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Investigating the Strain Rate Effects on Cumulative Damage in a Highly Filled Polymeric Material

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Introduction

Particle reinforced composites are widely used for attaining increased modulus, strength and/or toughness depending on the application. Such composites exhibit non-linear constitutive response due to various factors such as damage (debonding, cavity or vacuole formation, cracking), hysteresis during loading-unloading (Mullins effect), and viscoelasticity. Such non-linear behavior is observed extensively in filled polymer or rubber products such as toughened plastics, tires, and solid propellants. A number of studies have been performed to address one or more of the issues contributing to the non-linear behavior of these composites (1-4).

Throughout the loading history, the progressive development and interaction of various damage modes change the state of the material, or the mechanical response of the material. In general, when the particulate composite material is tested under a constant strain rate condition, the initial linear portion of the stress-strain curve is associated with a stretching on undamaged material, with the filler particles bonded to the binder. As the external load is continuously increased, at a certain critical stress level, dewetting occurs. When the density of the dewetted particles reaches a critical value, the rigidity of the material is thereby reduced, and usually this critical dewetting state coincides with the transition from linear response to nonlinear behavior. As the specimen is continuously stretched, the number of dewetted particles is increased, and the formed voids start to grow and coalesce. This damage process is related, primarily, to the nonlinear response of the material, and it can be characterized by bulk volume change during stretching. The bulk volume change during straining is usually known as the strain dilatation. The extent of the volume dilatation depends on the nature of the binder/particle system, the testing temperature, and the strain rate. Therefore, to effectively use the material in structural applications one needs to understand the damage initiation and evolution processes and the effects of damage on the material's response.

The Experiments

In this study, the effect of strain rate on the damage state in a highly filled polymeric material, containing hard particles embedded in a rubbery matrix, was investigated. Two different loading conditions, constant strain rate and dual-strain rate, were considered. For the constant strain rate tests, a series of tests were conducted under four strain rates (0.0073, 0.073, 0.73, and 7.3 cm/cm/min). For the dual-strain rate tests, the strain rate was changed when the applied strain level reached 10%, and the specimens were subjected to either a low-high (0.0073 cm/cm/min-7.3 cm/cm/min) or a high-low (7.3 cm/cm/min –

0.0073 cm/cm/min.) strain rates. During the tests, the load, the axial displacement, and the volume of the specimen were recorded on disk and strip chart recorder. These data were used to calculate the stress, strain, and volume dilatation.

Results

Typical plots of stress, strain, and volume dilatation as functions of different constant strain rates and dual-strain rates are shown in Fig. 1 and Fig. 2, respectively. From Fig. 1, it is seen that strain rate has a significant effect on the material response and the volume dilatation. However, the values of the volume dilatation measured from the begin of the test to the maximum stress for different strain rates are insensitive to the strain rate. It is interesting to note that the change of the strain rate in the dual-strain rate test does not cause a sudden change in the volume dilatation. In other words, the volume dilatation is continuously increased when the strain rate is suddenly changed in the dual-strain rate test.

To determine the damage state in the material, a linear cumulative damage theory was used to derive a time-dependent damage parameter, $D(t) = \left[\int_0^t \sigma^\beta \, dt \right]^{1/\beta}$. Plots of D (t) as functions of time are shown in Fig. 3. From Fig.3, for a given strain, D (t) is highly dependent on the strain rate. However, the critical value of D (t) is insensitive to the strain rate.

Conclusions

In this study, the constitutive behavior and damage state in a particulate composite material under different displacement rate conditions were investigate. Experimental data show that loading rate has a significant effect on the constitutive behavior and the volume dilatation of the material. It also shows that for a given time, the damage state is highly dependent on the displacement rate. However, the critical damage state is insensitive to the displacement rate and the loading history.

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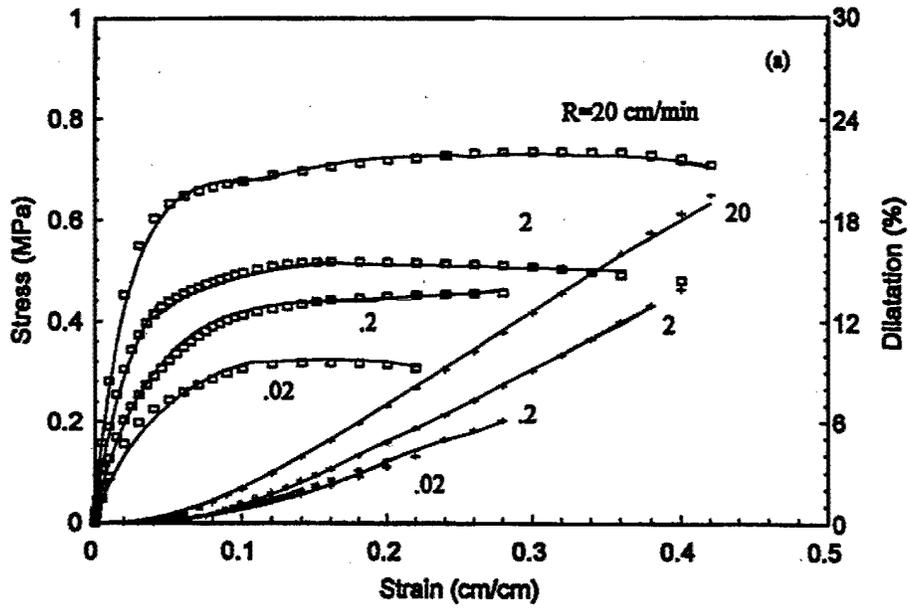
Fig.1 Stress-Strain and Dilatation Curves for Different Displacement Rates
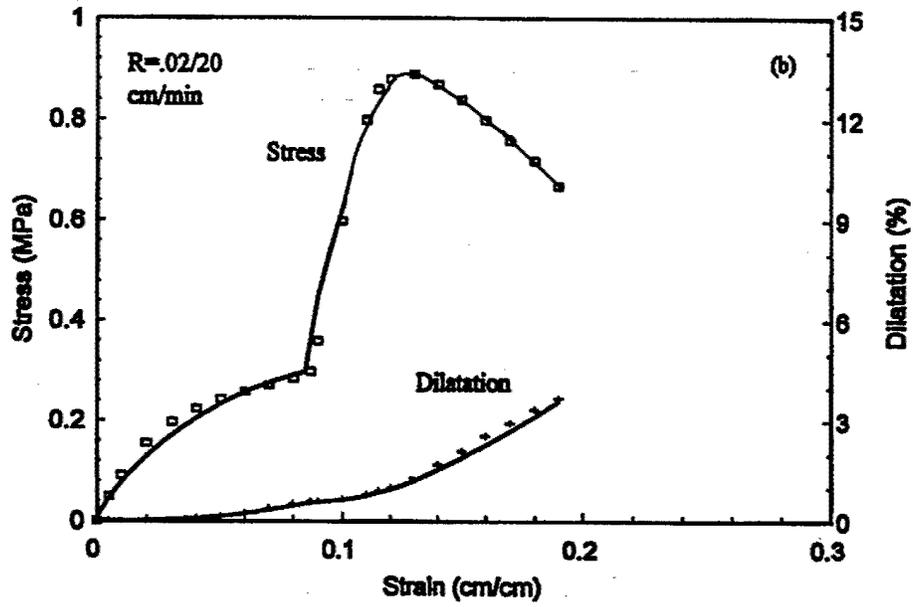
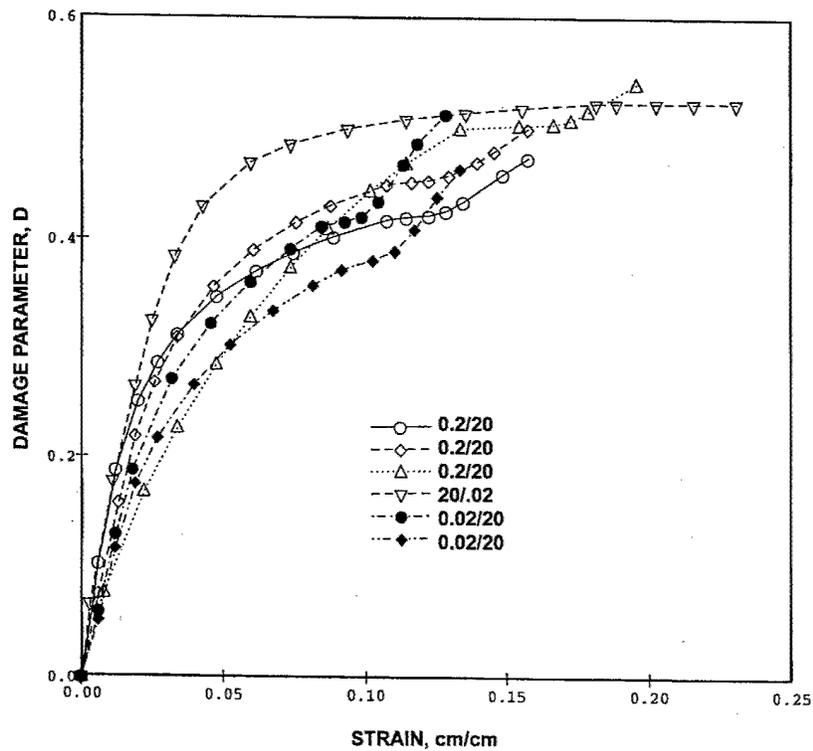Fig.2 Stress-Strain and Dilatation Curves for Dual-Displacement Rate

Fig.3 Damage Parameter versus Strain for Dual-Displacement Rates.