COMPRESSIVE CREEP BEHAVIOR OF EPS GEOFOAM

E. G. Missirlis
Dept. of Civil Engineering, University of Patras, Greece

D. K. Atmatzidis
Dept. of Civil Engineering, University of Patras, Greece

D. A. Chrysikos
Dept. of Civil Engineering, University of Patras, Greece

ABSTRACT: The time-temperature superposition principle was applied to investigate the compressive creep behavior of expanded polystyrene (EPS) geofoam. Cylindrical samples, 100mm in diameter and 200mm in height, were obtained from commercially produced blocks with nominal density of 10, 15, 20, 25, 30 and 35 kg/m^3. Tests were conducted in a controlled temperature – humidity chamber at relative humidity equal to 65% and temperatures of 20, 30, 40 and 50^{o}C. Each test had a duration of up to 3 months. Axial loads were applied to produce three different levels of initial axial strain (0.25, 0.50 and 0.75%) covering the range of elastic behavior of EPS geofoam in monotonic loading. Data were combined to yield creep curves covering a time span of over 100 years at the reference temperature of 20^{o}C. The validity of the time-temperature superposition principle for EPS geofoam was verified using the Arrhenius equation. A constitutive relation was obtained describing the linear viscoelastic response of EPS geofoam for normal stress values lower than 30% of the compressive strength or for initial axial strains less than 0.5%.

1 INTRODUCTION

Expanded polystyrene (EPS geofoam) products in the form of blocks are utilized for the construction of a variety of projects as light-weight material or compressible inclusion. For the design of structures where volumes of EPS geofoam are incorporated, it is necessary to have appropriate information for the behavior of EPS geofoam in compression. Most of the required design parameters are obtained from unconfined compression tests which yield values for the initial modulus of elasticity, E_i (slope of the initial linear segment of the stress-strain curve), the compressive strength, σ_{c10} (usually defined as the axial stress at 10% axial strain) and the yield stress, σ_y (point of intersection of the initial linear segment and the post-yield linear segment of the stress-strain curve). Furthermore, it is frequently necessary to obtain Poisson ratio values, to establish the elastic limit, to describe the behavior of EPS geofoam in compressive creep and to define a deformation or stress limit beyond which undesirable creep effects may appear.

Previous experimental investigations of the compressive creep behavior of EPS geofoam have resulted in design rules or criteria for avoiding the adverse effects of deformation due to creep (Horvath 1995, Duskov 1997, AIPE 1997, Srirajan et al. 2001) and in constitutive relations between applied normal stress, axial strain and time (Magnan and Serratrice 1990, Horvath 1998, Srirajan et al. 2001). As a general rule, it is suggested that compressive creep strain of EPS geofoam will be negligible if the applied normal stress is less than 25% of the compressive strength, σ_{c10}, or if the initial axial strain is less than 0.5%. For applied normal stresses larger than 50% of the compressive strength, creep strain is expected to be significant and to have adverse effects on the safety or the function of a structure. Intermediate normal stress levels will yield creep strain which may be tolerated by the structure.

The constitutive relations proposed to describe compressive creep behavior of EPS geofoam are in the form of power-law equations with parameters mathematically related to material properties in order to match the observed behavior. The creep tests conducted had different durations. Horvath (1998) reported the maximum duration of 10000 hours or, approximately, 14 months. The proposed relations do not correspond to a physical or theoretical model of material behavior and are not in agreement in terms of predictive capabilities. Frydenlund and Aaboe (1996) and Duskov (1997) have reported results which are in disagreement with the predictions obtained by applying the relations proposed by Magnan and Serratrice (1990) and Horvath (1998). The differences between measured compressive creep behavior may be attributed to the significant dependence of the measured compressive behavior of EPS geofoam on the size and the aspect ratio of the samples tested (Atmatzidis and Missirlis 2001, Elragi et al. 2001). The effects of sample size and creep test duration have also been recognized by the European Committee for Standardization (TC88/CEN 2001). It is specified that EPS geofoam samples should have a size of 300mm x 300mm x d where d is the full thickness of the product and that data extrapolation should be constrained according to the actual duration of the creep tests (4, 10 and 20 month tests can be extrapolated to 10,25 and 50 years, respectively).

The time-temperature superposition principle is referenced by ASTM Standard D6112-Appendix X5 (ASTM 1997) as a method for predicting the long term creep behavior of viscoelastic materials. According to this method, a number of creep curves are obtained by conducting relatively stort-term tests at different temperatures. These curves are shifted horizontally along a logarithmic time scale to yield a single curve (master curve) covering a large range of time for a selected reference temperature. The authors know only of one case where Hart et al. (1973) applied this method to investigate the creep behavior of extruded polystyrene (XPS) and obtained creep master curves for a temperature of 23^o C covering a time period of 10^6 hours (114 years).

The information presented herein is part or an extensive experimental investigation of the mechanical properties and behavior of commercially produced EPS geofoam blocks. Scope of this presentation is to offer the necessary information which establishes the applicability of the time-temperature superposition principle to the investigation of the creep behavior of EPS geofoam. Applicability of the principle offers two major advantages: it allowes for a constitutive relationship to be obtained according to the behavior of linear viscoelastic materials and negates the need for data extrapolation over an extended time period. Drozdov (1998) has presented the theoretical basis for application of the time-temperature superposition principle to linear viscoelastic materials.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

Commercially produced EPS geofoam blocks measuring 2.5m x 1.0m x 0.5m with nominal densities of 10, 15, 20, 25, 30 and 35kg/m^3 were obtained for the purposes of the investigation reported herein. Samples were obtained from these blocks and were cut and shaped using hot wires. Samples are referred to in this text using the symbol EPS and the nominal density (i.e. EPS 15) although it is recognized that compressive strength is being established as the material parameter to distinguish between EPS geofoam types (TC88/CEN 2001, Frydenlund and Aaboe 2001, Thelberg 2001). Only cylindrical samples were tested with a diameter of 100mm and an aspect ratio of 2. It has been shown (Atmatzidis and Missirlis 2001) that such samples have very similar behavior in uniaxial compression with 500mm cube samples and their behavior is considered representative of the field behavior of the as produced blocks. Presented in Figure 1 are the results obtained from unconfined compression tests. Very good exponential correlations of sample density, ρ, with compressive strength, σ_{c10}, and initial modulus of elasticity, E_i, were obtained.
Creep tests were conducted at four different temperatures and three different initial axial strains. The temperatures applied were 20^{o}C (reference temperature), 30^{o}C, 40^{o}C and 50^{o}C. Results reported by Hart et al. (1973) indicate signs of non-linear response of extruded polystyrene at a

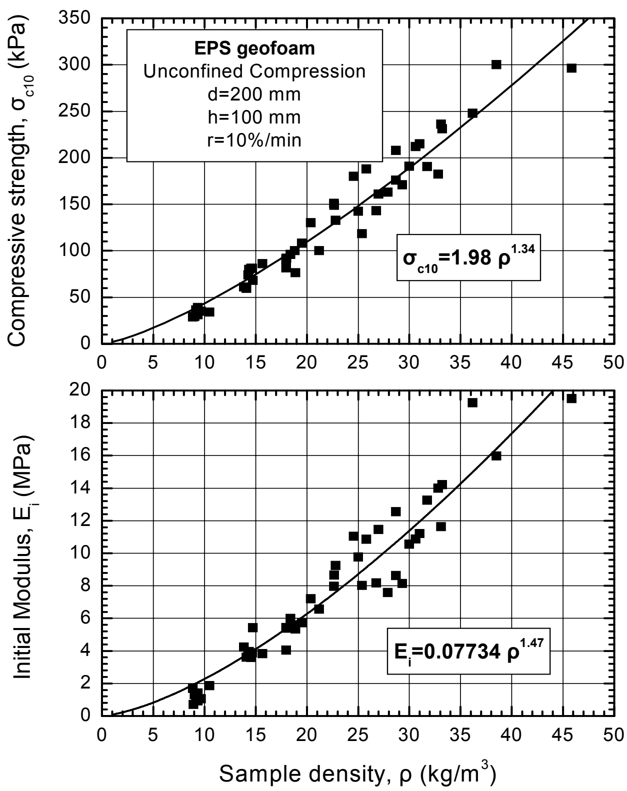

Figure 1 Unconfined compression test results

temperature of 52^{o}C. Accordingly, the temperature of 50^{o}C was set as the upper limit for this investigation. Unconfined compression test results indicated linear elastic behavior of the EPS geofoams for axial strain up to 0.8% and, beyond this limit, yielding at a constant rate. Accordingly, in order to investigate the long-term compressive behavior of the EPS geofoams, three different normal stresses were applied yielding initial axial strains equal to 0.25%, 0.50% and 0.75%.

All creep tests were conducted in a controlled temperature-humidity chamber where up to eighteen samples could be tested simultaneously. The relative humidity was constant and equal to 65%. The samples were placed in loading frames, as shown schematically in Figure 2, and were allowed to remain in the controlled conditions chamber for 48 hours before loading. Dead weights were used to apply the required constant normal stress. Zero time was considered to be the moment that the last load was placed on the sample. Axial displacement was measured using mechanical dial indicators with a resolution of 0.01mm. Each test, at a given temperature and a given initial axial strain, had a duration of up to three months.

3 CREEP TEST RESULTS

The development of axial strain with time was obtained for each creep test using the measured axial displacements and the initial sample height. Typical results of total measured axial strain versus time are presented in Figure 3. It can be observed that (a) initial strains correspond to the expected strains as computed from unconfined compression test results using the expressions shown in Figure 1, (b) the effect of temperature becomes evident after 10min to 100min of testing and (c) creep strains increase as the testing temperature increases. A small number of tests (3 out of 72) were discarded due to sample buckling during the test (see, for example, sample with normal load 10.4kPa at 30^{o}C in Figure 3).
Application of the time-temperature superposition principle requires calculation of the creep compliance or time-dependent modulus, E(t), which is defined as the ratio of the applied normal stress, σ, to the measured time-dependent total axial strain, ε(t). A typical example of the results obtained in terms of creep compliance versus time is presented in Figure 4 (closed symbols) together with a typical example of the application of the time-temperature

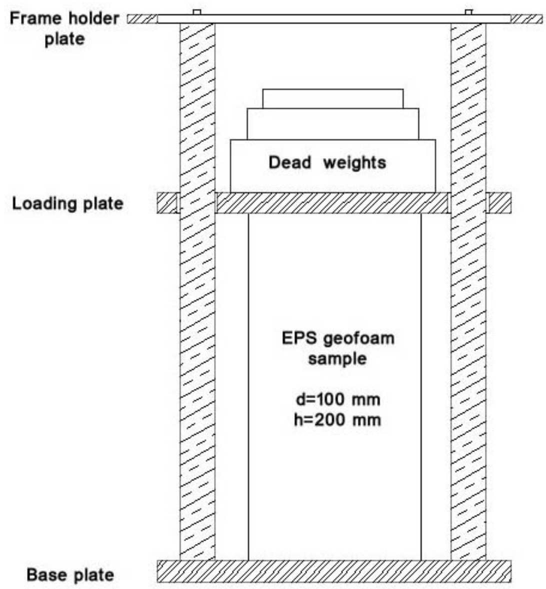

Figure 2 Schematic representation of creep testing frame

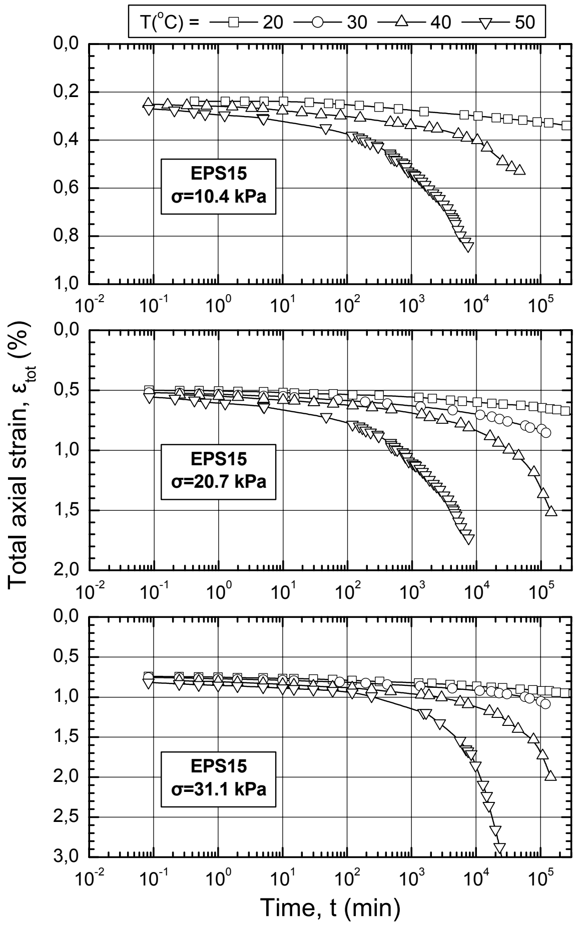

Figure 3 Typical creep test results

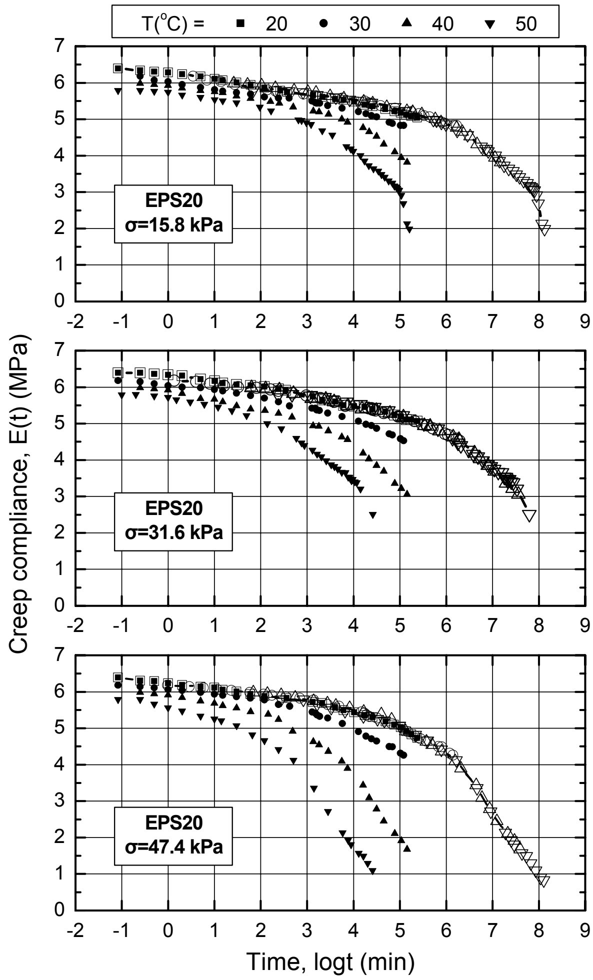

Figure 4 Typical application of the time-temperature superposition principle

superposition principle (open symbols). According to this principle, the data curves obtained at temperatures higher than the reference temperature (20°C) were shifted to the right until an adequate superposition or "match" was obtained between curves of successive temperatures (i.e. 30°C curve to "match" a portion of the 20°C curve). It was observed that the range of superposition between successive curves covered at least two logarithmic cycles on the time scale and was considered adequate for the determination of the exact magnitude of the required shift. As shown in Figure 4, experimental results obtained by testing for 12 months (four different temperatures and three months duration of each test) yielded a master curve for the reference temperature covering at least 100 years. The magnitude of the required shift is equal to log [1/a(T)], where a(T) is defined as the "temperature shift factor". The available data led to the observation that the values of the temperature shift factor are dependent on the test temperature and are not significantly affected by EPS geofoam type (density) or applied normal stress.

According to the principles of the theory of linear viscoelasticity, the values of the temperature shift factor, a(T), should follow the Arrhenius equation (Drozdov 1998):

$$\log a(T) = \frac{\Delta H}{2.303R}\left(\frac{1}{T} - \frac{1}{T_o}\right) \quad (1)$$

where ΔH is the activation enthalpy in kcal/mol/K, R is the universal gas constant (1.987 kcal/mol) and T and T_o are the absolute test and reference temperatures, in K, respectively. The activation enthalpy values for polystyrene range between 43 and 52 kcal/mol/k (Hart et al. 1973). The values obtained for the temperature shift factors were used to prepare the graph shown in Figure 5. According to the Arrhenius equation, the data should form a straight line with slope equal to the activation enthalpy, ΔH. It can be observed that almost all the data obtained from this experimental investigation are included in the zone specified by the range of the activation enthalpy values for polystyrene. A linear fit to the mean values yielded a value for the activation enthalpy equal to 48.10 kcal/mol/k. Accordingly, it can be stated that the time-temperature superposition principle is applicable to EPS geofoam.

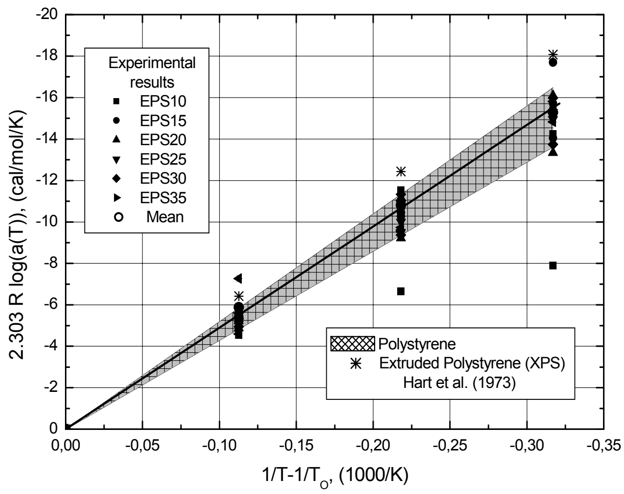

Figure 5 Correlation of creep test data to the Arrhenius equation

The creep compliance master curves derived by the application of the time-temperature superposition principle were used to calculate the development of total axial stain at 20°C. Presented in Figure 6 are the results obtained for all EPS geofoam types tested, in terms of the magnitude of initial strains. It can be observed that the data extend over a time period of more than 100 years and that, generally, creep behavior does not differ significantly according to the type (density) of EPS geofoam.

Using data from Figure 6, isochronous curves can be constructed for each EPS geofoam type tested and conclusions can be drawn regarding the linearity of the viscoelastic response. As an example, such data are presented in Figure 7 for EPS20. It can be observed that for short time periods (until 30 d to 100 d) the response of EPS20 is linear for all values of the applied normal stress. After 180 d, a deviation from linearity is noted for the larger normal stress applied. The same behavior was observed for all EPS geofoam types tested in the present investigation.

4 CONSTITUTIVE RELATIONSHIP

The foregoing results and analysis indicate that, for initial strains 0.25% and 0.50%, EPS geofoams exhibit linear viscoelastic behavior regardless of product type. For the derivation of a constitutive relationship that can model creep behavior in the linear region and can be applied to all types of EPS geofoam, normalized stress-total strain isochronous curves were plotted. The values of normal stress applied to each EPS geofoam sample were normalized in terms of the corresponding compressive strength,

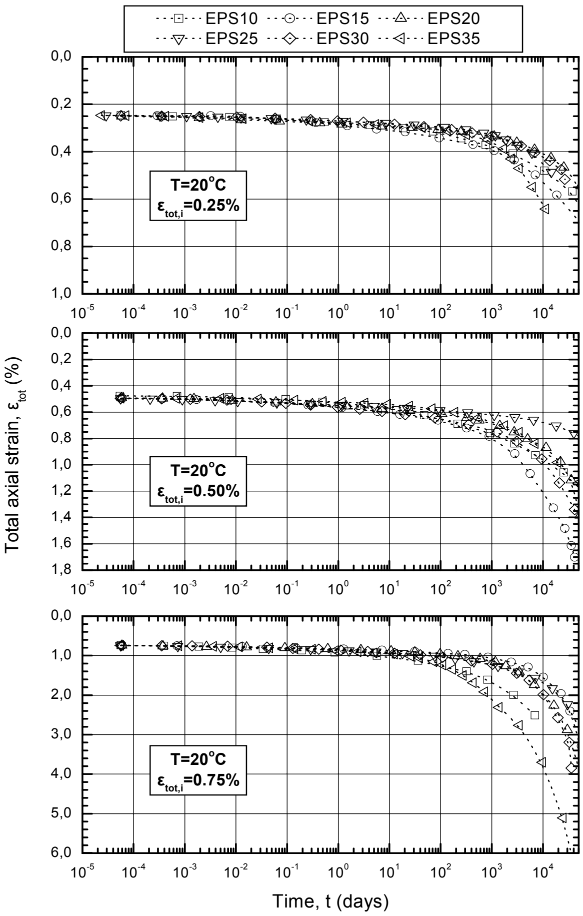

Figure 6 EPS geofoam creep test results

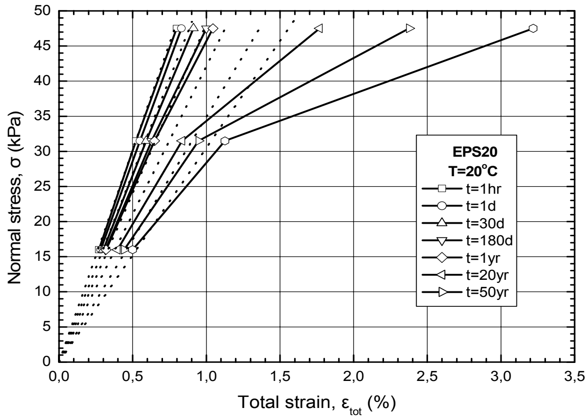

Figure 7 Isochronous stress-strain curves for EPS20

σ_{c10}, which was obtained using the density, ρ, of each sample and the relationship shown in Figure 1. The normalized stress-strain isochronous curves are presented in Figure 8 along with straight lines obtained by linear fitting through the origin of the data which correspond to initial strains equal to 0.25% and 0.50%. The correlation coefficient, R, of these linear fits ranged between 0.836 and 0.985. The straight lines shown in Figure 8 follow the relationship:

$$\frac{\sigma}{\sigma_{c10}} = A(t)\cdot\varepsilon_{tot} \tag{2}$$

where ε_{tot} is the total axial strain (%), σ/σ_{c10} is the normalized stress (%) and A(t) is the slope of each isochronous curve. The values of the time dependent parameter, A(t), are plotted in Figure 9 with respect to time. A perfect correlation was obtained (R^2=0.999) using the following exponential relationship:

$$A(t) = 59.3737 - 5.98193\left(\frac{t}{t_o}\right)^{0.16746} \tag{3}$$

where time, t, is in days and t_o is an appropriate coefficient to convert arbitrary time units to days and yield a nondimensional ratio. By combining Equations 2 and 3, the constitutive relationship that describes the linear viscoelastic creep of EPS geofoam is obtained:

$$\frac{\sigma}{\sigma_{c10}} = \left[59.3737 - 5.98193\cdot\left(\frac{t}{t_o}\right)^{0.16746}\right]\cdot\varepsilon_{tot}$$
$$\frac{\sigma}{\sigma_{c10}} \le 30\% \quad \text{or} \quad \varepsilon_{tot}(t=0) \le 0.50\% \tag{4}$$

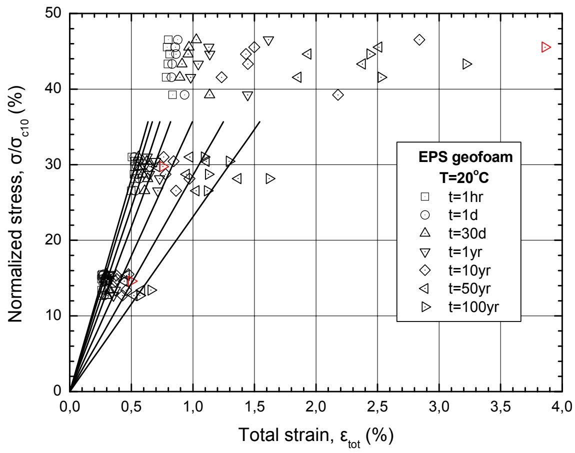

Figure 8 Normalized isochronous stress-strain curves

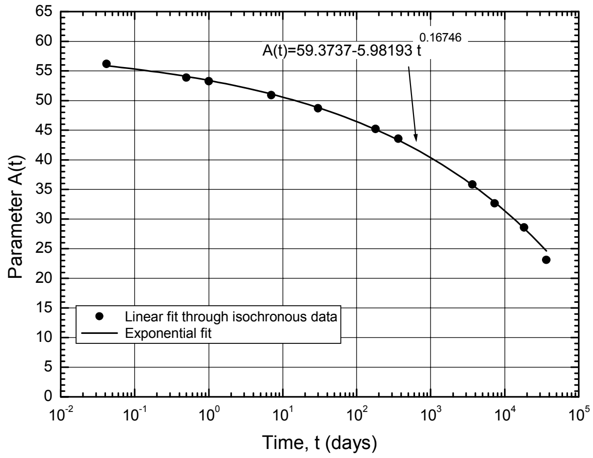

Figure 9 Correlation of parameter A(t) with time

The applicability of Equation 4 is restricted to values of the applied normal stress equal to or lower than 30% of the compressive strength, σ_{c10}, or to initial axial strain equal to or lower than 0.5%. Ongoing research focuses on the refinement of these limits as well as on the development of a relationship describing the non-linear viscoelastic response of EPS geofoam.

It is of interest to note that, if time is set equal to zero, Equation 4 is reduced to:

$$\sigma = \sigma_{c10} \cdot 59.3737 \cdot \varepsilon_{tot} \qquad (5)$$

which implies that the product σ_{c10}·59.3737 represents the initial modulus of elasticity, E_i. The difference between values of the initial modulus of elasticity computed using Equation 5 and obtained through correlations of unconfined compression test results (Figure 1) ranges between –5% and +11%.

The very good agreement of predictions made using Equation 4 to creep test results for initial strain levels of 0.25% and 0.50% is shown in Figure 10. It was computed that predictions according to Equation 4 differ from the mean value of the experimental results for initial strains equal to 0.25% and 0.50% by not more than 4.5%. However, for initial strain equal to 0.75%, the difference between predictions and experimental results increases with time from an average of –4% at 180 days to an average of –40% at 100 years, indicating strong deviation from linear viscoelastic response.

5 COMPARISON WITH AVAILABLE CONSTITUTIVE RELATIONS

Presented in Figure 11 are predictions made using Equation 4 as well as predictions made using the constitutive relations proposed by other researchers. All predictions were made for EPS20 geofoam under an applied normal stress equal to 30 kPa. In order to apply Equation 4, the compressive strength, σ_{c10}, was computed using the correlation shown in Figure 1 and was set equal to 110 kPa. It can be observed that the predictions made using Equation 4 are in good agreement with the predictions made using the relations proposed by Magnan and Serratrice (1990) and Srirajan et al. (2001) for the first 100 hours and, subsequently, deviate gradually toward the predictions made using the relations proposed by Horvath (1998). The observed differences in terms of the initial axial strains, which range between 0.44% and 0.70%, can be attributed to the effects of sample size and aspect ratio on the observed behavior of EPS geofoam in uniaxial compression (Atmatzidis and Missirlis 2001, Elragi et. al. 2001).

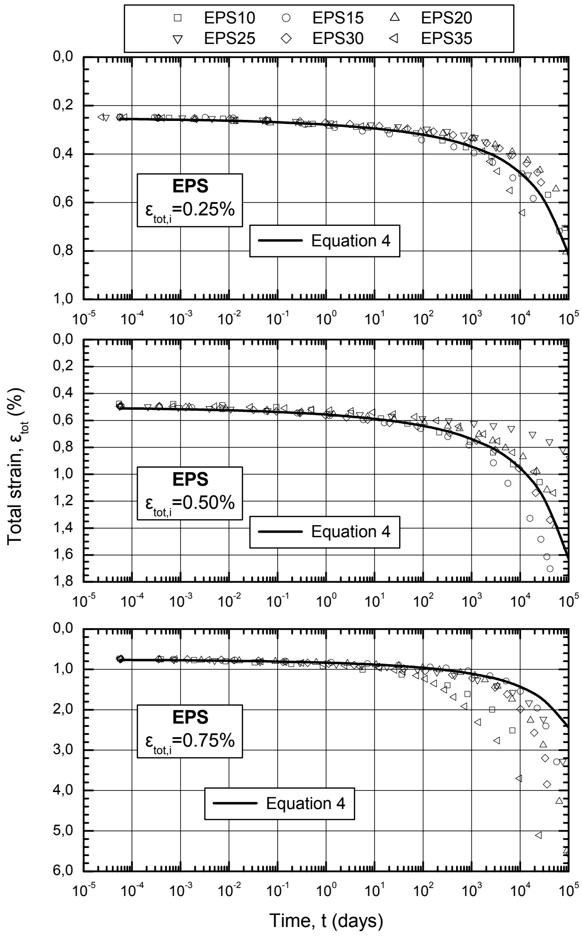

Figure 10 Comparison of predictions and experimental results

It is of interest to note that the existing constitutive relations were obtained from experimental data (creep tests) with variable duration. The tests by Magnan and Serratrice (1990) did not exceed 500 hours (21 days). Horvath (1998) utilized data from tests with a duration of 10000 hours (1.14 years). Srirajan et al. (2001) presented a relationship based on two-month long tests (1440 hours). If the curves shown in Figure 11 are displaced vertically so that they all have the same starting point (in order to exclude the effects of sample size and aspect ratio) it becomes apparent that the predictions made using Equation

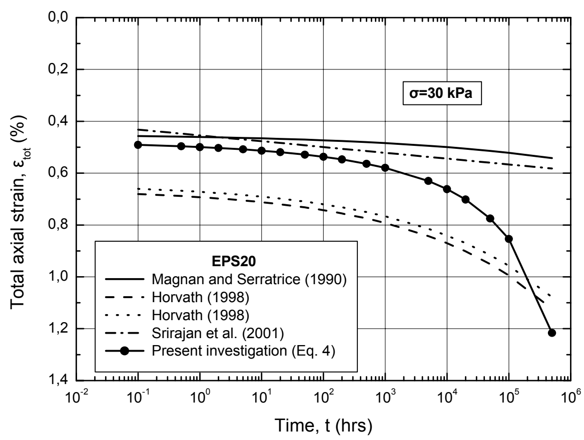

Figure 11 Comparison with published constitutive relations

4 are in very good agreement with the predictions made using available constitutive relations for the time span covering the actual testing time allowed (anywhere between 500 and 10000 hours). Accordingly, the observed differences for longer periods of time can be attributed to the need for mathematical extrapolation of the available data. In contrast, the approach taken by the investigation reported herein, provides a constitutive relation which is based on the principles of linear viscoelastic behavior and utilizes data covering a minimum time span of 100 years by employing the time-temperature superposition principle.

6 CONCLUSIONS

Based on the experimental results, analysis and comparisons presented herein, the following conclusions may be advanced with respect to EPS geofoam creep behavior:

1. The time-temperature superposition principle in applicable to EPS geofoam for temperatures up to 50°C. Using this methology, it is possible to extend data obtained from relatively short term creep tests (up to three months each at four temperatures) to cover a time span over 100 years for a reference temperature of 20°C.
2. The applicability of the time-temperature superposition principle to EPS geofoam was validated using the Arrhenius equation. Activation enthalpy was calculated equal to 48.1 kcal/mol/K, which is well within the range of the referenced values for polystyrene (43 to 52 kcal/mol/K)
3. When applying the time-temperature superposition principle, no corrections of the creep compliance values are needed to account for temperature effects on density and initial modulus of elasticity of the EPS geofoam samples.
4. The creep behavior of EPS geofoam is not dependent on density for values between 10 kg/m^3 and 35 kg/m^3. As a result, a constitutive relation was obtained which can be applied if the compressive strength of EPS geofoam, σ_{c10}, is known.
5. The constitutive relation obtained describes the linear viscoelastic response of EPS geofoam for normal stress values lower than 30% of the compressive strength, σ_{c10}, or for initial axial strains less than 0.5%.
6. For initial axial strains less than 0.5%, linear viscoelastic response is expected for a time span of at least 100 years. The total strain value after 50 years is expected to be double the initial axial strain.
7. For initial axial strains near the limit of linear behavior in monotonic loading (0.75%), non-linear creep response is expected after less than a year.

7 ACKNOWLEDGMENTS

This research was supported by the European Union and the Hellenic General Secretariat on Research through grant YPER 97 (YP 3-67), as well as by the Hellenic Association of Expanded Polystyrene Producers.

8 REFERENCES

AIPE, 1997: Isolare le fondazioni con l' EPS, Polistirene Espanso Sinterizzato, BE-MA editrice, 113p.

ASTM, 1997: Standard test method for compressive and flexural creep and creep-rupture of plastic lumber and shapes, Standard D6112, American Society for Testing and Materials, West Conshohocken, Pensylvania, USA.

Atmatzidis, D.K., Missirlis, E.G., 2001: Behavior of EPS geofoam in compression, Proceedings of the 7th International Conference on Geosynthetics, Nice, France, Volume 1, pp. 143-146

Drozdov, A.D., 1998: Mechanics of viscoelastic solids, John Wiley and Sons, Baffins Lane, West Sussex, England, 472p.

Elragi, A., Negussey, D., Kyanka, G., 2001: Sample size effects on the behavior of EPS geofoam", Geotechnical Special Publication No. 112- Soft Ground Technology, pp. 280-291

Frydenlund, T.E., Aaboe, R., 1996: Expanded polystyrene – The light solution, Proceedings of the International Symposium on EPS Construction Method, Tokyo, Japan, pp.31-46

Frydenlund, T.E., Aaboe, R., 2001: Long term performance and durability of EPS as a lightweight filling material, Proceedings of "EPS 2001", 3rd International Conference, December 10-12, Salt Lake City, Utah, USA, preprtints

Hart, G.M., Balazs, C.F., Clipper, R.B., 1973: Prediction of the long term compressive creep behavior of cellular polystyrene, Journal of Cellular Plastics, May/June, 1973, pp. 139-144

Horvath, J.S., 1995: Geofoam geosynthetic, Horvath Engineering, P.C., Scarsdale, N.Y., USA.

Horvath, J.S., 1998: Mathematical modelling of the stress-strain-time behavior of geosynthetics using the Findley equation: General Theory and application to EPS-block geofoam, Manhattan College Research Report No. CE/GE-98-3

Magnan, J.P., Serratrice, J.F., 1990: Mechanical properties of expanded polystyrene for use in the construction of road embankments, Bulletin Liaison de Ponts et Chauchee, 164 (TRRL Translation, No.3625), 15p.

Srirajan, S., Negussey, D., Anasthas, N., 2001: Creep behavior of EPS geofoam, Proceedings of "EPS 2001", 3rd International Conference, December 10-12, Salt Lake City, Utah, USA, preprtints

TC88/CEN, 2001: Lightweight fill and insulation products for Civil Engineering applications-Factory made products of expanded polystyrene (EPS) –Specification", CEN, European Committee for Standardization, Draft 08.2001, English Version, 36p.

Thelberg, S.E.B., 2001: Structural design of road embankments and foundations-New design Code for load bearing application, Proceedings of "EPS 2001", 3rd International Conference, December 10-12, Salt Lake City, Utah, USA, preprints