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The compressive creep behavior of an expanded polystyrene geofoam

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ABSTRACT: Expanded polystyrene (EPS) geofoams are used as a lightweight fill in many geotechnical applications. The creep behavior was evaluated using three different creep test methods; stepped isothermal method (SIM), short-term time-temperature superposition (TTS) with dwell time of 10^4 seconds, and long-term creep test method. The results indicated that the SIM test had limited applicability for the EPS geofoam due to the temperature and accumulated strain effects at temperature above 44°C. For the short-term TTS test, the resulting creep master curve exhibited a reasonable match with the long-term creep curve. Furthermore, the activation energy for the creep mechanism obtained from the short-term TTS tests was close to that published in the literatures at temperature below 43°C. However, the activation energy was much lower at temperature above 43°C, suggesting creep mechanism was changed.

1 INTRODUCTION

Expanded polystyrene (EPS) geofoams have been used as lightweight fills in many geotechnical applications, including embankments, bridge abutments, and road widening (Horvath 1995, Duskov 1997). In these applications, the geofoam is subjected to a static compressive stress throughout the service lifetime; creep deformation is thus expected.

Studies have been performed to evaluate the creep behavior of the EPS geofoam using the long-term creep test with duration ranging from 1,000 to 10,000 hours (Horvath 1995, Duskov 1997, Negussey 1997). However, data from such test duration were insufficient to predict the creep behavior for a service lifetime up to 100 years.

Alternatively, Hart et al. (1973) and Missirlis et al. (2004) have utilized an accelerated creep test based on time-temperature superposition (TTS) to determine the long-term creep behavior of geofoams. Instead of the long testing time, TTS utilizes temperatures to accelerate the creep deformation. Creep curves obtained at different temperatures can then be shifted along the log time axis to generate a creep master curve at a lower reference temperature.

Recently, the stepped isothermal method (SIM) was developed to further shorten the testing time using the TTS principle. Furthermore, SIM utilizes single test specimen to avoid material variability. The applicability of SIM on other geosynthetics, such as geogrid, geotextile, and geonet has been well documented, while no study has been performed on geofoams.

In this paper, the compressive creep behavior of an EPS geofoam is evaluated using SIM, TTS, and the long-term method. The resulting creep curves from the three methods are compared. The limitations of the acceleration methods for the EPS geofoam are identified.

2 TEST MATERIAL AND APPARATUS

The density of the EPS geofoam used in this study was 20.33(±0.19) kg/m^3 according to ASTM D1622. The dimension of the specimens was 50 mm cubes.

The compressive tests and accelerated creep tests were performed using an Instron® 5583 with Merlin® software for the load control and the strain measurement. The test temperature was controlled by an environmental chamber. The accuracy of temperature in the chamber was ± 0.5°C.

The long-term creep tests were performed using dead weight loading. The deformation of the specimen was monitored by a dial gage.

3 COMPRESSIVE PROPERTIES

The unconfined axial compressive tests of the EPS geofoam were performed according to ASTM D 1621 at six temperatures from 23°C to 58°C with 7°C increment. Three replicates were tested at each temperature. Stress/strain curves at 23°C are shown in Figure 1. The compressive strength of the EPS geofoam is determined at 10% strain (Stark et al. 2004). At test temperature of 23°C, the average compressive strength is 104.7 (± 2.8) kPa, which is used to calculate applied stresses for the creep tests. The effect of temperature on the compressive strength can be seen in Figure 2. The compressive strength decreases as temperature increases. A bi-linear relationship is observed, from 23°C to 44°C and from 44°C to 58°C.

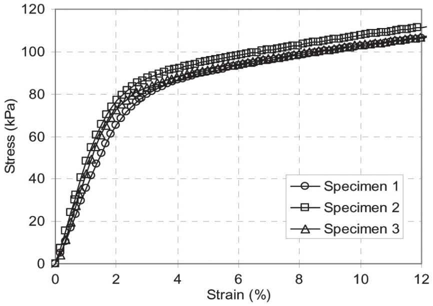

Figure 1.

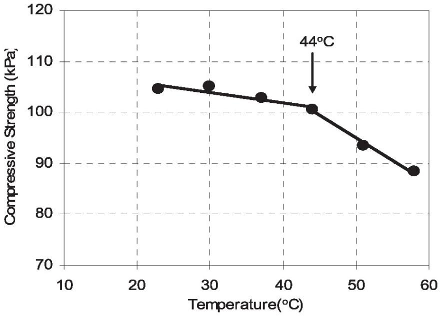

Figure 2. Compressive strengths at reference and elevated temperatures.

4 CREEP TEST PROCEDURES AND TEST DATA

The SIM test was performed according to ASTM D 6992. The test specimen was brought to equilibrium at 23°C for overnight. Prior to starting the test, a pre-stress of three percent of the compressive strength was applied on the specimen to ensure of the intimate surface contact. The desired applied stress was reached at a strain rate of 10% of the gauge length. Applied stresses of 20% and 40% of compressive strength were tested. The test specimen was exposed to six isothermal steps from 23°C to 58°C with increment of 7°C. The dwell time at each temperature was 10^4 seconds. Thus, the test specimen accumulated the strain from each isothermal step. The test data of SIM under 20% of compressive strength is shown in Figure 3(a).

For the short-term TTS test, test specimens were maintained in the environmental chamber at the test temperature for three hours prior to the loading. Test temperatures of 23°C, 33°C, 43°C, 53°C, and 63°C were used and the duration at each temperature was 10^4 seconds. New specimen was used at each temperature. Stress levels of 20% and 40% of compressive strength were tested. The test data of

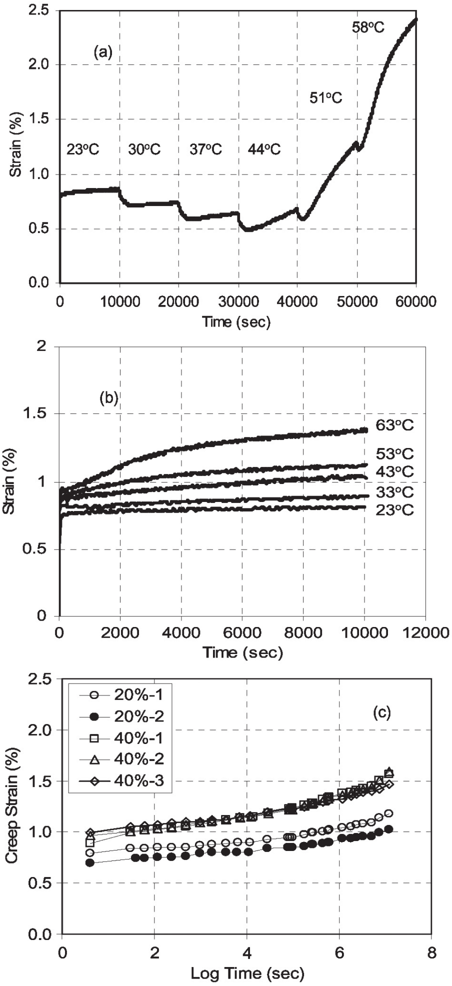

Figure 3. Test data of (a) SIM and (b) TTS tests at 20% stress, and (c) long-term test at 20% and 40% stresses.

TTS under 20% of compressive strength is shown in Figure 3(b).

For the long-term creep test, the test specimen was brought to equilibrium at 23°C for overnight. The dead weight was applied to the specimen. Two and three replicates were tested under 20% and 40% of compressive strength, respectively. The test data of the long-term method is shown in Figure 3(c).

5 TEST RESULTS AND DATA ANALYSIS

The resulting creep properties of the EPS geofoam using SIM, short-term TTS, and the long-term method are shown in Figure 4. The procedure to generate creep master curve in SIM is well described in ASTM D6992. For the short-term TTS test, horizontal shifting of the curves was employed to generate the creep master curve.

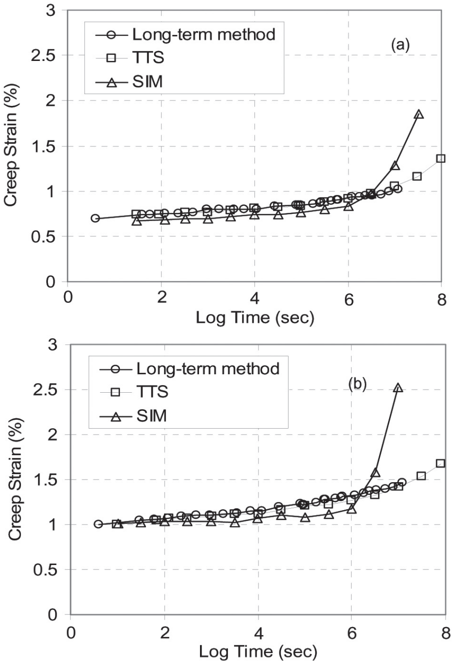

Figure 4. Comparing creep properties using three methods at (a) 20% and (b) 40% stresses.

As expected, creep strain increases with time and stress level. At both applied stresses, the results of the SIM tests exhibit exponentially increase in creep strain after 10^6 seconds; while such increase is not detected in the short-term TTS and the long-term tests. The creep behavior from short-term TTS and the long-term tests are very similar within $10^{7.2}$ seconds (~180 days).

6 DISCUSSION

6.1 *Creep Mechanism from Short-Term TTS Test*

The creep mechanism of the short-term TTS test is investigated using the activation energy. As shown in Figure 5, the activation energy is obtained by plotting the horizontal shift factor against reciprocal test temperatures based on the Arrhenius equation, Eq. 1:

$$a_T = A \exp\left(\frac{-E}{RT}\right) \qquad \text{(Eq. 1)}$$

where, a_T = the horizontal shift factor, A = the constant, E = the activation energy for the creep deformation (kJ/mol), R = the gas constant (kJ/mol·K), T = test temperature (K).

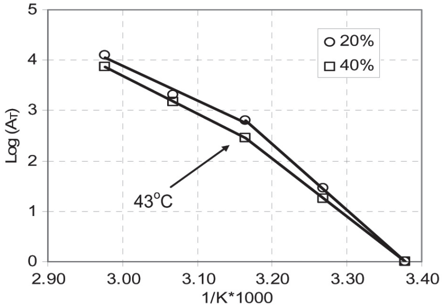

Figure 5. Horizontal shift factors.

At both stress levels, a bi-linear curve with transition temperature at 43°C is obtained. The transition corresponds to the change in compressive strength (see Figure 2). The activation energies are presented in Table 1. At temperature range between 23 and 43°C, the average activation energy is 240 kJ/mol, while a lower value is obtained at temperature from 43 to 63°C. The change in the activation energy at 43°C indicates different creep mechanisms between the two testing temperature ranges. At temperature below 50°C, Hart et al. (1973) found an activation energy of 239.4 kJ/mol for extruded polystyrene (XPS) and Missirlis et al. (2004) measured an activation energy of 202 kJ/mol for the EPS geofoam using TTS with dwell time of 10^3 hours.

Table 1. Activation energy of short-term TTS tests.

Temperature(°C)	20% (kJ/mol)	40% (kJ/mol)
23-43	267.8	213.6
43-63	129.2	141.9

6.2 *Temperature effect on creep behavior*

The temperature effect on the compressive strength of the EPS geofoam (see Figure 2) has a direct impact on the results of SIM and short-term TTS tests, since both methods utilize temperature as the acceleration factor. The temperature effect on SIM is reflected by the change of creep stage at 44°C. To illustrate different creep stages, data of the creep tests under 20% of compressive strength are presented in Sherby-Dorn plots, as shown in Figure 6. In SIM, the material exhibited a secondary creep stage (the plateau region of the curve) at temperature above 44°C. In contrast, only the primary creep stage is found in the results of short-term TTS and long-term tests.

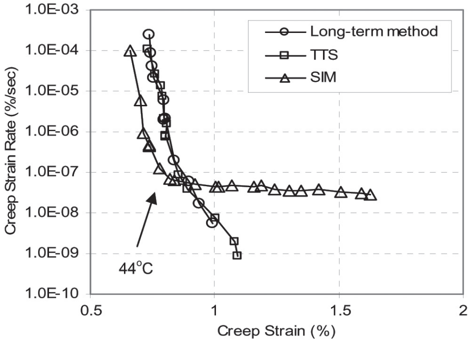

Figure 6. Sherby-Dorn plots for creep results from Figure 4(a).

For short-term TTS, the creep strain rate curve appears overlapping with that of the long-term test in Figure 6; however, different activation energies were obtained below and above 43°C. Thus, the change of creep response at temperature above 43°C limits the full potential of the acceleration tests, significantly shortening the predicted creep behavior.

6.3 *Accumulated strain effect in SIM*

As shown in Figure 6, a transition from primary to secondary creep stage is revealed in the SIM test, while such transition is not observed in the TTS test. The only difference between these two acceleration creep tests is the accumulated strain in the SIM test specimen. It seems that the accumulated strain, in this case, enhances the creep deformation of the test specimen; subsequently underestimates the creep resistance of the material.

7 CONCLUSION

The compressive property and creep behavior of the EPS geofoam with a density of 20.33(±0.19) kg/m^3 were evaluated in this paper. The compressive strength decreased bi-linearly as temperature increased. Above 44°C, the decrease of compressive strength was four times faster. Two acceleration methods (SIM and short-term TTS) and a long-term test were used to determine the creep behavior. For the SIM test, the creep deformation was enhanced by the accumulated strain from the sequence of temperature steps, particularly at temperature steps above 44°C. It is believed that the enhancement in the creep strain led to a premature secondary creep stage. Therefore, the SIM test is not suitable to evaluate the creep behavior of this EPS material. Regarding the short-term TTS test, the creep master curve was similar to that of the long-term test at the same applied stress. However, a change in the activation energy was observed at temperature above 43°C; thus, the portion of the creep master curve generated from TTS tests at temperature above 43°C is questionable. In conclusion, caution must be applied in the application of acceleration creep tests.

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