were recorded every 30 minutes using a CR300 Data logger, AM16/32B Multiplexer and a 2-Channel Vibrating-Wire Analyzer (AVW200) from Campbell Scientific. Tests were run at three different temperatures: 20°C (reference temperature), 60°C and 80°C. Three replicates were used for each temperature. The samples were heated to the test temperature before starting the creep test. The experiments were conducted in environmental chambers maintaining a constant temperature and relative humidity.
RESULTS

Cement Mortar Mix Properties

The compressive strength, $f'_c$, and elastic young’s modulus, $E$, of the cement mortar samples were measured at different ages: 3, 7, 14, 28 and 90 days according to ASTM C39 and ASTM C469, respectively. The mortar was mixed according to ASTM C305-99 and immediately cast into 100 mm x 200 mm cylindrical mold. All samples were kept in the mold until the testing time. Axial deformation was measured using an extensometer with a 100 mm gage length. Three samples were tested at each age. The results are shown in the Table 2.

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>3</th>
<th>7</th>
<th>14</th>
<th>28</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength (MPa)</td>
<td>22.31</td>
<td>28.66</td>
<td>33.54</td>
<td>37.53</td>
<td>43.92</td>
</tr>
<tr>
<td>Elastic Young’s Modulus (GPa)</td>
<td>18.82</td>
<td>22.34</td>
<td>24.13</td>
<td>25.44</td>
<td>25.44</td>
</tr>
</tbody>
</table>

Uniaxial creep test

The results from a sample uniaxial creep tests are shown below. Figure 2a shows the fitted stress function. Figure 2b shows the total strain output from the vibrating wire gages, free strain reading, which is the deformation in an unloaded specimen at the same age undergoing shrinkage, and the creep strain, which is the difference between the total strain and free strain. In spite of sealing the samples with aluminium foil, some drying did occur and the free strain measured was mostly from drying shrinkage.

![Figure 2](image-url)

Figure 2. (a) Fitted stress versus the time of loading, (b) Strain output versus the time of loading.

As shown in Figure 2b, the average creep strain was calculated for the three specimens running at different temperatures for a period of 200 days. It was observed that after 200 days, the creep strain at 60°C was 2.04 times higher than that at 20°C and the creep strain at 80°C was 3.24 times higher than that at 20°C. These multipliers are higher than that available in the literature, as this study focuses on creep in mortar samples rather than concrete samples. The creep strains for the three temperatures are plotted in Figure 3.

A more reasonable way to compare the creep tests at different temperatures is to look at their creep compliance function, $J(t)$. The creep compliance function was calculated using three methods.
The first method is an approximate method whereby load history effects are neglected, and strains are simply divided by their respective stress values at each time increment such that

\[ J(t) = \frac{\varepsilon(t)}{\sigma(t)} , \]  

(1)

Figure 3. Average creep strain data at different temperatures

where \( \varepsilon(t) \) is the creep strain and \( \sigma(t) \) is the applied stress at time \( t \).

The second approximate method completely neglects the time variance in the stresses and considers the stress to be constant and equal to the initially applied stress \( (\sigma_0) \):

\[ J(t) = \frac{\varepsilon(t)}{\sigma_0} . \]  

(2)

The third method (“fitted”) employs the constitutive equations for a linear viscoelastic material to derive the compliance functions accounting for the time-dependency of the stresses and the history dependence of the strains. This method is the most fundamentally accurate approach to determine the compliance functions. The previous two methods may be used for estimating compliance but do not yield precise measurements. The constitutive function for a linearly viscoelastic material is

\[ \varepsilon(t) = \int_0^t J(t-t') \frac{\partial \sigma(t')}{\partial t'} dt' , \]  

(3)

where \( t \) is the present time and \( t' \) is the dummy time variable.

Figure 4 shows the graph of the compliance function at different temperatures obtained using the three methods. Even though springs were used in the load frame in an attempt to keep the load constant, there is significant load loss at higher temperatures. At higher temperatures, creep in the sample is higher, which results in stress relaxation in the springs. Hence, significant errors could result in calculating the compliance functions, if the load was assumed constant.
Figure 4. The creep compliance function calculated using the three methods, (i) simple division, (ii) assuming load to be constant, (iii) fitting the compliance in the constitutive equation at 20°C, 60°C and 80°C temperatures. The “fitted” function is the most accurate method of determining the compliance function.

**Time-Temperature Superposition Principle**

The fitted creep compliance curve obtained at higher temperatures (60°C and 80°C) were shifted along the logarithmic time axis to obtain the creep compliance data at room temperature (20°C) as depicted in Figure 5.
The temperature dependent shift factors, $A_t$, were calculated as

$$A_t = \frac{t}{t_r},$$  \hspace{1cm} (4)

where $t$ is the present time and $t_r$ is the reduced time. The shift factors are shown in Table 3.

Table 3. Shift factors.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Shift Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>1 (reference)</td>
</tr>
<tr>
<td>60°C</td>
<td>4.62</td>
</tr>
<tr>
<td>80°C</td>
<td>32.80</td>
</tr>
</tbody>
</table>

Using the corresponding shift factors for the different temperatures, the creep master curve was obtained which predicts the creep compliance data for 6000+ days. The shifted data were fitted into a five unit Kelvin chain as shown in equation 5. The units of creep compliance are 1/GPa. The master curve is presented in Figure 6.

$$J(t) = 0.00613(1-e^{-t}) + 0.01066(1-e^{-0.10t}) + 0.00723(1-e^{-0.1000t}) + 0.14507(1-e^{-1/100}) + 0.09020(1-e^{-1/1000})$$  \hspace{1cm} (5)
CONCLUSION

Using the time-temperature superposition principle, the creep compliance of mortar specimens measured at elevated temperatures of up to 80°C for a period of 200 days were fitted to obtain a master curve to predict long-term creep compliance corresponding to 6000+ days. Running creep tests at 80°C allows one to predict creep at 20°C at 32.80 times the time duration of the 80°C test using temperature shifting. Another important conclusion is that, the load history has to be accounted for while calculating the creep compliance, especially at higher temperatures. Assuming load to be a constant, can result in significant error in the creep compliance. The study provides improved analysis and prediction of remaining life of existing concrete containment structures, post-tensioning losses, effects of creep on structural capacity, and the likely impact of repair activities on stress fields and crack potential. These findings are expected to have a tremendous impact on the ability to continue utilizing containment structures past their original design lifetime.

REFERENCES


temperatures,” In: Rep. No. UCESM 76-3 Prepared for General Atomic Company, Department of Civil Engineering, University of California, Berkeley.


Mc Donald, J. E. (1975) “Time dependent deformation of concrete under multiaxial stress conditions,” In: Technical Report C-75-4 Concrete Laboratory, US Army Engineering Waterways Experiment Station, Vicksburg, MS.


