COMPRESSIVE CREEP BEHAVIOR OF HDPE USING TIME TEMPERATURE SUPERPOSITION

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ABSTRACT: This paper is concerned with the compressive creep behavior of viscoelasic materials, such as high density polyethylene (HDPE) commonly used to manufacture Fiber Reinforced Polymeric (FRP) piling. Accelerated methods to predict the tensile creep of polymers are already available. The Time-Temperature Superposition (TTS) phenomenon is the basis of several available methods, and an ASTM standard for tensile creep is based on one of its derivatives. In this paper, TTS has been adapted to study the compressive creep of HDPE. Experimental test results on virgin HDPE indicated that TTS is applicable for compressive loading with, some limitations.

INTRODUCTION

Coastal communities recovering from disasters in Louisiana, Mississippi, and elsewhere are now required to build above the *Advisory Base Flood Elevations,* which may result in structures being elevated by as much as 25 feet above ground level, requiring large amount of exposed piling. Use of piling made of recycled plaqstics in these situations is advantageous because (1) it is unlikely to be attacked by termites, which feed on exposed timber piling, and (2) it utilizes plastics, which would have been otherwise landfilled. The primary reason preventing designers from specifying polymeric piling is lack of information regarding their long-term performance. Polymers are viscoelastic and designers are concerned that polymeric piling may exhibit unacceptable creep under service loads (Karbhari et al, 2002).

One of the main constituents of available polymeric piles is High Density Polyethylene (HDPE). To be able to predict the creep behavior of the polymeric piles, studying the creep behavior of HDPE is inevitable. HDPE has already been used in geosynthatics, and methods to predict its tensile creep are readily available. This paper presents the results of accelerated compressive creep tests on virgin HDPE.

CREEP of POLYMERS

Creep is an important design consideration for civil engineering structures, especially when a viscoelastic element like FRP is involved. Creep refers to a time-dependent

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deformation at stress less than the strength of the material. The creep property varies with the type of polymer and in-service temperature with respect to the glass transition temperature and melting temperature (Nielsen, 1974). The manufacturing processing varies with polymer type, causing a large difference in the creep behavior among different polymeric products. Therefore, the creep property of each product should be evaluated so that the appropriate reduction factors can be applied in the design calculation. Creep of FRP is made complex by a combination of factors as follows:

- The materials are often loaded in the plastic non-linear range, and the stress-strain behavior of the material is highly time (rate) dependant.
- Unlike conventional construction materials which have well documented creep behavior in service, there is virtually no reliable data on the in-service creep behavior of FRP that can be used to calibrate the predictive models.
- Most HDPE used in construction is recycled. The physical and engineering properties of recycled HDPE typically exhibit a high coefficient of variation.

Ideally, the creep behavior of polymers should be evaluated according to the ASTM D 5262, which requires a long testing time to obtain data at ambient temperature. Although ASTM D 5262 allows for extending creep data by to one log cycle (e.g. from 10,000 hrs to 100,000 hrs), this is not practical for predicting creep for the 50 to 100 years design life. The alternative is to use an accelerated test method. The available accelerated methods can be grouped under two main categories

- **Thermal Methods**, such as *Time Temperature Superposition* (TTS), and its derivative *Stepped Isothermal Method* (SIM). These methods take advantage of the similarity between the effect of time and temperature on the creep behavior of polymers. Thus time is accelerated by elevating temperature (Nielsen, 1974; Ferry, 1980).
- **Energy Methods**, such as the Strain Energy Density Method (Lynch, 2002). These methods take advantage of the equivalence of energy points in specimens tested using different strain rates. Thus creep is predicted by extrapolating the stress-strain behavior of specimens tested under different strain rates (Merry et al., 2005).

THERMAL CREEP ACCELERATION METHODS

The tensile creep behavior of HDPE geogrids has been evaluated using TTS and SIM (Farrag 1998). TTS is already a well-accepted acceleration method to evaluate viscoelastic behavior of polymeric materials in tension (Zornberg et al 2004). Meanwhile SIM has been developed mostly in the last decade to shorten testing time and utilize a single test specimen to minimize material property's variability effects (Hsuan & Yoe 2005a, b and Thornton et al. 1998a, b). In TTS and SIM, a sequence of creep responses is generated using a series of temperature steps under a constant load. TTS uses different specimens for each temperature step, while SIM uses the same specimen for all temperature steps. Four 2-hour isothermal exposures are typically used in either method.

Both methods depend on the time–temperature superposition concept, i.e. that time can be scaled by a known shift factor that depends on the creep test temperature. The fundamental premise of thermal acceleration testing is that viscoelastic processes are accelerated at elevated temperatures in a predictable manner. The Arrhenius equation provides the basis for the relation between the rate of reaction and temperature. In addition, The Williams–Landel–Ferry (WLF) equation and Boltzmann superposition principle provide justification for scaling and shifting strain data obtained at each isothermal exposure in order to define a master creep curve corresponding to the reference (room) temperature.

Arrhenius Equation

The Arrhenius (1912) equation describes the relation between the rate of reaction and temperature for many reactions. This methodology was first used in civil engineering by Koerner *et al* (1992) to predict the degradation of geosynthetic materials. The equation can be used to predict the creep strain rate at a reference (room) temperature from the creep strain rate measured at an elevated temperature. The Arrhenius equation assumes that the viscoelastic creep mechanism remains unchanged at elevated temperatures.

Williams–Landel–Ferry Equation

A procedure for shifting data obtained at elevated temperatures to a reference temperature was developed by Williams, Landel, and Ferry (Ferry 1980). Specifically, the WLF equation introduces a time shift factor, a_T, to relate strains at different temperatures. The shift factor, a_T, is the ratio between the time for a viscoelastic process to proceed at an arbitrary temperature and the time for the same process to proceed at a reference temperature:

$$\varepsilon(T_0, t) = \varepsilon(T, a_T t) \qquad (1)$$

Where T_0 is an arbitrary reference temperature, T is the elevated test temperature, t is time, and a_T is the shift factor. The shift factor, a_T, is described by the empirical WLF equation as (Ferry 1980):

$$Log \quad a_T = \frac{c_1(T - T_0)}{(c_2 + T - T_0)} \qquad (2)$$

where c_1 and c_2 are empirical constants given by Ferry (1980) as 5.77 and 155.6, for HDPE respectively for temperatures in Fahrenheit.

Thus, creep strain measured at various isothermal steps during an accelerated test can be shifted to form a master creep curve. The empirical constants c_1 and c_2 are a function of the polymer type and the reference temperature, T_0. Use of the WLF equation to quantify strain shifts is discussed in detail by Farrag (1998).

EXPERIMENTAL PROGRAM

This study was initiated in order to verify that accelerated thermal procedures are valid for compressive loading. Virgin HDPE rods were used to eliminate scatter and uncertainties that may be introduced due to the use of recycled HDPE commonly used to manufacture FRP piling. The diameter of all specimens reported tested is 1.5” (38 mm) and the ratio of the height to the diameter is 2.

Prior to beginning the creep testing protocol, stress strain tests were performed at different strain rates in order to define the strength characteristics of virgin HDPE (Fig. 1). The stress strain curves exhibited a bi-linear behavior, with noticeable strain softening occurring at a stress of 2000-3000 psi (14-21 MPa) depending on the strain rate. The creep stresses used in this study were 400, 800, 1600, and 3200 psi (2.8, 5.5, 11, and 22 Mpa). These stresses were selected such that they fall in the first linear part of the curve.

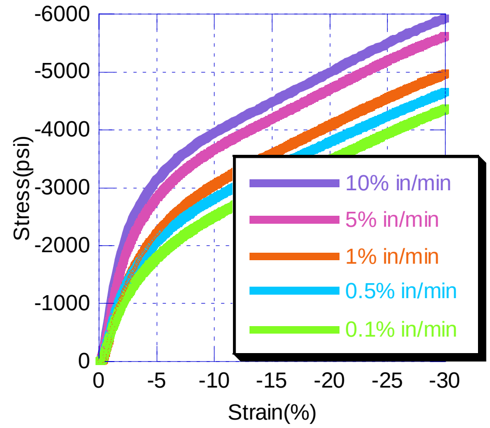

Fig. 1 – Stress-Strain on HDPE

In this study TTS was employed with the following temperatures 24, 38, 49, and 60°C for each stress level. These temperatures were selected to match the ones prescribed in ASTM D6992 standard test method for accelerated tensile creep and creep rupture of geosynthetic materials based on time temperature superposition using SIM. Higher temperatures were also not possible due to softening in the material stress-strain response at elevated temperatures. When these temperatures are substituted in Eq. 2, the shift factors shown in Table 1 are obtained.

Table 1 — Shift factors for Different Temperatures

Temperature	24° C (72°F)	38°C (100°F)	49°C (120°F)	60°C (140°F)
a_T	1	5.26	14.45	33.12

Creep tests were performed using an *Instron* 8800 controller and an *MTS* load frame. Stress was ramped at a rate of 80 psi (550kPa)/min until the desired creep stress, was reached and maintained constant for the duration of the test. Specimens were immersed in a water basin during loading. The water was heated using thermal tape and temperature was controlled using an *Omega* CNI3233 temperature controller.

TTS Test RESULTS:

Creep test results at 24, 38, 49, and 60°C are presented for the four selected creep stresses in Fig. 2-5. In each figure the actual strain versus time is plotted on the left, and time is scaled on the right according to Table 1.

Time temperature superposition works well in compression up to 1600 PSI. This is established by comparing the shifted curves for tests conducted at 38-60°C to each other and to the creep data obtained at room temperature. Time temperature superposition was not possible for the creep tests conducted at 3200 psi (Fig. 5). At 3200 psi, HDPE experiences significant plastic deformation, which is not represented by the Arrhenius model. As the stresses approach the linear limit the results are worse.

Comparison with a conventional creep test (Fig. 6) shows good correlation between conventional creep and accelerated creep for 2 months. (Only 3 days shown here but 60 days will be shown in the final manuscript). This good correlation is expected to continue over a much longer period because unlike tensile loading where creep ends in rupture (Fig. 7) compressive loading densifies the polymer chains, thus the constant linear creep stage is expected to sustain until creep ends.

A logarithmic equation can be fit in the accelerated master creep curve for 400 psi (2.8 MPa). Substituting in the logarithmic equation for a duration of 100 years, yields a creep strain of 1.7% (Fig. 8). A stress of 400psi (2.8 MPa) represents 5% of working stress for the tested HDPE (taken at 2% strain). Therefore, it is reasonable to assume that HDPE piles loaded in compression may sustain a creep on the order of 2% in 100 years.

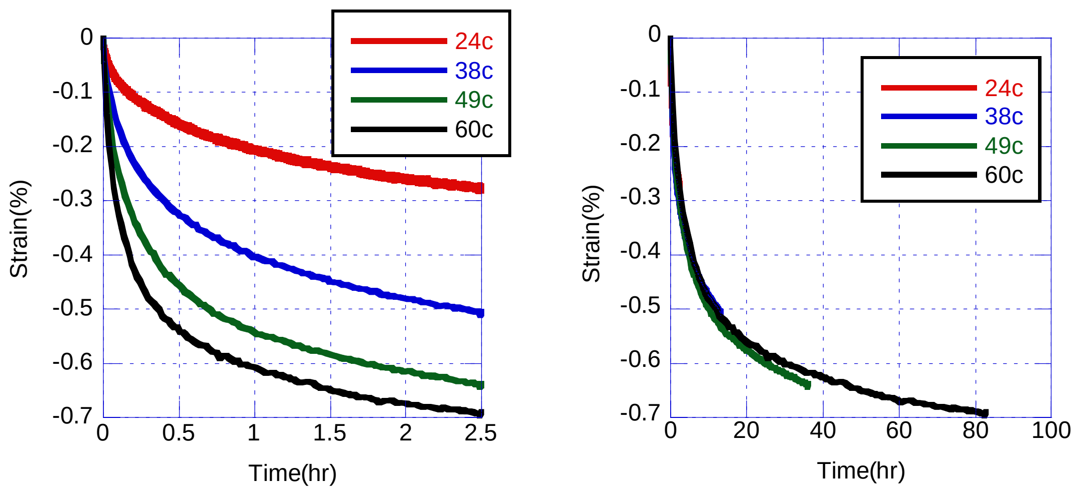

Fig. 2 — Creep at 400 psi, LHS before scaling, RHS after scaling with a_T

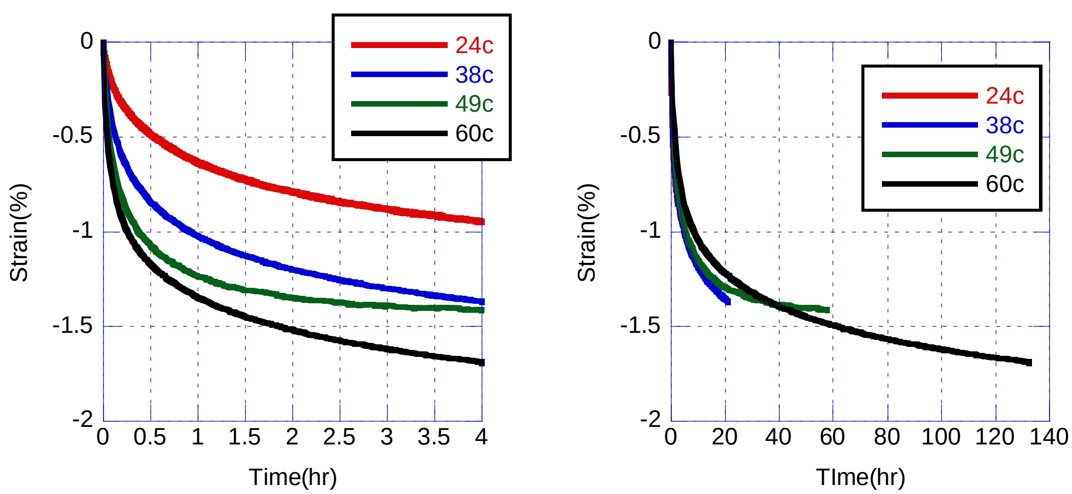

Fig. 3 — Creep at 800 psi, LHS before scaling, RHS after scaling with a_T

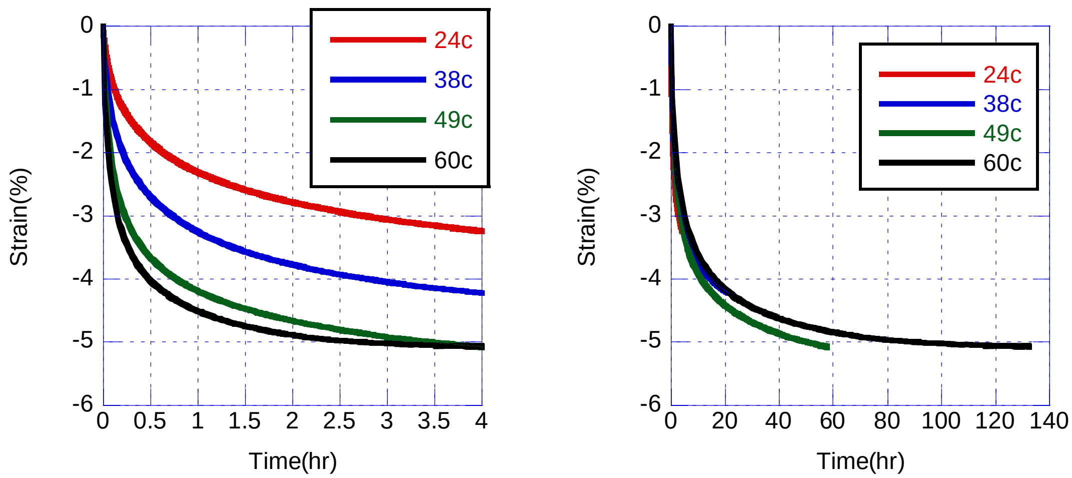

Fig. 4 — Creep at 1600 psi, LHS before scaling, RHS after scaling with a_T

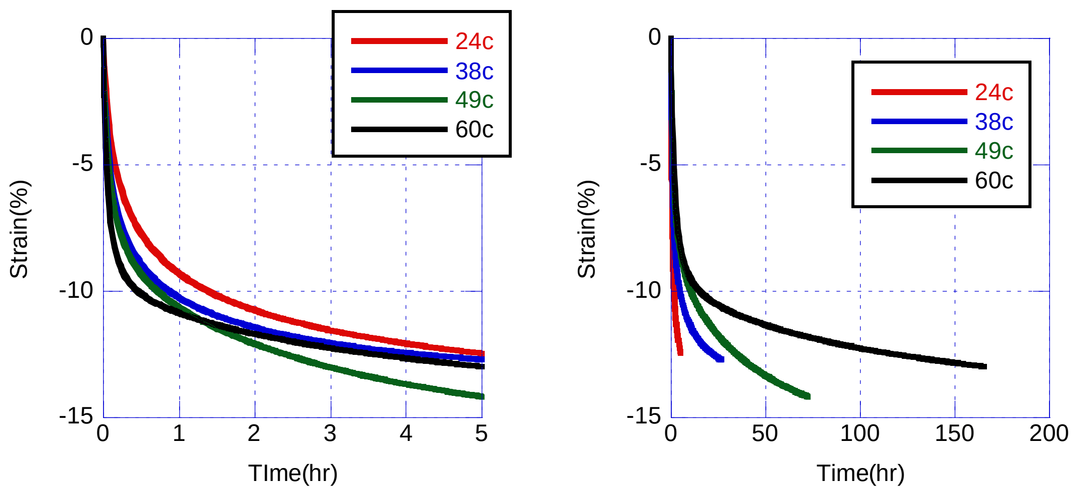

Fig. 5 — Creep at 3200 psi, LHS before scaling, RHS after scaling with a_T

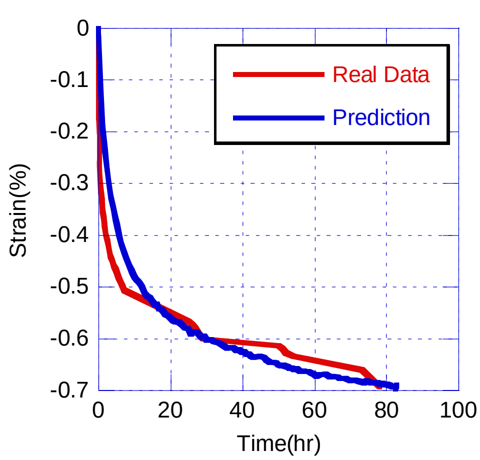

Fig. 6 — Real & Accelerated Creep

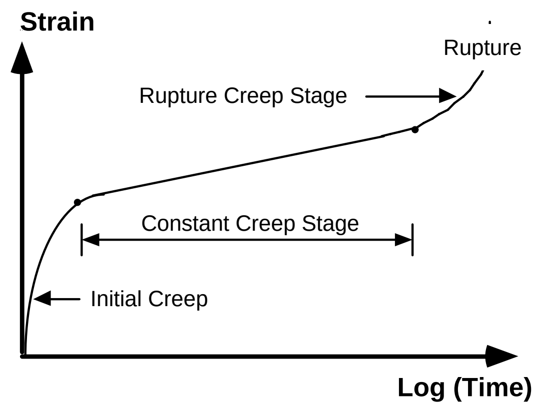

Fig. 7 — Tensile Creep in Polymers

CONCLUSIONS

The results of the accelerated creep tests conducted on virgin HDPE indicate that (1) time temperature superposition is an appropriate method for accelerating creep in compression at stresses below 1600 psi; (2) the constants, C_1, C_2, and the shift factor a_T appear to be the same in tension and compression, at least at low stress levels; and (3) preliminary results indicate that the tested HDPE loaded in compression will creep by approximately 2% in 100 years when loaded at 400 psi (2.8 MPa)

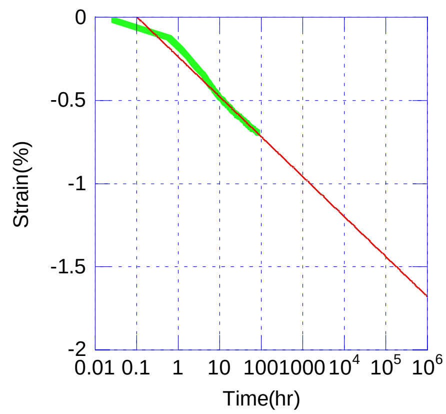

Fig. 8 — Projected creep of HDPE

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REFERENCES

Arrhenius, S. (1912). *Theories of Solutions*, Oxford University Press

Farrag, K. (1998). "Development of an accelerated creep testing procedure for Geosynthatics. II: Analysis." *ASTM Geotech. Test.* J., Vol. 21, No. 1, pp. 38-44

Ferry, J. D. (1980). *Viscoelastic properties of polymers*, 3rd Ed., Wiley, New York.

Hsuan, Y. G., Yeo, S. S. (2005a) "Comparing the Creep Behavior of High Density Polyethylene Geogrid Using Two Acceleration Method." *Slopes and Retaining Structures Under Seismic and Static Conditions (GSP 140)*, ASCE 166, 23

Hsuan, Y. G., Yeo, S. S. (2005b) "Compression Creep Behavior of Geofoam Using the Stepped Isothermal Method." *Geosynthetics Research and Development in Progress* (GRI-18), ASCE 161, 12

Karbhari, V. M., Chin, J. W., Hunston, D. (2002) "Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure." *ASCE Journal of Composites for Construction*, Vol. 7, No.3, pp. 238-247

Koerner, R. M., Lord, A. E., Jr., and Hsuan, Y. H. (1992). "Arrhenius modeling to predict geosynthetic degradation." *Geotext. Geomembr.*, Vol.11, No.2, pp. 151–183.

Lynch, J. K (2002) "Time Dependence of the Mechanical Properties of an Immiscible Polymer Blend" *PhD. Dissertation*, Rutgers University, NJ

Merry, S.M., Bray J.D., Yoshitomi S. (2005), "Axisymmetric Temperature- and Stress-Dependent Creep Response of 'New' and 'Old' HDPE," *Geomembranes Geosynthetics Internationa*l, Vol. 12, No. 3, pp. 156-161.

Nielsen, L E. (1974) *Mechanical properties of polymers and composites*.

Thornton, J. S., Allen, S. R., Thomas, R. W., and Sandri, D. (1998a). "The stepped isothermal method for time-temperature superposition and its application to creep data on polyester yarn." *Proc., 6th Int. Conf. on Geosynthetic*, Atlanta, 699-706.

Thornton, J. S., Paulson, J. N., and Sandri, D. (1998b). "Conventional and stepped isothermal methods for characterizing long term creep strength of polyester geogrids." *Proc., 6th Int. Conf. on Geosyntheti*c, Atlanta, 691-698.

Zonberg, J. G., Byler, B. R., Knudsen, J. W. (2004) " Creep of Geotextiles Using Time-Temperature Super position Methods" *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No.11, pp. 1158-1168