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Mechanical Behavior of PBXW-128 and PBXN-110 under Uniaxial and Multiaxial Compression at Different Strain Rates and Temperatures

Özgen Ü. ÇOLAK
Department of Mechanical Engineering, Yıldız Technical University, İstanbul-TURKEY
e-mail: colako@alum.rpi.edu

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Abstract

The influence of strain rate, temperature and confining pressure on the mechanical behavior of PBXN-110 binder "inert" (HTPB, Hydroxy-terminated Polybutadiene) and PBXW-128 simulant "inert" that is mixed with small particles of sugar, approximately 50% by weight, is presented. The polymer PBXN-110 is used as the matrix for the particle reinforced polymer composite (PBXW-128); the latter is the mock or inert equivalent of actual explosive material. The stress-strain response of both polymeric materials under uniaxial compression is dependent on the strain rate. On the other hand, it is observed that PBXW-128 exhibits temperature dependent behavior, while the mechanical response of PBXN-110 is not significantly affected at temperatures above the glass transition temperature. Compression experiments in the presence of confining pressure reveal that the stress-strain responses of both materials are rate insensitive.

Key words: Polymeric materials, Rate dependency, Temperature effect, Compression, Confining pressure.

Introduction

Polymers have been replacing metallic materials in many engineering applications such as load bearing components and applications involving the use of high explosive materials. Both single constituent polymers and composites have been used. The polymeric components are expected to perform as reliably as the metallic components that they are replacing. When they are used as matrix constituents for plastic bonded explosives, in order to determine the threshold pressure value for detonation and for enhancing the ignition process, it is imperative that a complete understanding of the mechanical response of polymers be known under different loading conditions.

It is well known that polymers exhibit strain rate and temperature dependent behavior. In addition, significant creep and relaxation can be observed even at room temperature. The material behavior of polymers can change from brittle to visco-plastic depending upon loading conditions and temperature. Their behavior can be explained in terms of their microstructures. Polymers can have either an amorphous or semi-crystalline structure. The degree of crystallinity and the size and distribution of the crystallites in a semi-crystalline polymer have a large effect on the mechanical properties of these materials. If the polymer has an amorphous structure, inelastic behavior depends on molecular chain flexibility, entanglement and on differences in the structure of the molecular chains. Molecular structures can be linear, branched, cross-linked and network. Linear long molecular chains have backbone bonds, which permit rotation but little extension. In cross-linked polymers, adjacent linear chains provide additional rigidity. At temperatures well below the glass transition, long molecular chains are rigid and result in a brittle character. At high temperatures, backbone bonds rotate and allow molecules to partially disentangle and move relative to one another. As a result, both viscoelastic and viscoplastic behavior can be observed (Bardenhagen *et al.*, 1997).

Structural components, which are subjected to severe loading conditions, need reliability and performance analyses prior to production. The first step in these analyses is the inelastic analysis, which provides information about stresses and strains during manufacturing and service time. During the design process, to perform inelastic analysis and the life predictions of engineering components, experimental results and constitutive models are needed to estimate the precise deformation behavior of these materials.

The modeling of inelastic deformation behavior of polymers has recently received considerable interest due to the increased use of polymers in many applications, such as from Peeters and Hackett (1981), Hasan and Boyce (1995), Krempl and Bordonaro (1995), Takashi *et al.* (1997), Bardenhagen *et al.* (1997), Krempl (1998), Krempl and Ho (1999), Khan and Zhang (2000), Krempl and Khan (2003) and Colak *et al.* (2003).

However, the complexity of polymeric behavior makes constitutive model development difficult. The following properties observed in polymers should be considered to develop an appropriate constitutive model.

1. Material behavior can be highly nonlinear and strain and temperature dependent.
2. Unloading curve is nonlinear.
3. Yield behavior is significantly affected by hydrostatic pressure.
4. Recovery at zero stress is significant.

Considering the behaviors listed above, the constitutive models developed for metallic materials need to be modified to represent the accurate mechanical behavior of polymers. To develop an experimental based constitutive model, the mechanical response of polymers needs to be investigated under different loading conditions, such as uniaxial and multiaxial monotonic and cyclic loading. In addition, a detailed knowledge of the influences of temperature and strain rate is essential.

In this study, the mechanical behavior of PBXW-128 and PBXN-110 under uniaxial compression with and without confining pressure is investigated. This paper explores the characteristics of the aforementioned polymeric materials at different strain rates and temperatures. The compressive stress-strain response of PBXW-128 and PBXN-110 was found to be dependent on strain rate and temperature. Particular attention is given to the mechanical behavior of polymeric materials under compression loading in the presence of confining pressure.

Experimental Procedures

The materials investigated in this paper are PBXW-128 simulant "inert" reinforced with sugar particles approximately 50% by weight and PBXN-110 binder "inert" (HTPB, Hydroxy-terminated Polybutadiene). The former is an inert or mock equivalent of an explosive. They have been used as a structural substitute for explosives.

Displacement controlled quasi-static compression experiments are performed on PBXW-128 and PBXN-110 at different strain rates and temperatures. In addition, the mechanical response of the polymeric materials named above is investigated under compression loading in the presence of confining pressure.

All experiments are performed in a servo hydraulic, computer controlled, MTS axial-torsional mechanical testing machine.

Uniaxial compression tests at different strain rates

Compression experiments at room temperature were conducted at 3 different strain rates, 10^{-4}, 10^{-2}, 10^{0} 1/s. Cylindrical specimens 1.0 inch (25.4 mm) in diameter and 1.5 inches (38 mm) in length were deformed up to 30% and 50% engineering strain and unloaded at the same strain rate. Standard vacuum grease was used to reduce the friction between the interfaces of the specimen with platens and to eliminate non-homogeneous deformation. During the test no bulging or buckling of the sample was observed indicating that friction was sufficiently reduced. Due to the low strength of the materials investigated, it was quite difficult to get an accurate amount of compressive load from the MTS machine. In order to determine the accurate force applied on the specimen during the experiments, external load cells (300 lbf (1334.4 N) and 10 lbf (44.48 N)) were used. Axial displacements are monitored from the displacement transducer inside the MTS.

Uniaxial compression tests at different temperatures

Uniaxial compression tests are performed on the same materials and geometry at temperatures of –73, 0, 22 and 65 °C. All temperature tests were conducted at a strain rate of 10^{-2} /s. Using a heating tape, the specimens were heated up to 65 °C until the temperature stabilized and loaded up to a 30% engineering strain. Low temperature compression tests were performed at –73 and 0 °C. These temperatures are reached by leaving the specimen in dry ice and ice-water, respectively for 2 h. In order to reduce the friction and eliminate the barreling that can be commonly observed during compression experiments, Dow corning 41 lubricant was used for high temperature tests.

Room temperature compression test in the presence of confining pressure

Experimental investigations were conducted to determine the mechanical response of PBXW-128 and PBXN-110 under uniaxial compression in the presence of confining pressure. A cylindrical specimen was placed inside a metallic tube and compression loading was applied from both directions axially at strain rates ranging from 10^{-4}, 10^{-2} and 10^{0}/s (Figure 1). The circumferential surface of the test sample was lubricated, thus free to deform axially, while it was constrained in the radial direction by the aluminum tube. The thin walled tube was made of 6061-T6 Aluminum. The strain along the circumferential direction of the tube was recorded by means of strain gages. The force was determined from the MTS load cell, and the MTS displacement transducer provided the axial displacement measurements. The aluminum thin-walled tube first underwent elastic deformation and then plastic deformation. Therefore, the confining pressure created by applying the axial compression was not constant and depended on the material properties of aluminum. From uniaxial compression experiments on 6061-T6 Aluminum solid cylinders, the Young's Modulus, yield stress, strain hardening coefficient and exponent were determined. The true stress-strain curve of 6061-T6 Aluminum at a strain rate of 10^{0} /s is given in Figure 2. The Young's modulus of 6061-T6 Aluminum is E = 60331 MPa. Yield strength is σ_y = 310 MPa. For some metals and alloys, the plastic region of the true stress-strain curve up to necking can be approximated by

$$\sigma = H\varepsilon^n \tag{1}$$

where H and n are material constants. The parameter n is often called the strain-hardening exponent where H is termed the strain-hardening coefficient. These material parameters can be determined using the plastic region of the true stress strain curve of 6061-T6 Aluminum. To determine n and H parameters, ln(σ) versus ln(ε) in the plastic region is plotted in Figure 3. Using trend line analysis, line equation of ln(σ) versus ln(ε) curve is

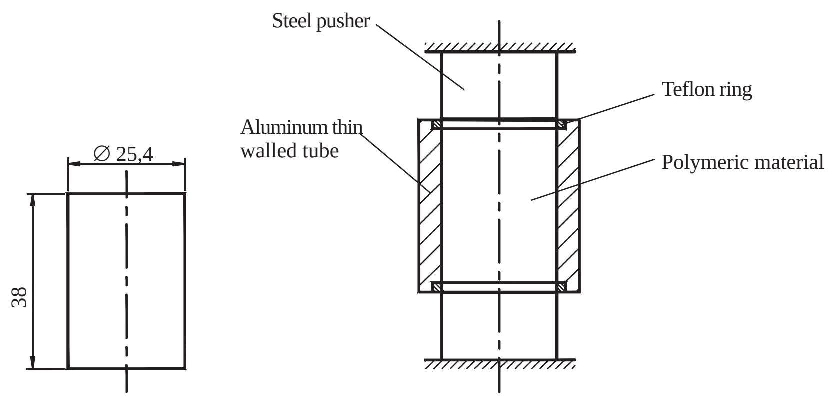

Figure 1. a) A standard compression specimen with circular cross section. b) Schematic representation of the apparatus used to conduct compression test with confining pressure.

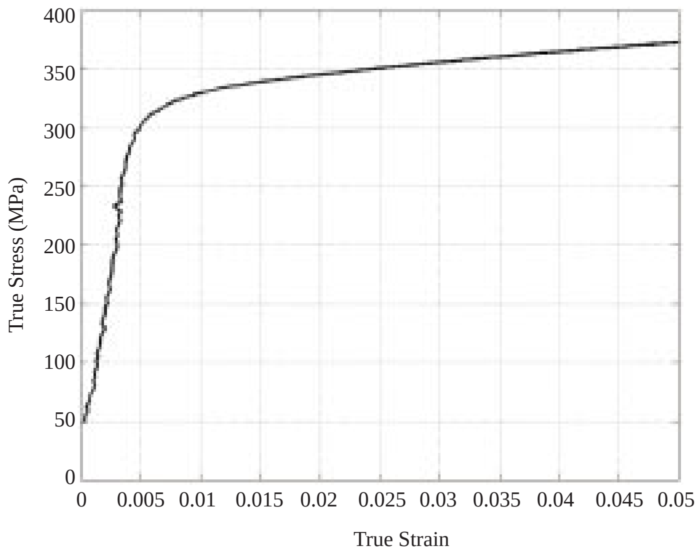

Figure 2. True stress-strain curve of 6061-T6 Aluminum at a strain rate of 10^0 /s under uniaxial tension.

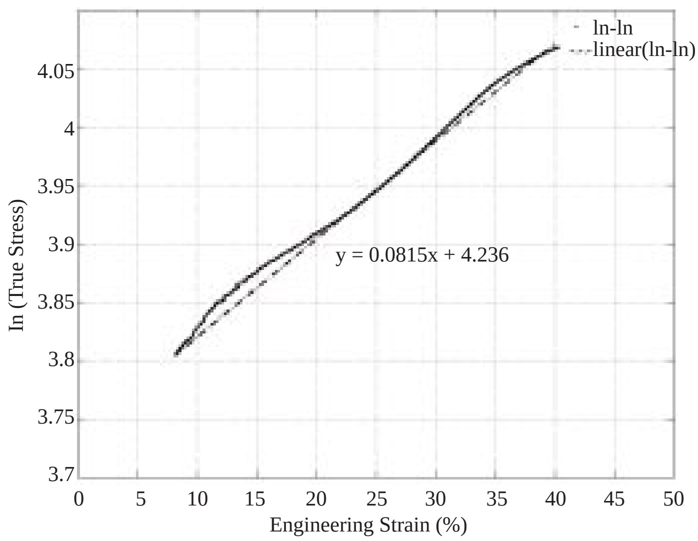

Figure 3. Ln(true stress) versus ln(true strain) of 6061-T6 Aluminum in the plastic region. Solid line represents the experimental data.

$$\ln(\sigma) = 0.0815\ln(\varepsilon) + 4.236 \tag{2}$$

If the logarithm of Eq. (2) is considered,

$$\ln(\sigma) = \ln(H) + n\ln(\varepsilon) \tag{3}$$

and Eqs. 2 and 3 are set to equal to each other, the strain hardening exponent is $n = 0.0815$ and strain hardening coefficient H is $H = \exp(4.236) = 69$ ksi (476 MPa).

Using this information and measured circumferential strain, true circumferential strain was ($\varepsilon_{\theta\theta}$) calculated and the circumferential stress in the tube was calculated as follows:

$$\begin{aligned} \sigma_{\theta\theta} &= E\varepsilon_{\theta\theta}(\sigma_{\theta\theta} \leq \sigma_y) \\ \sigma_{\theta\theta} &= H\varepsilon_{\theta\theta}^n(\sigma_{\theta\theta} > \sigma_y) \end{aligned} \tag{4}$$

Confining pressure, i.e. pressure in the radial direction at the interface of polymer and aluminum, was obtained using this calculated stress and the geometry of the tube. The aluminum tube used is a thin walled tube having $D_o = 1.123$ inches (28.5 mm) outer diameter and $D_i = 0.877$ inches (22.2 mm) inner diameter (thickness t = 0.123 inches (3.12 mm)).

It is assumed that the pressure in the radial direction of a thin walled tube is approximately equal to the confining pressure on the polymer and the confining pressure is calculated as follows:

$$p = \frac{\sigma_{\theta\theta} 2t}{D_o} \tag{5}$$

where t and D_o are the thickness and outer diameter of the aluminum tube respectively.

A maximum 80 MPa confining pressure was obtained with this experimental method. By changing the material and thickness of the tube, confining pressure can be increased.

Considering axial strain and circumferential strain, change in volume is calculated as

$$\%\text{ Change in volume } = 100\left(\frac{V - V_o}{V_o}\right) \tag{6}$$

where V and V_o are current and initial volumes respectively.

Results and Discussion

Uniaxial compression tests at different strain rates

Cylindrical specimens of PBXW-128 inert simulant were subjected to quasi static uniaxial compression loading at the strain rates of 10^{-4}, 10^{-2} and 10^{0}/s up to 50% engineering strain and unloaded at the same loading rates. Engineering stress versus strain curves of PBXW-128 under quasi-static compression loading and unloading at 3 different strain rates are given in Figure 4. Note that, throughout the paper, compression strain and stresses are plotted as positive values. It is observed that material exhibits nonlinear rate dependency under compression loading at room temperature, a 100-fold increase in loading rate results in much less than a 100-fold increase in the stress level. Nonlinear rate dependency is obvious even in the initial elastic region. Upon changing loading direction, nonlinear unloading behavior is observed for all loading rates. Unloading curves merge and at the end of unloading, and approximately the same amount of residual strain remains. Most of the residual strain vanished with time, leaving some permanent strain in the material. Thus, the overall behavior of PBXW-128 polymeric material can be described as nonlinear visco-elastic and visco-plastic.

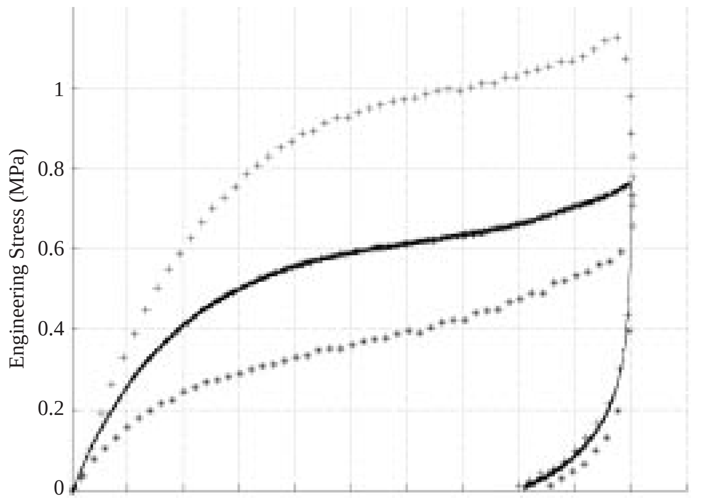

Figure 4. Engineering stress versus engineering strain curves of PBXW-128 under monotonic compression loading at room temperature with the strain rates of 10^{-4} (bottom curve), 10^{-2} and 10^{0}(top curve) /s.

A second set of room temperature compression tests was performed on PBXN-110 binder "inert". Figure 5 exhibits the experimental results at the strain rates of 10^{-4}, 10^{-2} and 10^{0}/s. Quite different behavior from PBXW-128 is observed. Material behavior is predominantly nonlinear visco-elastic. However, some dissipation is observed and dissipation increases with increasing strain rate. Nonlinear rate sensitivity is also apparent; however, rate sensitivity is small compared to PBXW-128 simulant composite. Engineering stress versus the strain curve with fastest strain rate reaches zero stress at a larger strain (at 4.3%) than the other stress-strain curves (at around 2 and 2.5%).

Uniaxial compression tests at different temperatures

The mechanical characteristics of polymers are much more sensitive to temperature changes than those of metallic materials: increasing temperature produces i) a decrease in elastic modulus and ii) a reduction in tension or compression strength.

Engineering stress versus strain curves of PBXW-128 simulant composite under compression at different temperatures, -73, 0, 22 and 65 °C, are depicted in Figure 6. It is observed that increasing temperature decreases the strength of the material, as expected. Similar to room temperature experimental

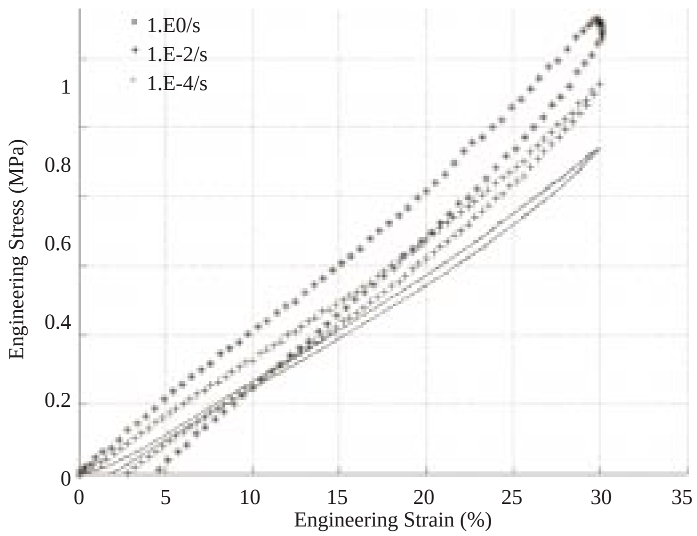

Figure 5. Engineering stress versus engineering strain curves of PBXN-110 under monotonic compression loading at room temperature with the strain rates of 10^{-4}, 10^{-2} and 10^{0}/s.

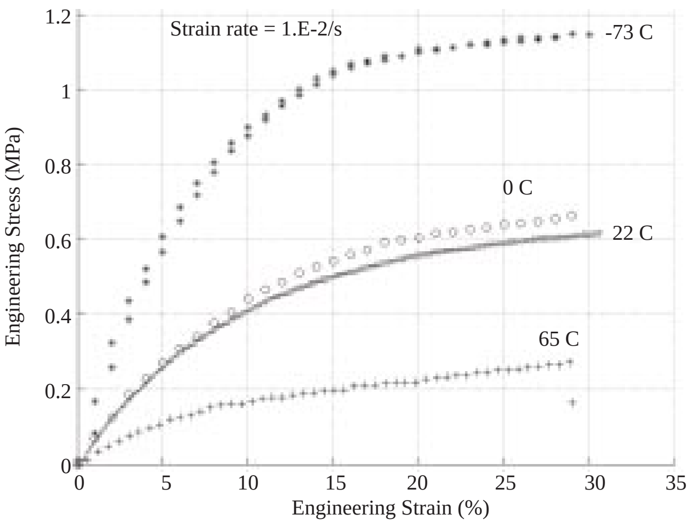

Figure 6. Engineering stress versus engineering strain curves of PBXW-128 under monotonic compression loading at different temperatures with the strain rate of 10^{-2} /s.

results, the polymeric material, exhibits nonlinear visco-elastic and visco-plastic behavior at different temperatures, ranging from –73 to 65 °C.

The mechanical behavior of PBXN-110 binder under uniaxial compression test at 4 different temperatures is depicted in Figure 7. All different temperature tests were performed at a strain rate of 10^{-2} /s. At a temperature of –73 °C, which is below the glass transition temperature, the strength of the material increases while an insignificant temperature effect is observed at temperatures above the glassy transition temperature. Dissipation at high temperatures appears to be less than for the room temperature case. On the other hand, the stress level is the same at room and high temperature. It is concluded that PBXN-110 exhibits temperature insensitivity at temperatures above ambient conditions.

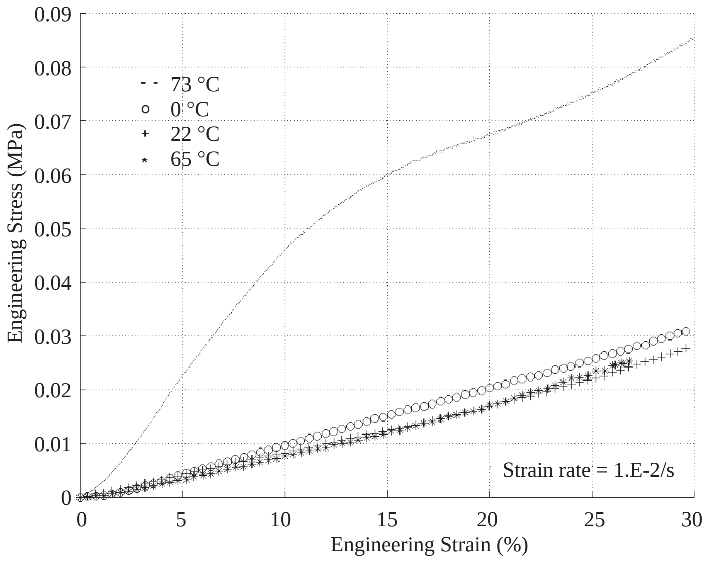

Figure 7. Engineering stress versus engineering strain curves of PBXN-110 under monotonic compression loading at different temperatures with the strain rate of 10^{-2} /s.

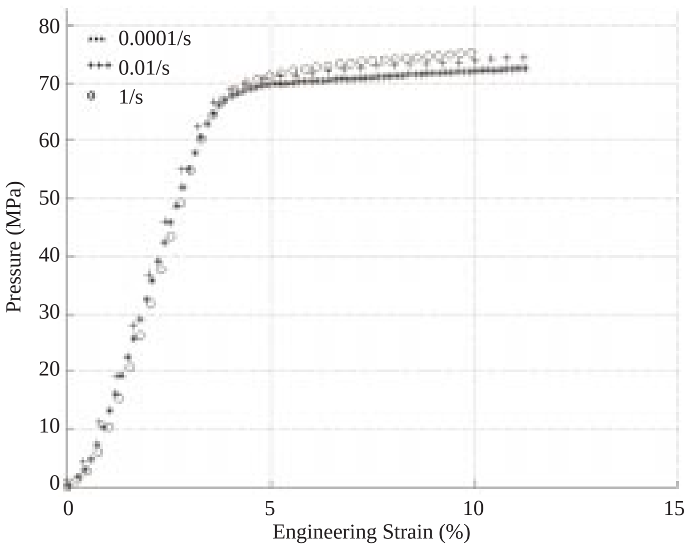

Figure 8. Engineering stress versus engineering strain curves of PBXW-128 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

Room temperature compression test in the presence of confining pressure

Engineering stress and confining pressure versus engineering strain curves of PBXW-128 and PBXN-110 are given in Figures 8 through 11 for 3 different strain rates. Both the materials investigated exhibit almost linear elastic and inelastic behavior under confining pressure. It is apparent that their material behavior is almost rate independent under compression loading in the presence of confining pressure. Confining pressure depends on the tube material and, when the tube deforms elastically, materials exhibit linear elastic behavior, and after the point where the aluminum tube undergoes inelastic deformation, linear hardening is observed. It is observed that material behavior is rate insensitive in the elastic region contrary to the behavior under compression loading without confining pressure.

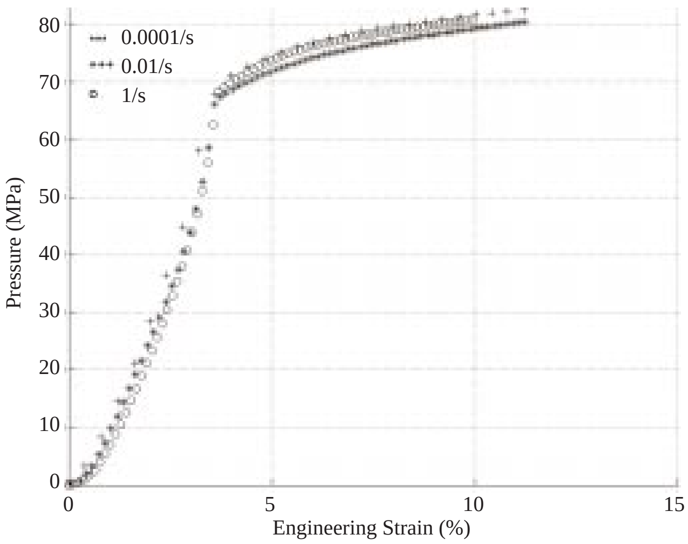

Figure 9. Confining pressure versus engineering strain curves of PBXW-128 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

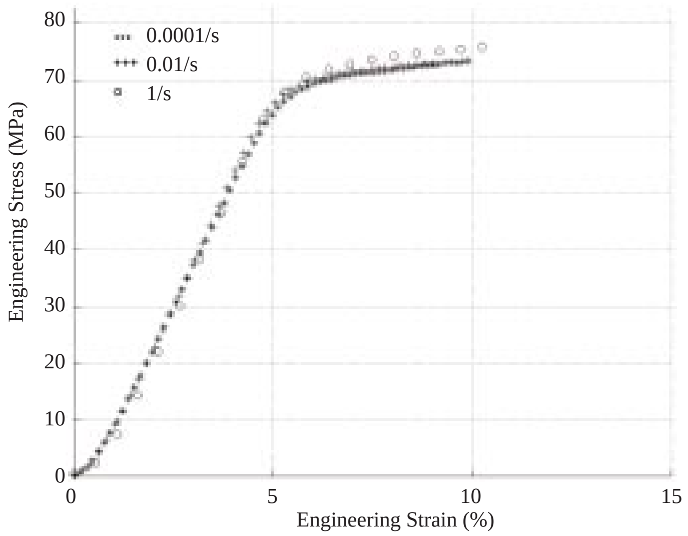

Figure 10. Engineering stress versus engineering strain curves of PBXN-110 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

Figures 9 and 11 depict the confining pressure versus engineering strain of PBXW-128 and PBXN-110 under monotonic compression loading with confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} and 10^{0}/s. Both figures reveal similar results: pressure depends on the material properties of the aluminum tube; it changes with the deformation of the aluminum tube and reaches 80 MPa at 10% engineering strain.

Contrary to metallic materials, the mechanical response of polymeric materials is influenced by hydrostatic pressure. As a result of hydrostatic pressure, volume change can be observed. The change in volume under confining pressure is investigated and confining pressure versus change in volume curves are given in Figures 12 and 13 for PBXN-110 and PBXW-128, respectively. A 5% volume change at 80 MPa pressure is observed for PBXN-110 while volume change in PBXW-128 is approximately 3%.

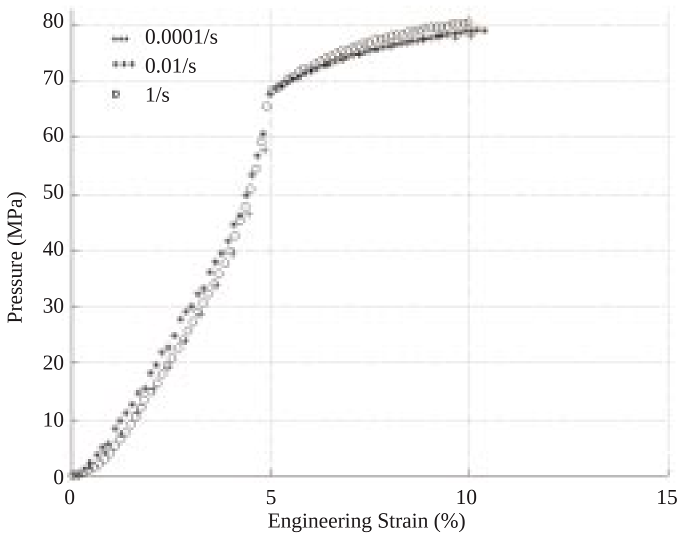

Figure 11. Confining pressure versus engineering strain curves of PBXN-110 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

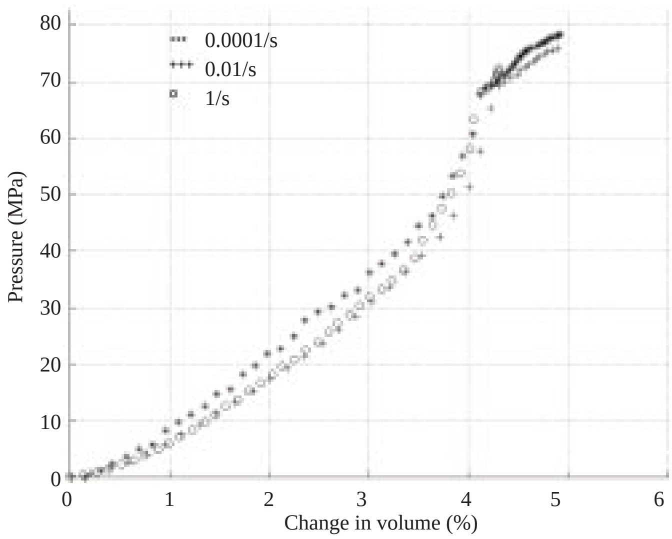

Figure 12. Confining pressure versus change in volume curves of PBXN-110 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

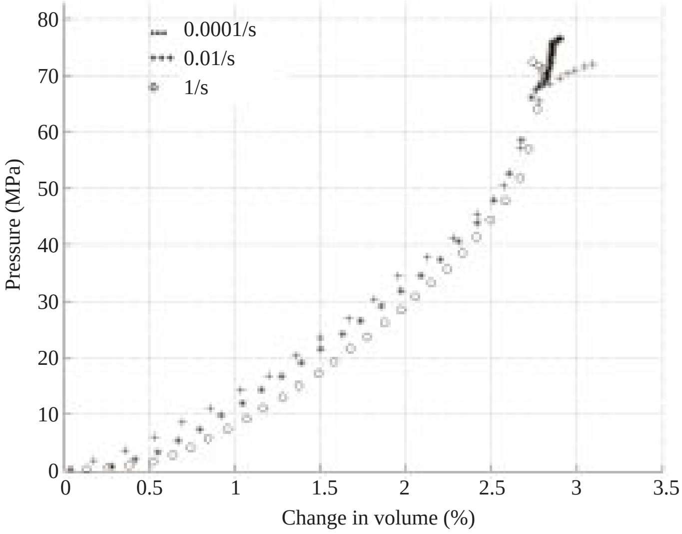

Figure 13. Confining pressure versus change in volume curves of PBXW-128 under monotonic compression loading in the presence of confining pressure at room temperature with 3 different strain rates of 10^{-4}, 10^{-2} 10^{0}/s.

Conclusions

The mechanical response of polymer PBXN-110 and a particle reinforced composite PBXW-128 was investigated under compression loading with and without confining pressure at different temperatures and loading rates. For both materials, behavior under uniaxial compression loading was found to be dependent upon loading rate. PBXW-128 was temperature dependent under compression loading without confining pressure. On the other hand, PBXN-110 was found not to be significantly sensitive to temperatures above the glass transition temperature. It was observed that the material response of both materials under compression loading with confining pressure was rate independent.

As technology has evolved over the past couple of decades, the analysis of the inelastic deformation behavior of engineering materials became an important element in the design, life prediction and fatigue performance of components subjected to severe mechanical and thermal cycling. As a computational tool, inelastic finite element analyses are used to calculate the stresses and strains as a function of position and time for a given operating history. In finite element analyses, realistic constitutive models are needed to describe the material behavior accurately. A critical investigation of constitutive models for elastic and plastic or viscoelastic and viscoplastic deformation requires experiments under different loading conditions, temperatures and strain rates. One of the most challenging obstacles in the implementation of these models is the determination of material constants. Experiments performed on PBXN-110 and PBXW-128 can be used to determine the material constants for further constitutive models.

Acknowledgments

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