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Comparison of Accelerated Compressive Creep Behavior of Virgin HDPE Using Thermal and Energy Approaches

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This article compares two available approaches for accelerating the creep response of viscoelastic materials, such as High Density Polyethylene (HDPE), which is increasingly gaining attention for use in construction. Thermal acceleration 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 of geosynthetics is based on one of its derivatives, the Stepped Isothermal Method (SIM). In this article, both TTS and SIM have been adapted to study the compressive creep of virgin HDPE. An alternate approach, based on the equivalence of strain energy density (SED) between conventional constant-stress creep tests and strain-controlled stress-strain tests, is also adapted for accelerated compressive creep of HDPE. There is remarkably a good agreement among the creep behaviors obtained from conventional tests, TTS, SIM, and SED predictions for virgin HDPE.

Keywords creep, high density polyethylene, mechanical testing, polymer matrix composites, strain energy density, structural plastics, time-temperature superposition

1. Introduction

Creep is an important design consideration for civil engineering structures, especially when a viscoelastic element like HDPE is involved (Ref 1, 2, 3, 4, 5). Creep refers to a time-dependent deformation at stress less than the strength of the material. Creep of HDPE is non-linear, viscoelastic, and time dependant (Ref 6, 7). Creep varies with the type of polymer and in-service temperature with respect to the glass transition temperature and melting temperature (Ref 8). The manufacturing process varies with polymer type, causing a large difference in the creep behavior among different polymeric products. Therefore, the creep of each polymeric product should be evaluated so that the appropriate reduction factors can be applied in structural design. Creep of polymers is made complex by (1) The materials are often loaded in the plastic non-linear range, and the stress-strain behavior of the material is highly time (rate) dependant; and (2) 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 polymers that can be used to calibrate the predictive models, particularly in compressive loading.

Models to predict the short-term creep behavior of polymers are available in the material science literature (e.g., Ref 9, 10). However, in civil engineering applications, the creep behavior of polymers should ideally be evaluated according to the ASTM D5262, which requires a long testing time to obtain data at ambient temperature. Although ASTM D5262 allows for extending creep data by one log cycle (e.g., from 10,000 to 100,000 h), this is not practical for predicting creep for the 50-100 years design life. The alternative is to use an accelerated test method. The available accelerated methods can be grouped under two main approaches, as follows:

- *Thermal Approaches*, 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 (Ref 11).
- *Energy Approaches*, such as the Equivalent Strain Energy Density (SED) Method (Ref 12). 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 to obtain long term static creep.

In this study, both thermal and energy approaches are adapted to accelerate the compressive creep of virgin HDPE, a viscoelastic polymer that is increasingly gaining attention for use in construction of water-front pile foundations (Ref 13). Virgin HDPE rods were purchased for testing from US Plastics, Inc. Specimens were cut from the rods to form right circular cylinders, with an aspect ratio of 2.

2. Thermal Creep Acceleration Approach

The TTS is already a well-accepted acceleration method to evaluate viscoelastic behavior of polymeric materials in tension

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(Ref 14, 15). 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 (Ref 16-19). 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-h isothermal exposures are typically used in either method. The compressive behavior of an expanded polystyrene (EPS) geo-foam was also tested with SIM, and the results showed that this method is applicable in compression (Ref 20).

Both TTS and SIM depend on the time-temperature superposition principle, 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. Time temperature superposition can be understood in the context of Arrhenius (Ref 21) modeling which provides a relationship between the rate of reaction and temperature increase, as well as the Boltzmann superposition principle which allows for shifting strain data obtained at different test temperatures to obtain a creep curve corresponding to room temperature (Ref 16).

2.1 Time Temperature Superposition Method (TTS)

In TTS, a family of creep curves conducted at the same creep stress can be scaled, each by a different scaling factor corresponding to its elevated test temperature, such that they converge to a creep test conducted at room temperature (Ref 22). The effect of increasing temperature is simply to cause the creep process to accelerate. This phenomenon is known as the Time Temperature Superposition Principle (Ref 23). The shift factor, at any elevated temperature, a_T, is the ratio between the time for a viscoelastic process to proceed at the test temperature and the time for the same process to proceed at a reference temperature, such that

$$\varepsilon(T_0, t) = \varepsilon(T, a_T t) \qquad \text{(Eq 1)}$$

where T_0 is an arbitrary reference temperature, T is the elevated test temperature, t is time, and a_T is the shift factor that relates strains at different temperatures. The shift factor, a_T, is described by the empirical Williams, Landel, and Ferry (WLF) equation as (Ref 11):

$$\log a_T = \frac{c_1(T - T_0)}{(c_2 + T - T_0)} \qquad \text{(Eq 2)}$$

where c_1 and c_2 are empirical constants given by Ferry (Ref 11) as 5.17 and 155.6, respectively, for virgin HDPE 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.

2.2 Experimental Program for TTS

TTS was employed with the following temperatures 24, 38, 49, and 60 °C for each stress level on specimens 38 mm in diameter (1.5 in.). 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 not possible due to softening in the HDPE 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 test temperatures (Ref 14)

Temperature	24 °C (75 °F)	38 °C (100 °F)	49 °C (120 °F)	60 °C (140 °F)
a_T	1	5.26	14.45	33.12

Compressive creep tests were performed using an *Instron* 8800 feed-back controller and an *MTS* load frame. Stress was ramped at a rate of 550 kPa (80 psi)/min until the desired creep stress, was reached and maintained constant for the duration of the test. Specimens were immersed in a metallic water basin during loading. The water temperature was kept constant using a feed back temperature controller (*Omega* CNI3233) connected to thermal tape wound around the water basin and a thermocouple attached to the middle of each specimen.

Creep test results at 24, 38, 49, and 60 °C are presented for the two selected creep stresses in Fig. 1 and 2. In each figure, the actual strain versus time is plotted on the left, and time is scaled on the right to a reference temperature of 24 °C according to Table 1. Time temperature superposition works well in compression for the shown stress levels of 2.8 and 5.5 MPa (400 and 800 psi). This is established by comparing the shifted curves for tests conducted at 38-60 °C to each other. A logarithmic equation can be fit in the accelerated master creep curve for 400 psi (2.8 MPa) as shown in Fig. 3. The slope of the logarithmic equation will be used later to compare with other test methods. The slope of the secondary creep stage (Fig. 4) is expected to continue over a much longer period because unlike tensile loading wherein creep ends in rupture, due to breakage of polymer chains, compressive loading densifies the polymer chains. Moreover, the stress decreases by time because of the effect of Poisson's ratio under constant load thus the constant linear creep stage is expected to sustain until creep ends.

2.3 Experimental Program for SIM

In SIM, one sample is exposed to different isothermal steps under a certain stress. Compressive creep stresses were applied using an *Instron* 8800 feed-back controller and an *MTS* load frame. Initially, stress was ramped at a rate of 550 kPa (80 psi)/min until the desired creep stress was reached and maintained constant for the duration of the test. Specimens were immersed in an oil basin during loading. The oil temperature was kept constant using feed back temperature controller (*Omega* CNI3233) connected to thermal tape wound around the oil basin and a thermocouple attached to the middle of each specimen.

The temperature controller device was programmed to apply four 2-h thermal steps at each specified creep stress. Temperature increase between steps took approximately 5-10 min. Two specimen sizes were used (19 and 38 mm in diameter), and each experiment was repeated three times for each stress level.

2.4 Interpretation of SIM Results

The Arrhenius (Ref 21) equation describes the relation between the rate of reaction and temperature for many reactions.

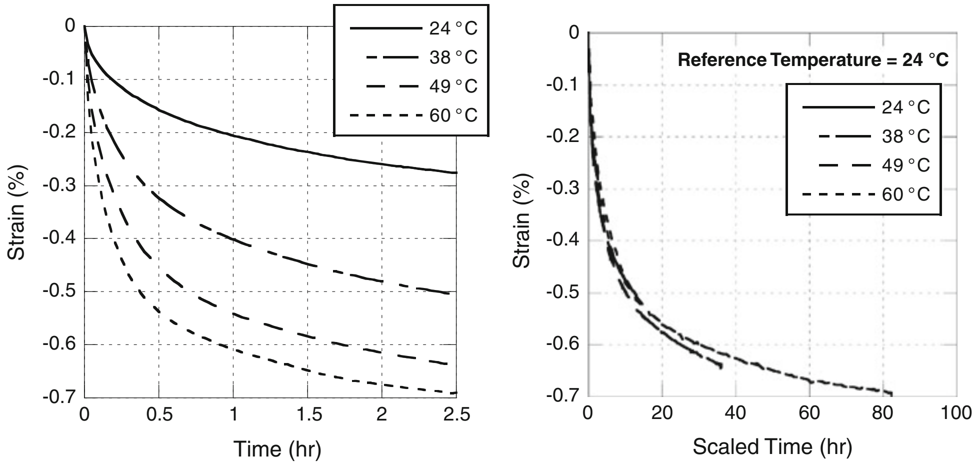


Fig. 1 Creep at 2.8 MPa (400 psi), LHS before scaling, RHS after scaling with a_T to a reference temperature of 24 °C

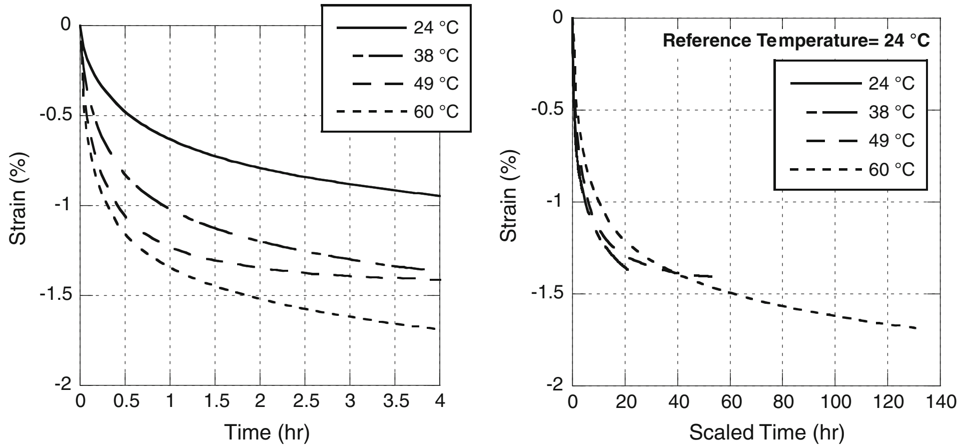


Fig. 2 Creep at 5.5 MPa (800 psi), LHS before scaling, RHS after scaling with a_T to a reference temperature of 24 °C

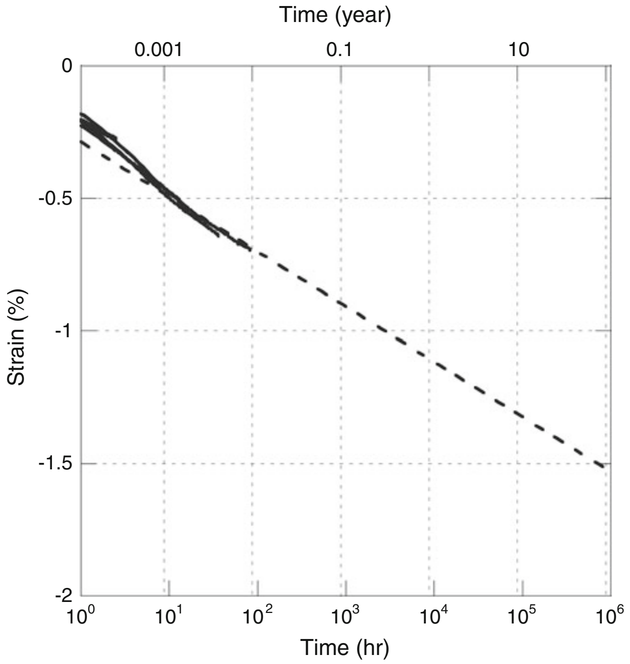


Fig. 3 Projected creep of HDPE

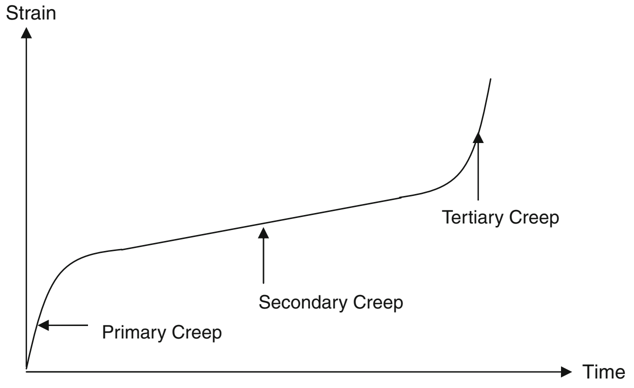


Fig. 4 Different creep stages

The methodology was originally developed for gases, in which chemical reactions were observed to proceed more rapidly at higher temperatures than at lower ones. Application of Arrhenius modeling to viscoelastic creep assumes that temperature accelerates viscoelastic creep, and that the mechanism of creep remains unchanged at elevated temperatures. According to the Arrhenius equation

$$K = K_0 e^{\frac{-E}{RT}} \tag{Eq 3}$$

This equation can be rewritten in this format:

$$\frac{K}{K_0} = e^{\frac{-E}{RT}} \rightarrow \ln\left(\frac{K}{K_0}\right) = -\frac{E}{RT} \tag{Eq 4}$$

where K is the kinetic reaction rate; K_0 the rate constant; E the activation energy; R the universal gas constant; and T is the absolute temperature.

In SIM, a sample is exposed to different isothermal steps under a certain stress. Assuming that the kinetic reaction rate is linearly correlated with the strain rate, the Arrhenius equation can be rewritten in following format when the sample is exposed to two different temperatures.

$$\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right) = \frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{Eq 5}$$

According to the equation, at the point where the strain rates in logarithmic scale are equal, the two different temperature exposures can be treated as the same temperature. Based on this argument, the different temperature exposures can be attached to each other at the point where they have the same strain rates (Ref 24).

A master creep curve describes the long-term creep behavior at a reference temperature. The master creep curve can be defined by composing into a single curve the creep responses measured at different isothermal exposures during SIM testing. The procedure for generating a master creep curve using SIM data is shown in Fig. 5. First, the strain versus time is plotted ignoring the temperature exposures (Fig. 5a). Second, each temperature exposure is scaled back to time $t = 0$ (Fig. 5b). Third, points having the same slope on the strain-log time curves are identified in Fig. 5 by a square, circle, or triangle. Finally, the portions of the curve which occur after the identified points are spliced together to form a master creep curve so that the final slope of a strain-time curve at a specific temperature step matches the initial slope of the strain-time curve at the subsequent temperature step (Fig. 5c). This empirical scaling technique is similar to the one used by Zornberg et al. (Ref 16) and ASTM 5262 for tensile loading of geosynthetics, and is consistent with the WLF equation.

A total of 12 sets of experiments have been performed on the virgin HDPE. Two stress levels were used (2.8, 5.5 MPa (400, 800 psi)). Master curves obtained using two different specimen sizes at two stress levels are shown in Fig. 6. In general, the slopes of the creep curves are remarkably consistent. A trend line is shown in gray along with the creep curves. These logarithmic trend lines are used later to compare the predicted creed using different approaches.

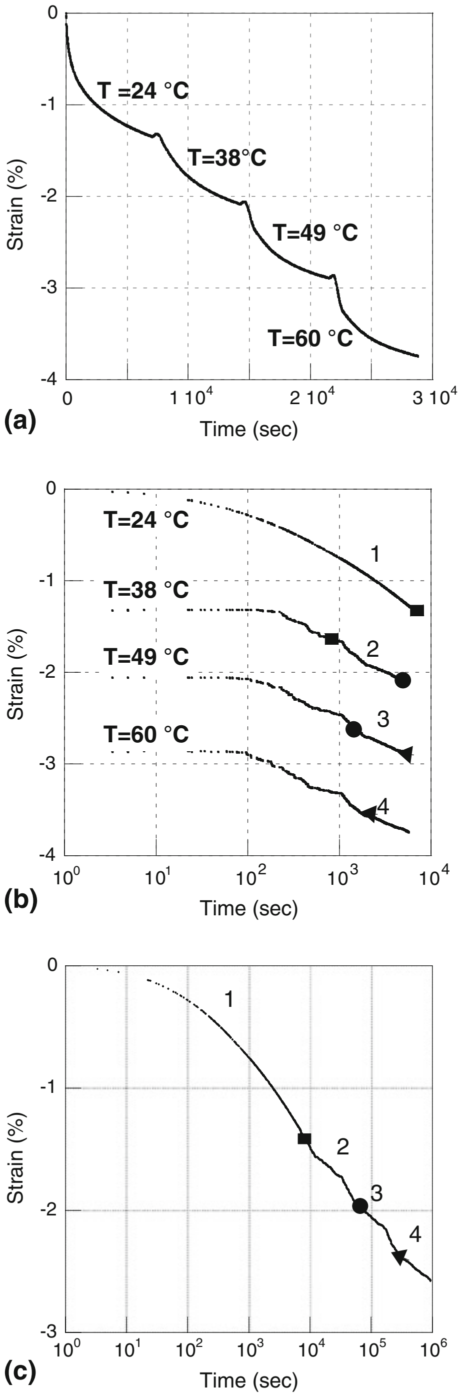


Fig. 5 Generating master curve for SIM: (a) measured strain vs. time, top; (b) each temperature exposure is scaled back to $t = 0$, middle; and (c) master creep curve, bottom

3. The Equivalent Strain Energy Density (SED) Approach

The basis of the SED approach was first pioneered by Ref 25. They succeeded in introducing a scheme for generating a stress-strain curve at any strain rate, temperature, or pressure; in tension, shear, or compression from a set of stress-strain data performed on a viscoelastic material. SED takes 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 to obtain long term static creep. A similar philosophy has been also used by Ref 26-31.

Although the theoretical basis of SED is somewhat complex, the resulting computational scheme is simple to implement. The SED is the area under the stress-strain curve (Fig. 7). For any two *reference* stress-strain curves performed at two different strain rates $(\dot{\varepsilon}_{r1}, \dot{\varepsilon}_{r2})$ it is assumed that a relationship between points having equal SED (ε_{r1}, ε_{r2}) exists, such that

$$\left(\frac{\dot{\varepsilon}_{r1}}{\dot{\varepsilon}_{r2}}\right)^{m} = \frac{\varepsilon_{r2}}{\varepsilon_{r1}} \qquad \text{(Eq 6)}$$

where the exponent m is a variable that changes as the SED changes. According to Matsuoka (Ref 12), for viscoelastic materials, any point on a stress-strain curve has a corresponding point on a different stress-strain curve conducted at a different strain rate so that the two points have the same energy density and satisfy Eq 6.

If a material exhibits a linear viscoelastic relationship between stress and strain (having constant modulus of elasticity), then the SED method can be reformulated to compute two reference stresses, σ_{r1}, σ_{r2}, corresponding to points having equal SED, as follows:

$$\sigma_{r1} = E_{r1} \times \varepsilon_{r1} \Rightarrow \frac{\sigma_{r1}}{\varepsilon_{r1}} = E_{r1} \qquad \text{(Eq 7)}$$

$$\sigma_{r2} = E_{r2} \times \varepsilon_{r2} \Rightarrow \frac{\sigma_{r2}}{\varepsilon_{r2}} = E_{r2} \qquad \text{(Eq 8)}$$

At the point where Area 1 = Area 2, we can derive the following relationship between the strains:

$$\frac{E_{r1} \times \varepsilon_{r1}^{2}}{2} = \frac{E_{r2} \times \varepsilon_{r2}^{2}}{2} \Rightarrow \left(\frac{\varepsilon_{r2}}{\varepsilon_{r1}}\right)^{2} = \frac{E_{r1}}{E_{r2}} \Rightarrow \frac{\varepsilon_{r2}}{\varepsilon_{r1}} = \sqrt{\frac{E_{r1}}{E_{r2}}} \qquad \text{(Eq 9)}$$

Rearranging Eq 6 and 9, we can obtain

$$\left(\frac{\dot{\varepsilon}_{r1}}{\dot{\varepsilon}_{r2}}\right)^{m} = \sqrt{\frac{E_{r1}}{E_{r2}}} \Rightarrow m = \frac{\log(E_{r1}/E_{r2})}{2\,\log(\dot{\varepsilon}_{r1}/\dot{\varepsilon}_{r2})} \qquad \text{(Eq 10)}$$

Therefore, by performing two reference experiments with different strain rates the value of m can be calculated.

Assuming the modulus of elasticity, E, changes with the rate of loading, but remains a constant for any particular strain rate, the term m would also be a constant number that no longer depends on the SED.

The fundamental assumption of SED is that the creep strain, ε_c (under constant load) can also be obtained from a stress-strain test, where the creep strain, $\varepsilon_{i,}$ corresponds to the creep stress, σ_c (Fig. 8). The strain rate of the imaginary equivalent-creep stress-strain (iECSS) test $\dot{\varepsilon}_i$, corresponding to the creep time of interest (e.g., 100 years), t_i, is unknown, but can be predicted as follows:

The iECSS is assumed to have a linear elastic behavior; therefore, the strain energy density, SED_{ci}, corresponding to the

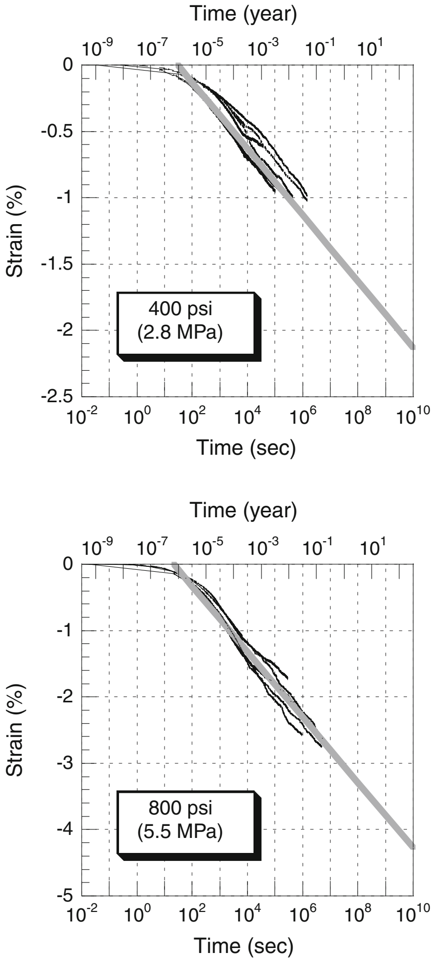


Fig. 6 Master creep curves for 2 diameters of HDPE at different stress levels

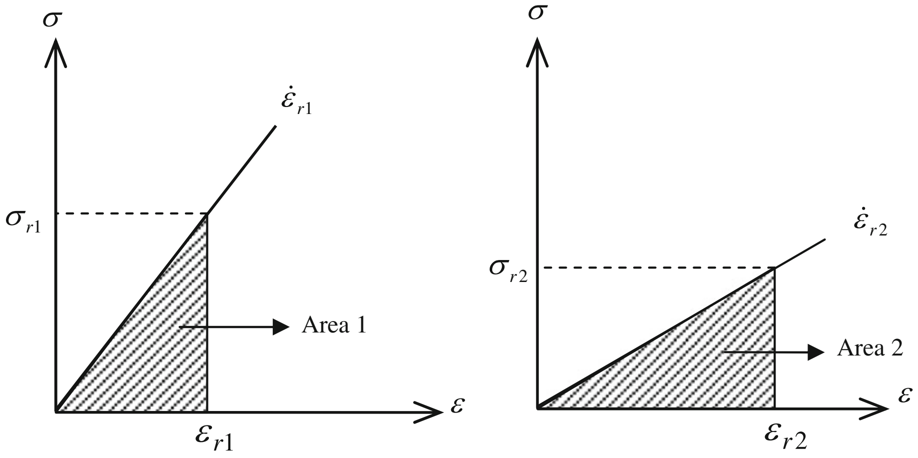


Fig. 7 Stress-strain curves of viscoelastic material with equal strain energy density (Area 1 = Area 2 and $\dot{\varepsilon}_{r1} > \dot{\varepsilon}_{r2}$)

creep stress of interest, $\sigma_{c,}$ and the creep time of interest, $t_{i,}$ can be calculated as

$$\mathrm{SED}_{ci} = \frac{\sigma_c \times \varepsilon_i}{2} \tag{Eq 11}$$

The only unknown in Eq 11 is the value of the creep strain ε_i. Performing two stress-strain experiments with different strain rates the value of m can be calculated, according to Eq 10. Choosing one of the performed experiments as a reference experiment, and substituting in Eq 6 yields

$$\left(\frac{\dot{\varepsilon}_r}{\dot{\varepsilon}_i}\right)^m = \frac{\varepsilon_i}{\varepsilon_r} = \frac{\dot{\varepsilon}_i \times t_i}{\dot{\varepsilon}_r \times t_r} \tag{Eq 12}$$

where $\dot{\varepsilon}_r, \dot{\varepsilon}_i$ are the stress-strain rates of the reference test, and the unknown strain rate of the iECSS test, respectively; ε_r, ε_i are the strains of points having equal SED on the reference and iECSS test, respectively; t_i is the time the creep is to be predicted (e.g., 100 days); and t_r is the time on the reference stress-strain test to achieve equal SED at the creep stress of interest, σ_c. The unknowns in Eq 12 are $\dot{\varepsilon}_i$ and t_r.

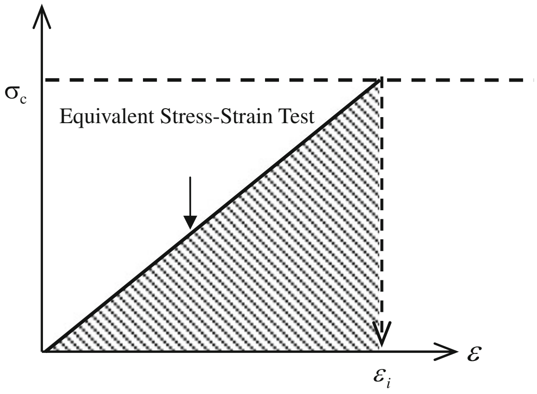


Fig. 8 Demonstration of an imaginary equivalent creep stress-strain (iECSS) test

The next step is to equate the SED of the reference and iESCC tests. The SED at any point in the reference experiment is

$$\mathrm{SED}_{ci} = \frac{E_r \times \varepsilon_r^2}{2} \Rightarrow \frac{E_r \times \dot{\varepsilon}_r^2 \times t_r^2}{2} \tag{Eq 13}$$

The SED for the iECSS is

$$\mathrm{SED}_{ci} = \frac{\sigma_c \times \varepsilon_i}{2} = \frac{\sigma_c \times \dot{\varepsilon}_i \times t_i}{2} \tag{Eq 14}$$

From Eq 13 and 14

$$\sigma_c \times \dot{\varepsilon}_i \times t_i = E_r \times \dot{\varepsilon}_r^2 \times t_r^2 \tag{Eq 15}$$

The unknowns in Eq 12 and 15 are $\dot{\varepsilon}_i$, t_r. Equation 12 and 15 are two equations with two unknowns that can be used to determine the values of $\dot{\varepsilon}_i$, t_r as follows:

$$\dot{\varepsilon}_i = \sqrt[2m+1]{\frac{\sigma_c \times \dot{\varepsilon}_r^{2m}}{E_r \times t_i}} \tag{Eq 16}$$

$$t_r = \sqrt{\frac{\sigma_c \times \dot{\varepsilon}_i \times t_i}{E_r \times \dot{\varepsilon}_r^2}} \tag{Eq 17}$$

The strain on the iECSS corresponding to creep, $\varepsilon_{i,}$ can be calculated from the strain rate of the iECSS test simply as

$$\varepsilon_i = \dot{\varepsilon}_i \times t_i \tag{Eq 18}$$

During the creep process, the stress is constant but in iECSS the stress varies. In order to take the variation of the stress into account the average of ε_i is used as the creep strain (ε_c).

$$\varepsilon_c = \varepsilon_i/2 \tag{Eq 19}$$

3.1 Application of SED Method to Computing Compressive Creep of HDPE

The SED method can be applied to compute the creep strain of viscoelastic polymers such as HDPE, as follows. First, two

Table 2 Representative calculation of creep strain using SED method

	Creep stress	**400 psi**	**2.76 MPa**		
Ref test 1	**Reference strain rate**	**0.00003 (in./in.)/min**		***m* = 0.0476 (Eq 10)**	
	Modulus of elasticity	**32549 psi**	**224.42 MPa**		
Ref test 2	**Reference strain rate**	**0.03 (in./in.)/min**			
	Modulus of elasticity	**62839 psi**	**433.26 MPa**		
t_i, days	**t_i, min**	**$\varepsilon_{i(rate)}$, (in./in.)/min Eq 16**	**t_r, min Eq 17**	**ε_i, in./in. Eq 18**	**ε_c, % Eq 19**
0	0	0	0.00	0.0000	0.00
0	5	1.68E−03	338.23	0.0084	0.42
1	1440	9.52E−06	432.65	0.0137	0.69
30	43200	4.27E−07	501.60	0.0184	0.92
60	86400	2.27E−07	516.94	0.0196	0.98
120	172800	1.20E−07	532.76	0.0208	1.04
365	525600	4.36E−08	559.16	0.0229	1.14
3650	5256000	5.32E−09	618.03	0.0280	1.40
7300	10512000	2.83E−09	636.94	0.0297	1.49
18250	26280000	1.22E−09	662.82	0.0322	1.61
36500	52560000	6.50E−10	683.10	0.0342	1.71
100000	144000000	2.59E−10	713.69	0.0373	1.87

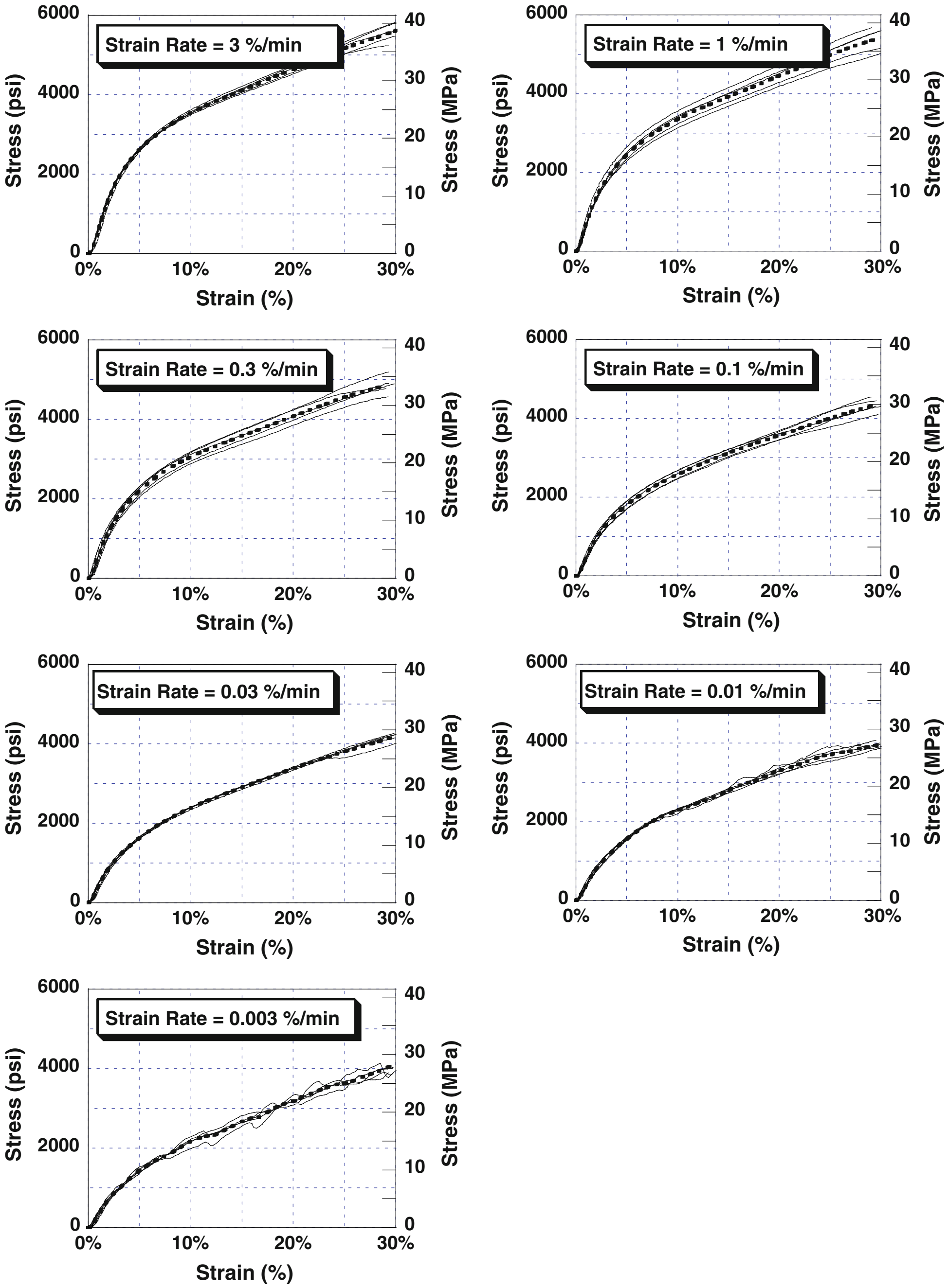


Fig. 9 Stress-strain curves of virgin HDPE at shown strain rates (individual tests are shown as thin solid lines, and average is shown as a thick dashed line)

stress-strain tests are performed to compute the value of the exponent *m* using Eq 10. Second, a creep stress, σ_c, is selected for computation. Third, a time is selected for computing the corresponding creep strain as shown in Table 2. Fourth, the stress-strain test having the slower of the two strain rates is selected as a reference for further calculations. Fifth, the strain rate of the iECSS test, $\dot{\varepsilon}_i$, corresponding to the creep time of interest is computed using Eq 16. Sixth, the strain on the iECSS corresponding to creep, ε_i, can be calculated from the strain rate $\dot{\varepsilon}_i$, using Eq 18. Finally, the creep strain is taken as half of ε_i, according to Eq 19.

The only assumptions that were employed are:

(1) linear elasticity;
(2) the relationship between points having equal SED on stress-strain curves performed using different strain rates is expressed by Eq 6;
(3) creep strain ε_c (under constant stress) for a given time of interest, t_i, can be obtained from an imaginary equivalent-creep stress-strain (iECSS) at a point whose SED is computed as $\frac{1}{2}\sigma_c\varepsilon_i$.

3.2 Experimental Program for SED

In this research, the material has been tested in compression with seven different strain rates. The applied strain rates were 3, 1, 0.3, 0.1, 0.03, 0.01, and 0.003%/min. All tests were performed using a computerized strain-controlled apparatus. Each experiment was repeated five times, and the results of those 5 experiments have been numerically averaged for each strain rate (Fig. 9). For any strain rate, virgin HDPE exhibits little variation in its stress-strain response, particularly at strain below 5%. Nevertheless, virgin HDPE exhibits a pronounced viscoelastic behavior (Fig. 10). The material is stronger as the strain rate increases. In our tests, the strain rate varied by three orders of magnitude ranging from 0.003 to 3%/min. The strength of the specimens tested using the fastest strain rate (defined at a strain of 4%) was over 75% larger than that of specimens tested using the slowest strain rate. A linear modulus of elasticity was fitted in the early segment of each of the average stress-strain curves shown in Fig. 10. The first 4% of the stress-strain curve was selected for the linear fit because (1) it corresponds to the strain of practical interest in civil engineering applications; and (2) the material exhibited marked softening after approximately 4%. The resulting linear fits are summarized in Fig. 11.

Any pair of the average strain curves shown in Fig. 11 can be chosen as the requisite references tests to calculate *m*. The variation of *m* with the order of magnitude for strain rate pairs is illustrated in Fig. 12. It is clear that *m* converges to a definite value as the order of magnitude of strain rate pairs is increased. *m* was found to be 0.0476 for the virgin HDPE tested in this study.

Bozorg Haddad (Ref 22) showed that when pairs involving stress-strain tests with rates differing by two or more orders of magnitude are used, the scatter in the computed creep is significantly reduced. Hence, for seven sets of experiments 21 combinations (pairs) of reference tests exist, but only five pairs differing in strain rates by two or more orders of magnitude can be chosen.

Each of the five pairs was used to compute creep strains according to the procedure described earlier and illustrated in Table 2 for two different creep stresses. The calculated creep curves are shown in Fig. 13 as thin solid lines, along with their average shown as a heavy dashed-line. The average line is fitted with a logarithmic equation whose slope is used for comparison with other methods.

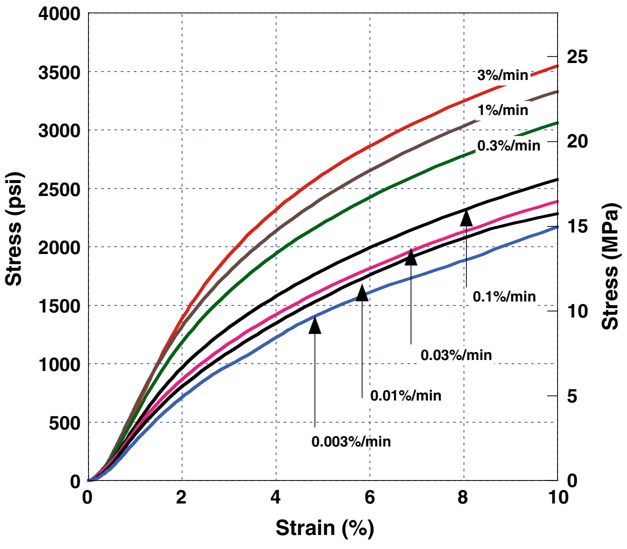
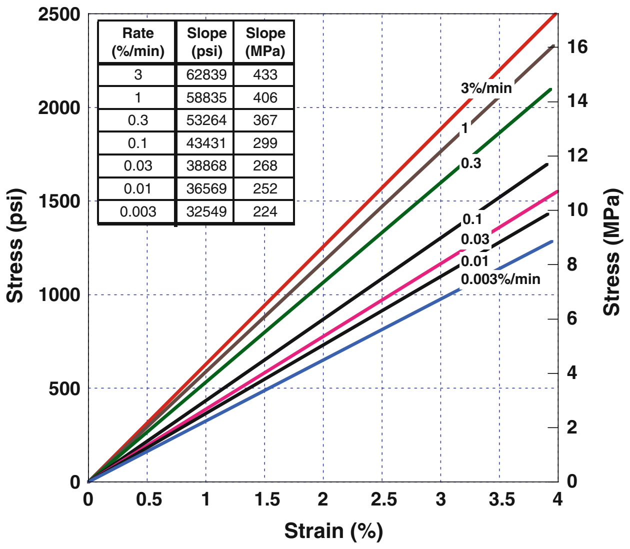


Fig. 10 Average stress-strain curves of virgin HDPE at shown strain rates

4. Comparison of Conventional Creep and Accelerated Creep Obtained Using Thermal and Energy Approaches

Two conventional creep tests were performed on virgin HDPE with creep stresses of 2.8 and 5.5 MPa (400 and



Rate (%/min)	Slope (psi)	Slope (MPa)
3	62839	433
1	58835	406
0.3	53264	367
0.1	43431	299
0.03	38868	268
0.01	36569	252
0.003	32549	224

Fig. 11 Assigned linear fit of average stress-strain curves shown in Fig. 10

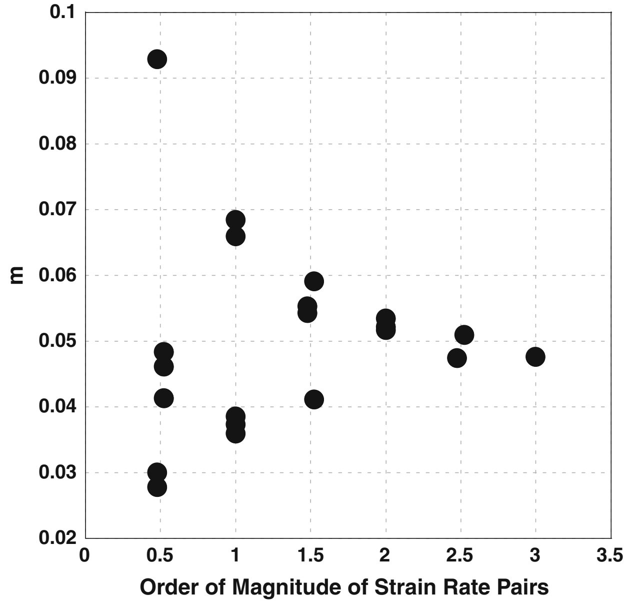


Fig. 12 Variation of *m* with the order of magnitude of strain rate pairs

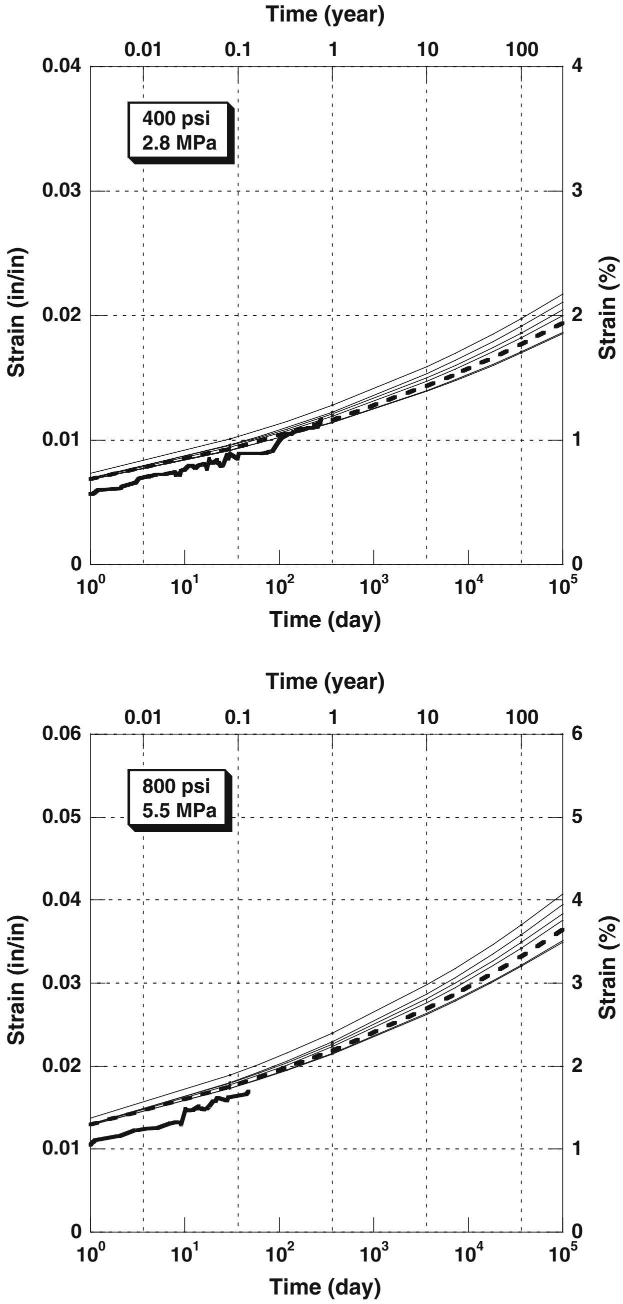


Fig. 13 Creep calculated using pairs of strain rates having a difference of two or more orders of magnitude (thin solid lines), along with the numerical average (thick dashed line) and measured conventional creep data (solid heavy line)

800 psi) for 270 and 120 days, respectively. The tests were performed using a mechanical system, which allows for loading the specimen via a fulcrum that provides a mechanical advantage of 10:1 (Fig. 14). The conventional creep tests was performed using a creep stress of 2.8 MPa (400 psi) applied for 275 days and creep stress of 5.5 MPa (800 psi) applied for 175 days on a specimen having a diameter of 19 mm (0.75 in.). Creep strain was measured using a dial gauge with a resolution of 0.00254 mm (0.0001 in.). The system was loaded gradually, and did not allow for capturing creep strain during loading; therefore, creep was lost during the first 10-20 s of loading. Both tests were terminated when the mechanical apparatus was disturbed by a passer-by.

Fig. 14 Apparatus used to measure creep

The results of the conventional creep tests are superimposed over the computed creeps from TTS, SIM, and SED as shown in Fig. 15. The slopes from TTS, SIM, SED, and conventional creep are remarkably similar. The vertical shift between the curves is due to two factors. First, the mechanism of initial creep is not modeled similarly in the various experiments. Second, the effect of physical aging on the HDPE during thermal creep is not included in the analysis of the test data of the TTS and SIM. The effect usually lowers the creep strain (Ref 32-34) thus pushing the TTS and SIM curves toward the Real time creep data in Fig. 15. Aging contributes to the difference between the SED curve and that of the thermal methods because in thermal methods aging and creep occur simultaneously (Ref 35). However, it is the slope of the constant creep stage (Fig. 4) that controls the long-term behavior of HDPE in compression. This indicates that both thermal and energy approaches are reasonable approaches for accelerating long-term compressive creep in the tested material.

Engineering strains have been employed throughout the study, without an area correction for the Poisson's effect. This introduces a small error (<2%) in the calculated stresses at the strain ranges of interest. The error contributes to a conservative (higher) prediction of creep strain.

Assuming that rupture creep does not take place, as discussed previously, and based on the measured creep slopes (Fig. 15) the expected creep strain for 2.8 and 5.5 MPa (400 and 800 psi) for a 100 year time span, typical of a civil engineering structure, would be 2 and 4%, respectively. Based on these results, an ultimate stress of 2.8 MPa (400 psi) is believed to be a reasonable upper threshold of compressive loading to limit compressive creep in the tested material. The predicted creep strain is believed to represent a conservative (higher bound) estimate since aging of the test specimens was not employed.

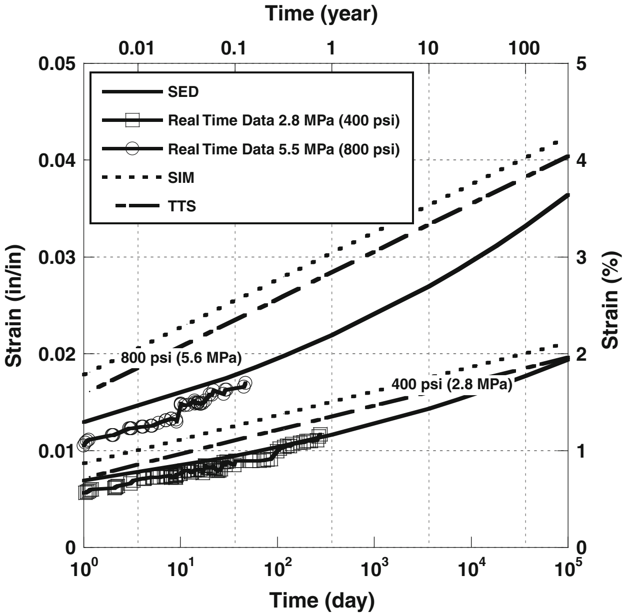


Fig. 15 Comparison of the predictive approach with real time creep data

5. Conclusions

The results of the accelerated creep tests conducted on virgin HDPE indicate that (1) both Time Temperature Superposition (TTS) and Stepped Isothermal Method (SIM) are appropriate methods for accelerating creep in compression of HDPE; (2) in TTS the constants, c_1, c_2, and the reported shift factor a_T (Table 1) appear to be the same in tension and compression, at least below 5.6 MPa (800 psi); and (3) preliminary results indicate that the tested HDPE loaded in compression will creep by approximately 2% in 100 years when loaded at an ultimate stress of 2.8 MPa (400 psi).

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