COMPRESSIVE BEHAVIOUR OF EPS GEOFOAM AT ELEVATED TEMPERATURES

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ABSTRACT

Monotonic triaxial compression tests as well as uniaxial creep tests were undertaken to investigate the compressive behavior of EPS geofoam at room and elevated temperatures. Relationships relating the following properties: compressive strength, yield stress, initial Young's modulus and the plastic tangent Young's modulus of EPS geofoam with the confining pressure and temperature have been established. These relationships are valid for the operating ranges of the confining pressure (0-20 kPa) and temperature (23 - 45°C). A sherby-dorn plot of strain versus the rate of creep strain based on 14-months creep data is presented. An attempt is also made to establish a creep model for the EPS geofoam based on visco-elastic concepts.

Keywords: geofoam, compression test, elevated temperatures, creep, triaxial test, visco-elastic

1. INTRODUCTION

Large parts of the world, including Australia, commonly experience temperature environments that rise above 40°C. In order to establish a more rigorous understanding of temperature effects on the material especially at elevated temperatures, an investigation involving a series of temperature controlled compression tests was carried out. Data gathered from the tests are used to assess temperature effects on the compressive strength, yied stress, initial Young's modulus, plastic tangent Young's modulus and intrinsic creep behavior of EPS geofoam. These results add to a body of technical data relevant in the geotechnical application of EPS geofoam. Relationships have also been established to quantify the consequences of confining pressure on the above properties of EPS geofoam, where appropriate. A Sherby-Dorn plot (strain versus rate of creep strain) is produced based on 14-months creep data was produced and rheological visco-elastic models of creep behaviour established, the latter to show that the application of such models give a good fit between the predicted and measured creep data of EPS geofoam.

2. TEST PROGRAM

2.1 Test Conditions and Specimen

The compressive behaviour of EPS geofoam at elevated temperature was investigated through a series of monotonic undrained triaxial compression and uniaxial compression creep tests. The series of compressive tests were conducted in a temperature range spanning +23 and +45°C. Room temperature in this context is considered to be 23°C - 25°C.

All specimens used in the testing program of this paper were prepared from material supplied by RMAX Rigid Cellular Plastics, an Australian manufacturer of EPS foam. Only EPS specimens with a nominal density of 20kg/m^3

were used in the investigation.

The standard cylindrical specimen was cut from a cylindrical EPS prism of 50mm diameter supplied by RMAX, and the ratio of the specimen height to diameter was 1:1. A 2:1 (height:diameter) aspect ratio was not adopted because signs of buckling were observed in some EPS specimens of this aspect ratio following yielding. Since an aspect ratio of 2:1 ratio (2:5:1 for rock) has often been recommended to minimise end effects, the authors performed a comparative study to assess the significance of end effects in the EPS specimens. The test results revealed that the 2:1 and 1:1 specimens produced virtually identical strength and elastic moduli values. Hence it would appear that the end effects in both types of specimens were not significantly different and a 1:1 specimen should not give rise to greater end effect problems.

2.2 Temperature-Controlled Triaxial Compression Test

As stated earlier, a series of temperature-controlled triaxial tests was performed in the temperature range 23°C (room temperature) to 45°C. Elevated temperature conditions above room temperature were realized by setting up the test apparatus in a Thermoline oven (Figure 1). The oven temperature was digitally set by means of the 3 term P.I.D. temperature controls and a safety thermostat adjusted to the maximum safe allowable temperature. Figure 2 shows the schematic diagram of the test system and the various components in the system are described below.

A 50kN TRITECH digital loading frame designed for undrained or drained triaxial test of soil specimens up to 100 mm diameter for compression or CBR tests by conventional means was used to provide the loading. The loading speed can be adjusted to range 0.0 to 6.0 mm per min, however, in this series of test a speed of 5 mm/min was adopted. The platen speed rate was set through a precise thumb wheel selector with an accuracy controlled to better than 1% (Wykeham Farrance 1995). The loading frame was wired up for control by the digital computer.

The test specimen was set up inside a Wykeham Farrance triaxial cell (WF 10201), which can withstand internal pressure up to 1700kPa. The readings of applied load, the vertical displacements and the temperature during the tests were recorded automatically by a load cell, an LVDT transducer and a temperature sensor respectively via the A/D converter and the digital computer. The measurement resolutions of the load cell and the LVDT are 1 Newton and 0.01mm respectively.

A GDS digit pressure/volume controller accurate to pressure/volume measurement of 1 kPa/1 mm^3 was used to control the cell (confining) pressure constant at a pre-set value and to measure any volume change in the cell fluid during the test. The recorded volume change is the sum total of the displaced fluid due to the loading plunger and the volume change in the specimen itself as it is loaded axially. The volume change in the specimen was determined by subtracting the displaced fluid due to the loading plunger from the total volume change reading recorded by the controller. Unlike the tests carried out by previous investigators (e..g. Preber *et al*. 1994), the triaxial tests in the present investigation were carried out at a lower range of confining pressure (0 to 20kPa, at increments of 5 kPa).

2.3 Uniaxial Creep Test

A series of creep tests was also carried out in the laboratory to study intrinsic time-dependent behaviour under a compressive loading. These tests were carried out at room temperature and at 40°C, the latter in order to examine the creep response of EPS geofoam under temperature conditions normally experienced in warmer parts of the world.

The creep test at 40°C was also set up in an oven using a slightly different arrangement shown in Figure 3. Cast-iron weights were used to apply the dead loads resting on a top cap while ensuring that the load was evenly distributed over the area of the test specimen. A dial gauge was securely fixed to a stand and was positioned to measure the displacement of the center of the top cap. The EPS specimen was set inside a smooth steel casing which is capped at the bottom to avoid overbalancing the weights.

The EPS specimens in the creep test were subjected to compressive loading for a range of vertical stresses: 30, 40, 50 kPa. It may be noted that at room temperature and at 40°C, stress values 20 to 60 kPa are considered to be within the elastic range of EPS geofoam of this density.

Displacement readings were taken at the following time intervals after the start of the loading: 0.25, 0.5, 1, 2, 4, 8, 16, 30, 60 minutes, then every hour for four hours, every day for the first ten days, then every three to four days till 90 days. After that, a reading was taken every 15 days or when there was a significant change in displacement. The strain reading at 0.25 minutes was regarded as the immediate strain. The details of the creep test program are tabulated in Table 2.

3. TEST RESULTS

3.1 Definitions

Figure 4 shows typical a stress – strain response in undrained triaxial tests. The stress-strain curves are typically bilinear. For the sake of completeness and to avoid any ambiguity in the definitions, the measured properties - compressive strength, initial and plastic tangent Young's modulus, and yielding stress are illustrated in Figure 4, and defined below. These definitions follow from Horvath (1995) and Preber *et al*. (1994).

Compressive strength, s_c. The compressive stress or deviator stress (in triaxial tests) measured at a 10% axial strain, which corresponds approximately to the end of the yielding range.

Initial tangent Young's modulus, E_i. The slope of the initial linear-elastic portion of the stress-strain curve.

Plastic tangent Young's modulus, E_p. The slope of the post-yielding linear portion of the stress-strain curve.

Yielding stress, s_y. The yielding stress is determined graphically by forward extrapolation of the initial linear portion and backward extrapolation of the post-yield linear portion of the stress-strain curve. The stress at which the two extrapolated lines cross is defined as the yielding stress.

3.3 Triaxial Compression Test Results

It is can be deduced from the experimental data that the initial and post-yielding slopes of the stress-strain curves decrease with temperature, albeit marginally. With rising temperature, the yield stress and the compressive strength of the EPS geofoam are also found to decrease. Further elaboration is contained in the discussion below.

The dependency of each of the above properties in terms of the confining pressure (s_3) and the temperature (T) is deduced (e.g. $s_c(s_3, T)$). Figure 5 shows the relationship between compressive strength and confining pressure at the temperature levels T = 23, 35 and 45°C). The following relationship was established:

$$s_c = (-0.00521T + 0.305)s_3 - 0.4088T + 105.7 \tag{1}$$

where s_c, s_3 are in kPa and T is in °C. The results indicated that compressive strength has a relatively low dependency on the confining pressure, increasing approximately for instance from 91.4 kPa at s_3 = 0 to 93.8 kPa at s_3 = 20 kPa, T = 35°C or at an approximate rate of 0.12 kPa per kPa increment. The compressive strength also decreases approximately linearly with increasing temperature, for example, decreasing from 98.1 kPa at room temperature and s_3 = 10 kPa to 88.0 kPa at 45°C and at the same confining pressure or a decrement rate of 0.46 kPa per degree Celsius.

The plot of the yield stress s_y against the confining pressure s_3 at various temperatures is shown in Figure 6. The results show that dependency of the yield stress on the confining pressure is negligible and quite inconsistent. It appears that the yield stress increases marginally with confining stress at room temperature and 45°C, yet it decreases marginally with confining stress at 35°C. The dependency of the yield stress on temperature was thus established without consideration of the confining stress, this yielding the relationship:

$$s_y = -0.074T + 83.2 \tag{2}$$

where s_y is in kPa and T is in degree Celsius. This relationship shows that the yield stress decreases at a rate of 0.074 kPa per degree Celsius increase in temperature.

Shown in Figure 7 is the plot of the initial Young's modulus (E_I) against the confining pressure at various temperature levels. The following relationship has been established:

$$E_i = (-0.00047T + 0.024473)s_3 - 0.00035T + 4.26 \tag{3}$$

where E_i is in GPa, T is in degree Celsius and s_3 in kPa. Equation (3) demonstrates the inverse relationship between the initial modulus and the temperature. It also shows that temperature has only a very small effect on the initial Young's modulus. For example, it decreases from 4.39 GPa, s_3 = 10 kPa at room temperature to 4.28 GPa at the same confining pressure and 45°C or a decrement of 0.15% per 1°C rise in temperature. The effect of the confining pressure is also small as evidenced by the small increase in E_i from 4.25 GPa, at no confining pressure, 35°C to 4.40 at s_3 = 20 kPa at the same temperature.

Finally, Figure 8 plots the plastic tangent Young's modulus (E_p) against the confining pressure at three different levels of temperature. The dependency of E_p on confining pressure is inconsistent and appears to be inconsequential. Thus the relationship is established between E_p and temperature only, which leads to the following relationship:

$$E_p = -0.8192T + 145.9 \tag{4}$$

where E_p is in GPa, T is in degree Celsius and s_3 in kPa. The dependency of E_p on temperature is apparent in equation (4) as seen by the rate of decrement of 0.8192 GPa per degree Celsius increase in temperature.

3.4 Creep Test Results

The time-dependent deformation of EPS geofoam under the application of loading can be represented generally by two separate parts: the immediate deformation and the intrinsic time-dependent response. Thus the total strain of a specimen under a given load can be written as:

$$e = e_0 + e_c(t) \tag{5}$$

where e is total strain at time t after a stress application, e_0 is the immediate strain upon a stress application, $e_c(t)$ is the creep strain at elapsed time t.

Figure 9 plots the total strain rate on a log scale against the creep strain on a normal scale (Sherby-Dorn plot) for stress levels 30-50 kPa and temperature levels 23 and 40°C. In a Sherby-Dorn plot, a stress level would be considered to be stable in the long term if the strain rate decreases with time and to be long term unstable if the strain rate increases with time. A transitional state would be between the stable and unstable where the strain rate will be constant with time (Horvath, 1995).

The 14-months data appears to show that the EPS geofoam at stress levels 30 and 40 kPa is still in the primary stage of creep, at both room temperature and 40°C. At 50 kPa however, the material appears to have passed through the primary creep stage into the secondary creep stage during the 14 months of test. A comparison of any corresponding sets of test data at room temperature and 40°C shows very clearly that an increase in temperature significantly increases the creep strain response of EPS geofoam. This is exemplified by secondary creep strain rate recorded at 50 kPa stress level, which showed an increase from approximately 1 x 10^{-6} %/min at room temperature to

1 x 10^{-5} %/min at 40°C, i.e. an increase by about an order. Based on these results, it is seen that the secondary creep rate increased approximately by a massive 60% for every 1°C rise in temperature above room temperature.

An attempt was made to describe the creep behavior of EPS geofoam based on concepts of rheological visco-elastic model. In a visco-elastic model, the component parts of the strain are given by (Findley et al., 1976),

$$e_0(t) = s(t) J_0 \tag{6a}$$

$$e_c(t) = \int_0^t J_c(t - t) \frac{\partial s(t)}{\partial t} dt \tag{6b}$$

where J_0 is the immediate elastic strain compliance , $J_c(t)$ is the kernel of the creep strain compliance corresponding to the chosen visco-elastic model and $s(t)$ is the applied stress. A modified 4-element model is chosen, this having the immediate elastic strain compliance and creep strain compliance as follows,

$$J_0 = \frac{1}{E_1} \tag{7a}$$

$$J_c(t) = \frac{t^n}{h_1} + \frac{1}{E_2}\left(1 - e^{-\frac{E_2}{h_2}t}\right) \tag{7b}$$

The modified 4-elements model (which allows the strain response to asymptote to a power curve) is shown giving a good fit with the measured data in Figure 10 for stress level = 50 kPa. The model gives the best fit among the 3 models examined: 3-elements, 4-elements (Burger's model) and the modified 4-elements models.

4. SUMMARY

Triaxial compression and uniaxial creep tests were carried out on EPS geofoam specimens in the elevated temperature range above the room temperature. The following were observations were made:

1. In a triaxial loading condition, the influence of confining pressure (0 to 20 kPa) on the EPS geofoam behaviour is very small in the temperature range +23°C to 45°C. In the series of test, the compressive strength and the initial Young;s modulus was found to have a small dependency on the confining pressure in the stated temperature range. Relationships of the compressive strength and the initial Young's modulus as functions of the confining pressure and the temperature have been established.
2. The series of tests have produced somewhat inconclusive results relating the dependency of the yield stress and the plastic modulus of EPS geofoam on the confining pressure. Relationships of the yield stress and the plastic modulus as functions of the temperature have been established.
3. Creep test shows that a rise in temperature will lead to an acceleration of the rate of creep strain. This is exemplified by the increase in the secondary creep rate from 1 x 10^{-6} %/min at room temperature to 1 x 10^{-5} %/min at 40°C under an applied stress of 50 kPa. This represents an approximate increase in the secondary creep rate by a massive 60% for every 1°C rise in temperature above room temperature.
4. A Sherby-Dorn plot of creep in EPS geofoam based on 14-months test data is presented. The creep data suggests that EPS geofoam can be modelled as a visco-elastic material in the range of the applied stress and temperature considered in this investigation.

5. REFERENCES

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Horvath, J.S. (1995), Geofoam Geosynthetic, Horvath Engineering, P.C., Scarsdale, N.Y., USA, 217 pp.
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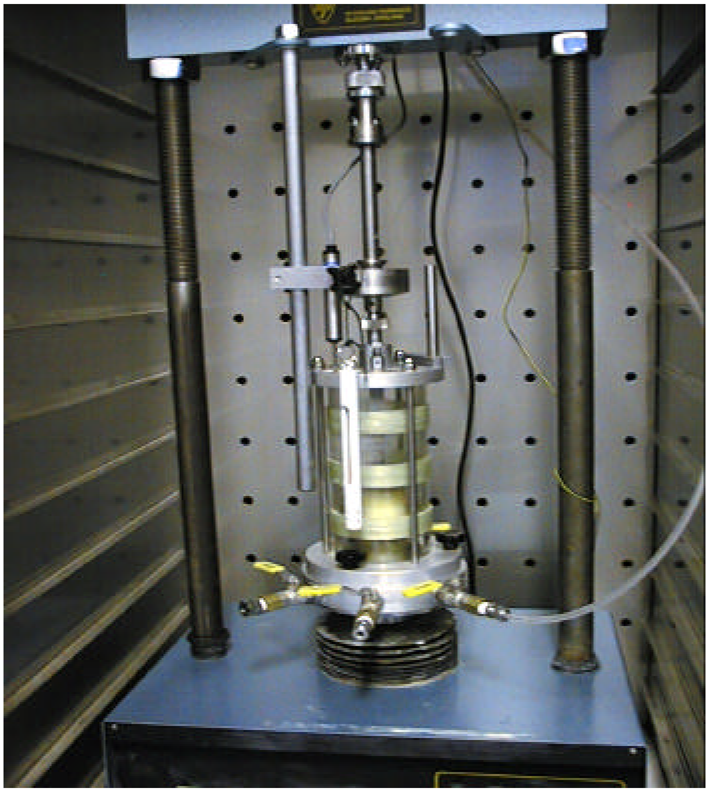

Figure 1 Set up of triaxial test in oven

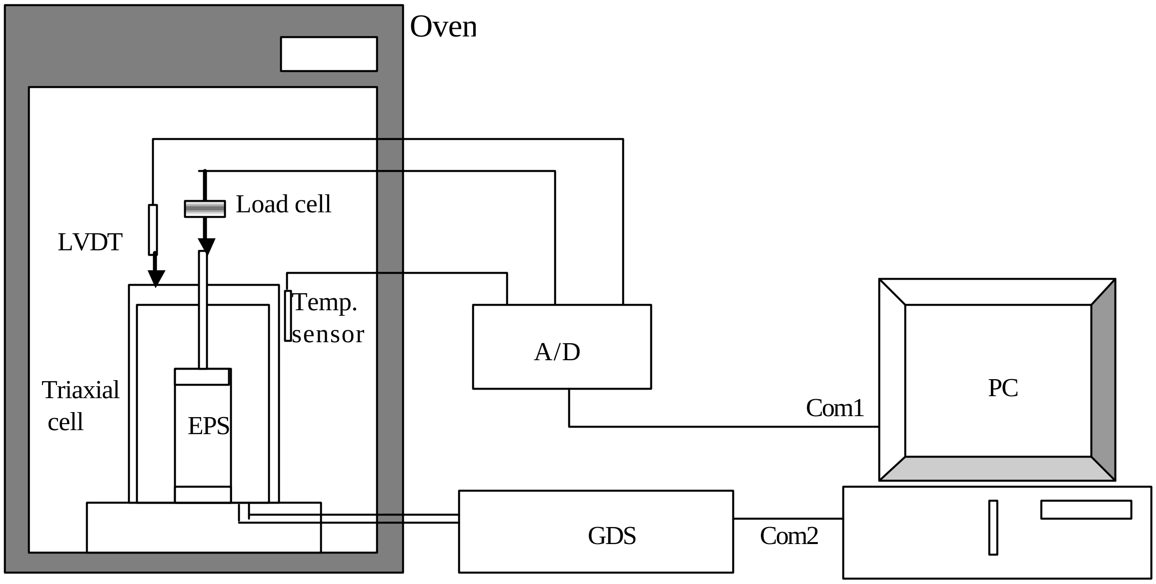

Figure 2 Temperature controlled triaxial test system

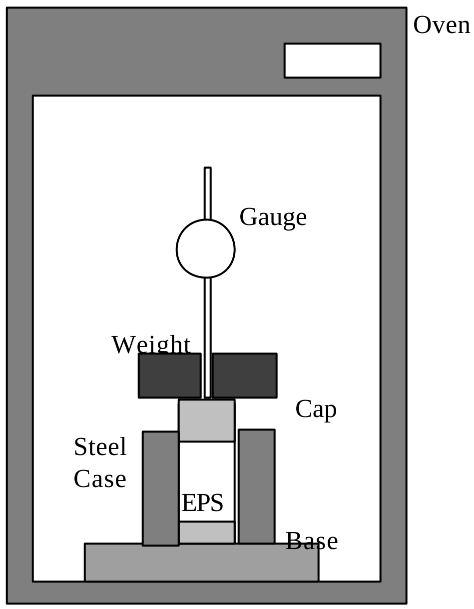

Figure 3 Set up of temperature controlled creep test

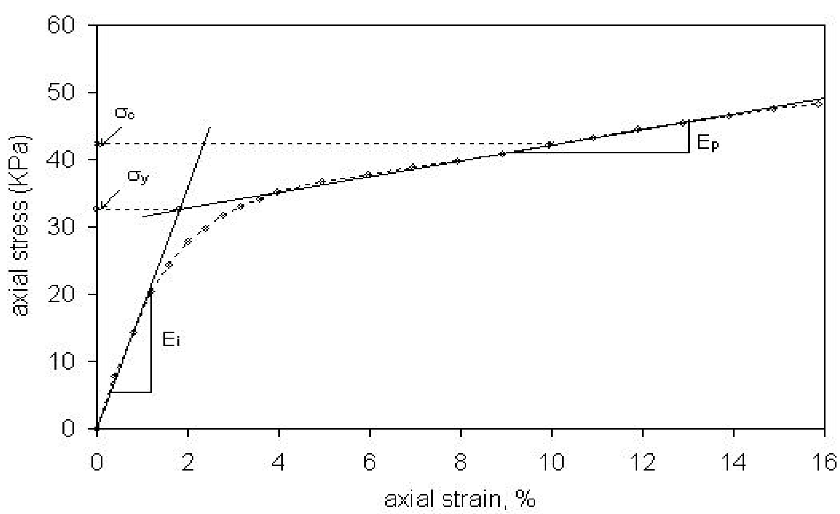

Figure 4 Definition of Parameters

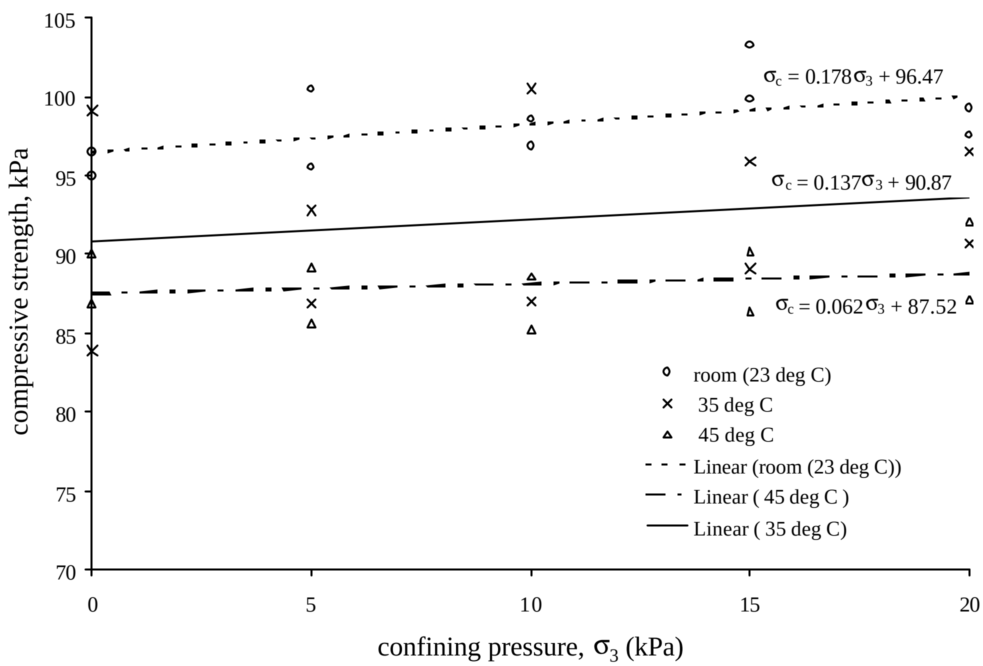

Figure 5. Compressive strength vs confining pressure at different temperature levels

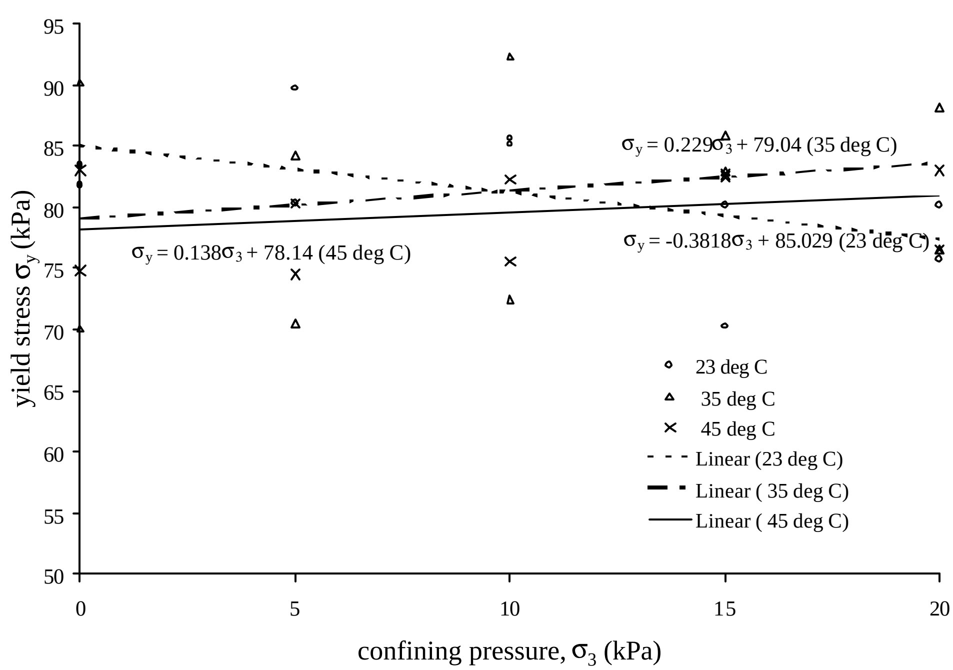

Figure 6. Yield stress vs confining pressure at different temperature levels

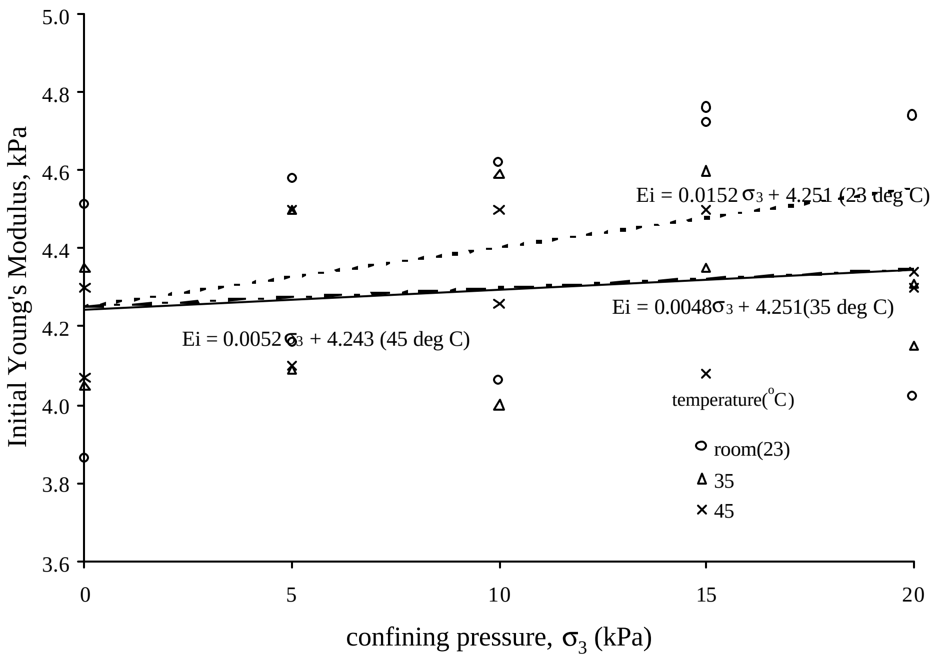

Figure 7. Initial Young’s modulus vs confining pressure at different temperature levels

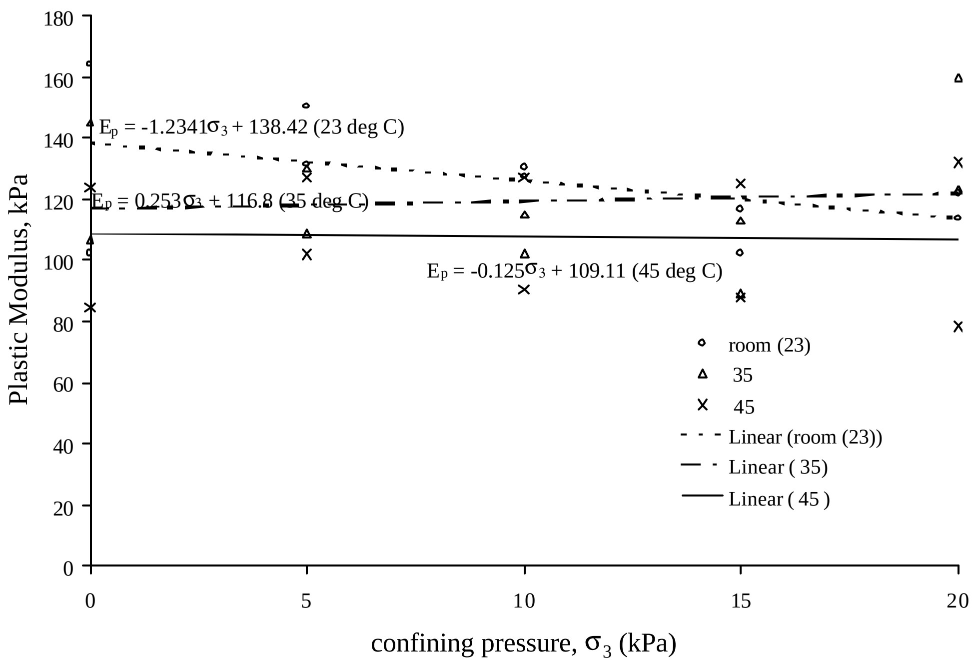

Figure 8. Plastic Young's modulus vs confining pressure at different temperature levels

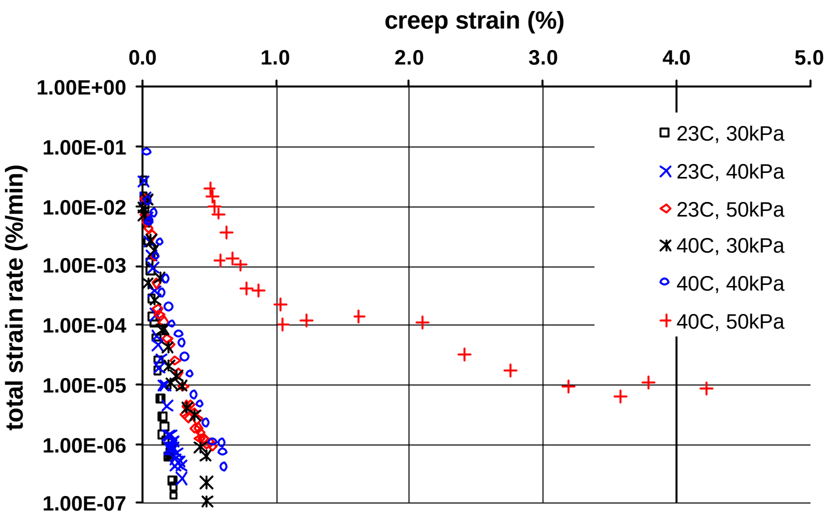

Figure 9. Sherby-Dorn plot for EPS geofoam

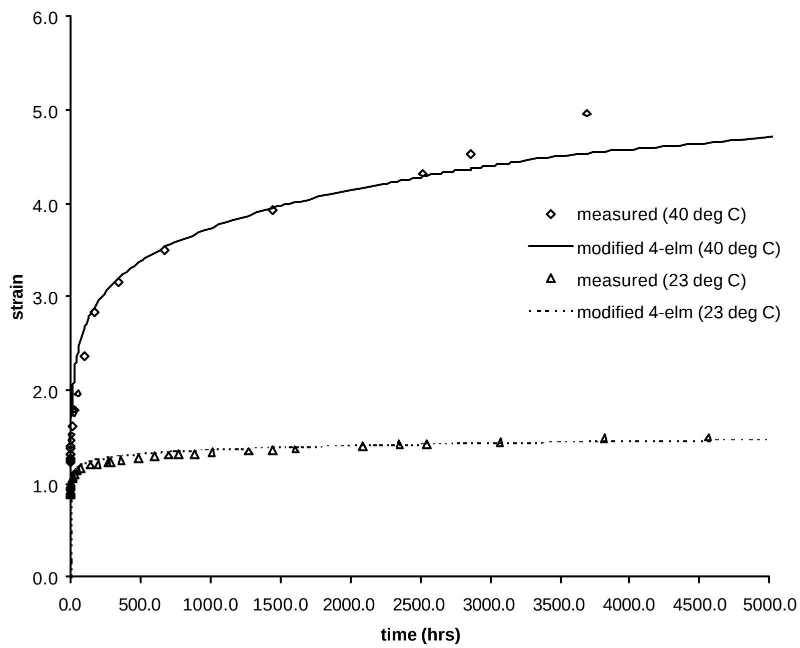

Figure 10. Predicted (modified 4-elements model) vs measured creep