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Time-Temperature-Stress Superposition of PBX 9502 Compressive Creep Data for Lifetime Predictions

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Abstract. The plastic-bonded explosive (PBX) 9502 is a viscoelastic, high-solids loaded polymer bound composite comprised of 95 weight% (wt%) TATB explosive crystals and 5 wt% FK-800 polymer binder. The uniaxial quasi-static mechanical properties have been studied and characterized extensively over 25+ years, including creep. Creep is the strain evolution over time as a result of an asymmetric load typically at temperatures above ambient. Creep measurements to failure can take excessively long periods of time depending on various factors including applied stress, temperature, and loading rate that render a single test to failure impossible. Using the principles of time-temperature-stress superposition (TTSSP), short-term creep tests at various applied stresses and temperatures can be used for long-term creep predictions. The TTSSP model shifts short-term test data using two factors, one for temperature and stress, creating a master curve at a reference test condition. The master curve can be shifted to predict the creep response at any desired test condition. PBX 9502 compression specimens were tested at three temperatures and various applied stresses. This work discusses the TTSSP analysis of PBX 9502 compressive creep data to create a single comprehensive master curve.

INTRODUCTION

A plastic-bonded explosive (PBX) is a high-solids loaded polymer bound composite and a viscoelastic material. PBX 9502 is comprised of 95 wt% TATB (1,3,5-triamino-2,4,6-trinitrobenzene) explosive crystals and 5 wt% FK-800, a fluoro-copolymer [1]. The quasi-static compressive and tensile properties of PBX 9502 have been studied extensively for over 25 years including, monotonic loading [2-6], cyclic loading [7], and creep loading [8-10]. The work presented here focuses on the long-term creep response of PBX 9502.

Creep is the displacement or strain evolution over time from a constant applied load or stress. The creep response of a viscoelastic material, like PBX 9502, is applied stress and temperature dependent. Therefore, there is a large range of creep responses resulting from the large parameter space of various constant stress and temperature combinations. Also, some test conditions can take an excessively long time to reach failure, i.e., low temperature and low applied stress combinations, rendering some tests impossible to complete in a reasonable amount of time. It has been shown that PBX 9502 monotonic data follows typical viscoelastic response, and the principles of time-temperature superposition can be applied to the mechanical properties [5-6], which provides a master curve of mechanical response at a reference temperature. In this work we use the principles of time-temperature-stress superposition [11-16] on PBX 9502 creep data to obtain a master curve of creep response at a reference temperature and constant applied stress for long-term predictions.

EXPERIMENTAL PROCEDURE

All PBX 9502 compressive creep specimens were machined from isostatically pressed hemispheres. Compression specimens were machined to dimension of 1.125 inches in length and 0.375 inches in diameter. Figure 1 shows a schematic of the compressive creep loading apparatus. A yellow line indicates the Instron thermal chamber used to control the temperature to within +/- 1°C of the desired test temperature. The loading fixture comes as two, interleaved halves. The first half is comprised of three plates, between each pair of plates are three rods that connect them firmly.

The second half is comprised of three other plates, also with plate pairs connected by three rods. The central plates have holes cut (top view of plates on left side of schematic) that allows the two plate assemblies to be interleaved, sliding through each other as the specimen is compressed. Plates and rods are made of invar which has very low CTE. Strain on the specimen is measured with two oppositely mounted knife-edge extensometers (Instron model 862-2026) placed directly on the specimen and a Heidenhain LVDT (linear variable differential transformer) that is mounted on a fixed plate with the probe touching a mobile plate that moves with the plate directly on top of the specimen. The load is applied via gravity when the lower actuator is moves down and lowers the bottom half of the loading fixture. Physical weights placed on the hanger outside of the bottom of the chamber is used to determine the load applied to the specimen. Load is measured by a load cell located in the crosshead of the load frame outside the top of the chamber.

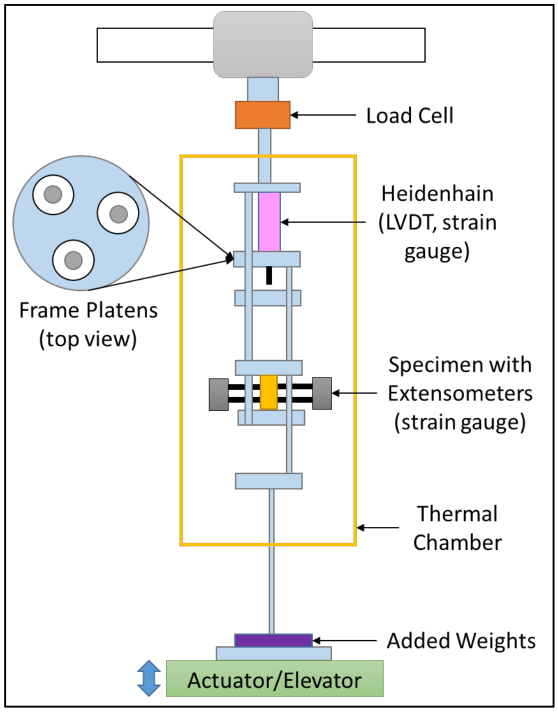

FIGURE 1. Schematic of the loading fixture for long-term compressive creep test. Load is applied via gravity with physical weights.

Compressive creep tests were all performed with an approximate loading rate of 0.001 in/in/sec and performed at three temperatures of 40, 50, and 60°C. At each temperature multiple applied constant creep stresses were applied between 3 MPa and 90% of the failure stress for that temperature and loading rate. The applied load on the specimen takes into account the bottom half of the loading fixture and hanger before weight is added. The maximum length of tests were 10 weeks if failure did not occur first.

RESULTS AND DISCUSSION

Figure 2, left, shows the axial strain (in units of in/in) versus time (in units of hours) for all compressive creep tests performed to-date. The time axis is plotted on a log scale for visual purposes. In the legend values presented in parentheses is the stress ratio for each test. Stress ratio is the ratio between the applied constant stress during the creep test and the ultimate failure stress at that test condition (loading strain rate and temperature dependent). Therefore, a stress ratio of 0.9 (90% of ultimate failure stress) is different for each temperature in this test series (strain rate held constant). For further analysis, the creep behavior under uniaxial stress is represented by creep compliance, which is defined as the time-dependent strain per constant creep stress. The creep compliance is plotted versus the log of time in Figure 2, right, and all further graphs will be plotted the same.

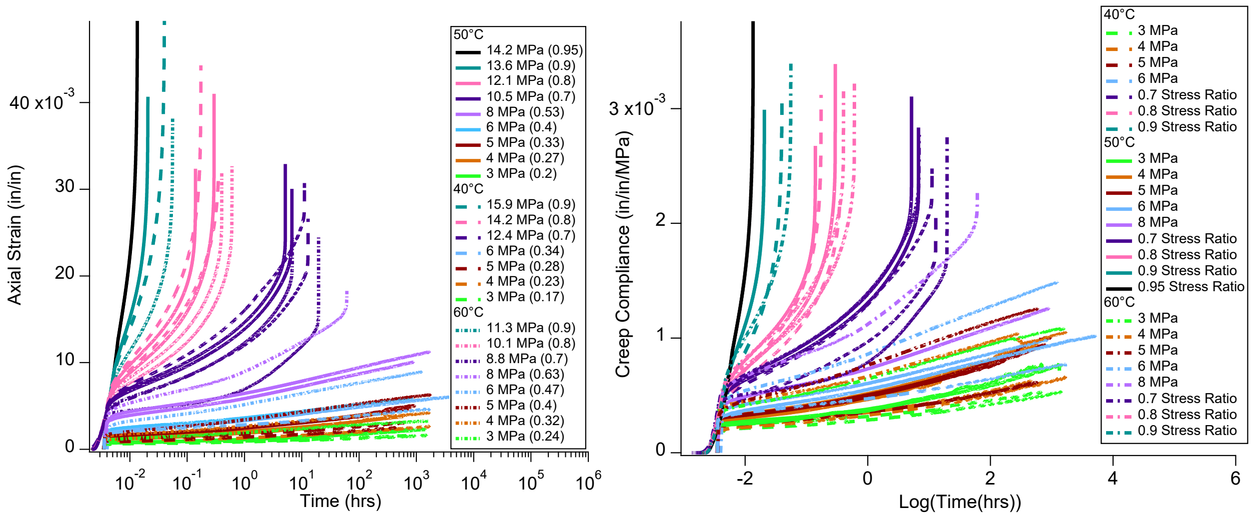

FIGURE 2. Strain vs. time (on a log scale) and creep compliance vs. Log (time) on the left and right, respectively, for all tests performed at three temperatures and multiple applied stresses. Values in parentheses are stress ratio at that test temperature.

PBX 9502 was demonstrated to be a viscoelastic material that follow the principles of time-temperature superposition (TTS) specifically applied to monotonic data previously [5]. Therefore, here we apply TTS to the creep data [5,6,11,12], first by plotting tests performed at the same applied stress together. The top plots in Figure 3 show the unshifted creep data for four applied stresses as an example. The same temperature shift factor of 6°C per decade of time is applied to all the data creating a master curve for each applied stress at the reference temperature of 40°C. The shifted stress master curves are shown for the four examples in the bottom plots of Figure 3.

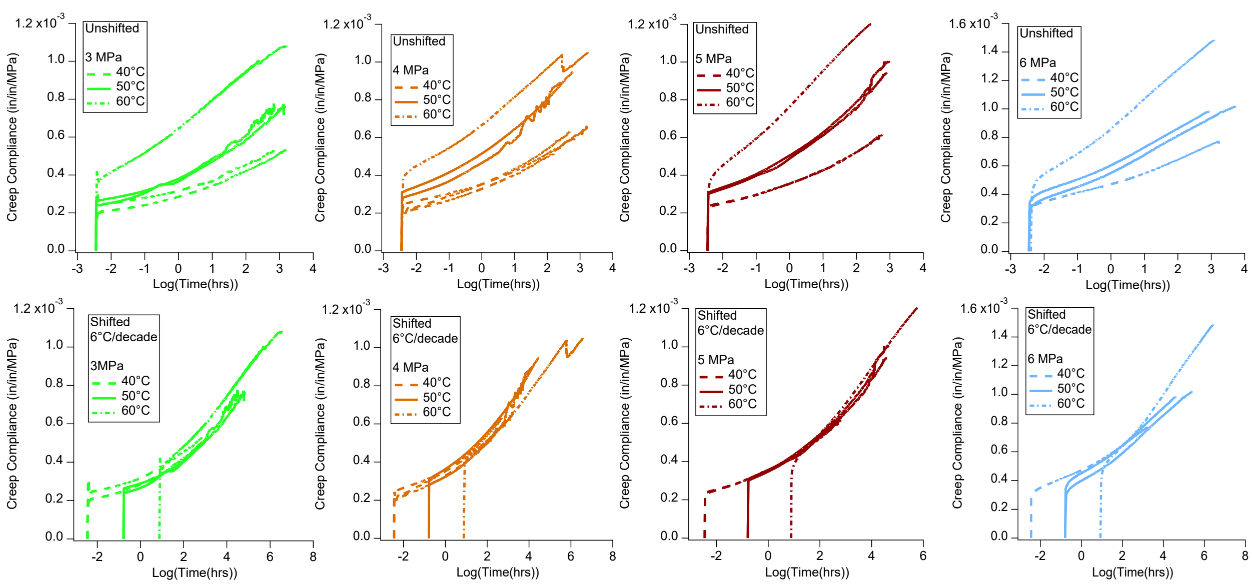

FIGURE 3. Creep compliance vs. Log (time) for tests performed at 3 MPa (far left), 4 MPa (second to left), 5 MPa (second to right), and 6 MPa (far right) and three temperatures at each stress (see legend for temperatures). Unshifted creep data on top and shifted master curves on bottom.

The principles of time-stress superposition (TSS) [13-15] can also be applied to the data by shifting tests performed at the same temperature but different creep stresses to create a temperature master curve at a reference stress. This is demonstrated in Figure 4 for the three test temperatures. Note that not all compressive creep tests have been completed at this time and gaps in the parameter space still exist (i.e, 8 MPa at 40°C). The remaining tests are still being performed to fill in all conditions at all temperatures, but analysis is still performed with the data currently available. All tests performed at each temperature are plotted unshifted in the top plots of Figure 4. Using the same stress shift factor of 1.2 MPa per decade of time for all data creates a master curve for each of the temperatures at a reference stress of 3 MPa. The shifted temperature master curves are shown for the three temperatures in the bottom plots of Figure 4.

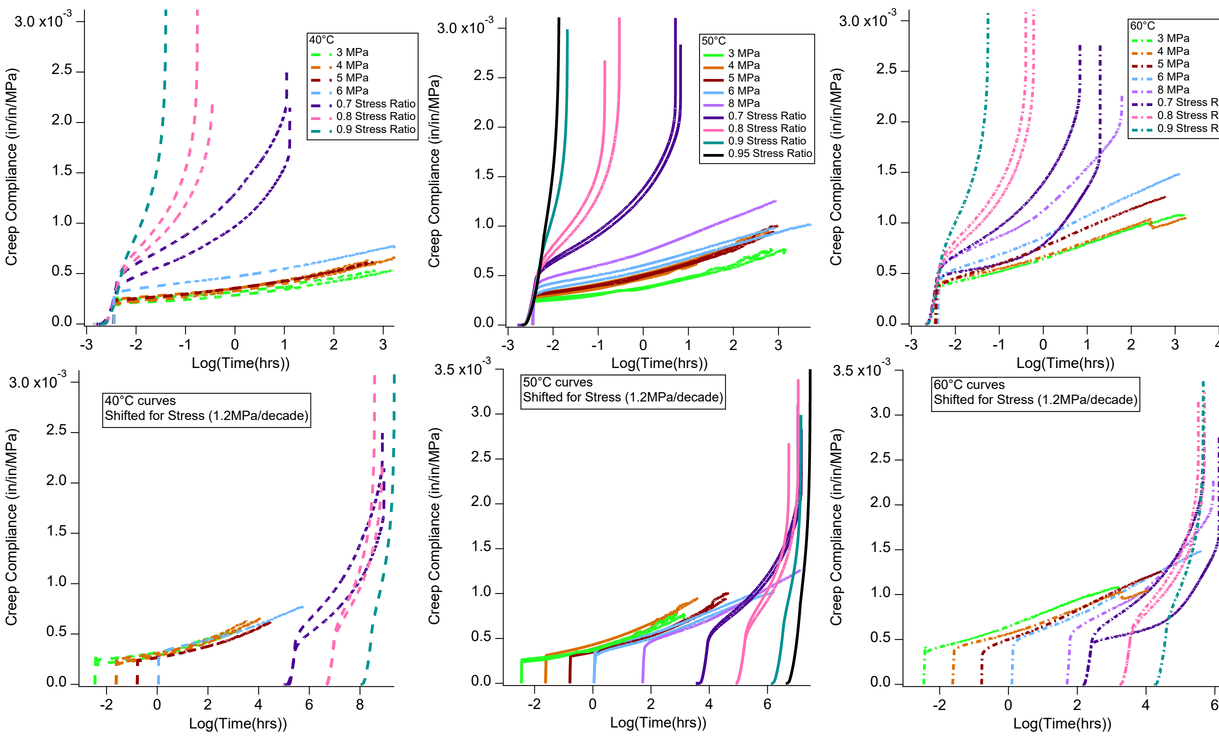

FIGURE 4. Creep compliance vs. Log (time) for tests performed at 40°C(left), 50°C (middle), and 60°C (right) at multiple stresses at each temperature (see legend for stresses). Unshifted creep data on top and shifted data on bottom.

The two time-dependent relationships shown above can be combined to form the Time-Temperature-Stress Superposition (TTSS) principle to create one master curve at a reference temperature and stress [16]. Figure 5 shows the final master curve using both the time-temperature and time-stress shift factors of 6°C and 1.2 MPa per decade of time, respectively, at reference conditions of 40°C and 3 MPa. From the master curve we see that the failure converges at approximately 10^8 hours which is 11,415 years at this condition. The shift factors can be used to shift the whole master curve to other conditions for failure predictions.

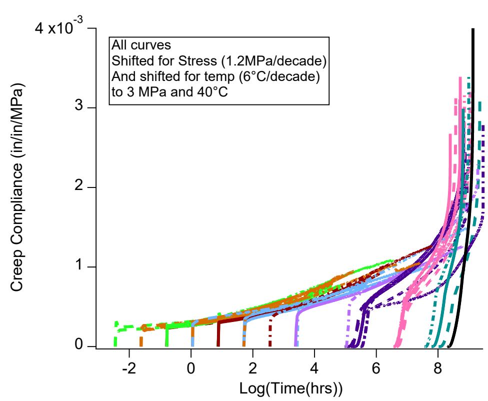

FIGURE 5. Creep compliance vs. Log (time) master curve for PBX 9502 compressive creep behavior shifted to equivalent test condition of 3 MPa and 40°C. Creep failure at this condition is predicted at ~10^8 hours, or ~11,415 years.

CONCLUSION

We have demonstrated that PBX 9502 follows the assumptions for viscoelastic behavior and the principles of time-temperature-stress superposition can be applied to long-term compressive creep data. The master curve produced from this analysis provides strain evolution behavior and failure time predictions for conditions that are impossible to measure, i.e., at very low applied stress and temperatures. The master curve can be shifted with the factors determined to any other test condition for creep behavior estimates at other temperatures and creep stress.

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