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Title: Observed physical processes in mechanical tests of PBX9501 and recomendations for experiments to explore a possible plasticity/damage threshold

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Observed physical processes in mechanical tests of PBX9501 and recommendations for experiments to explore a possible plasticity/damage threshold

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Abstract

This memo discusses observations that have been made in regards to a series of monotonic and cyclic uniaxial experiments performed on PBX9501 by Darla Thompson under Enhanced Surveilance Campaign support. These observations discussed in Section Cyclic compression observations strongly suggest the presence of viscoelastic, plastic, and damage phenomena in the mechanical response of the material. In Secton Uniaxial data analysis and observations methods are discussed for separating out the viscoelastic effects. A crude application of those methods suggests the possibility of a critical stress below which plasticity and damage may be negligible. The threshold should be explored because if it exists it will be an important feature of any constitutive model. Additionally, if the threshold exists then modifications of experimental methods may be feasible which could potentially simplify future experiments or provide higher quality data from those experiments. A set of experiments to explore the threshold stress are proposed in Section Exploratory tests program for identifying threshold stress

Cyclic compression experiment

Darla Thompson performed several experiments on PBX 9501 to explore the behavior of the material under cyclic loading. She used a standard compression specimen (cylindrical 0.5 in diameter 1.125 inch tall) and performed the experiments at 23°C. She applied two displacement schedules. Both schedules loaded the sample in displacement control at a rate of 0.05 in/min to a predetermined displacement. The displacements were then held for 1 second before returning to zero displacement at a rate of 0.05 in/min. Both load schedules increased the maximum displacement with each cycle to explore the affect of peak stress on subsequent cycles. The two displacement schedules differed in their recovery time. One of the schedules shown in Figure 1 included 1 second of recovery time. The other included 3000 seconds recovery time as shown in Figure 2. Each displacement schedule was applied to two samples for a total of four experimental data sets. One flaw in the load schedules identified by Darla was that the long and short recovery schedules used different displacement hold points which may make one to one comparison difficult but there is still much to be discovered in analyzing this data.

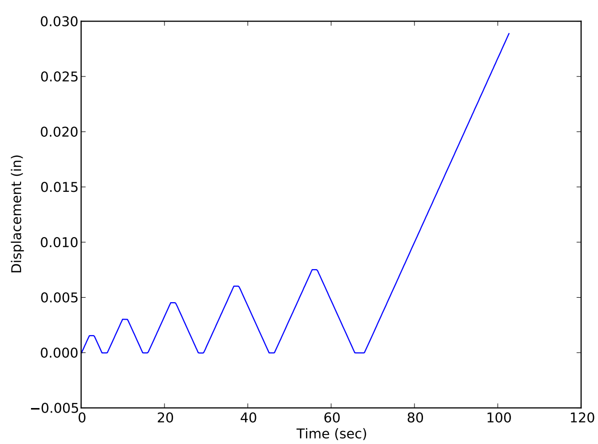

Figure 1: Displacement with 1 second recovery

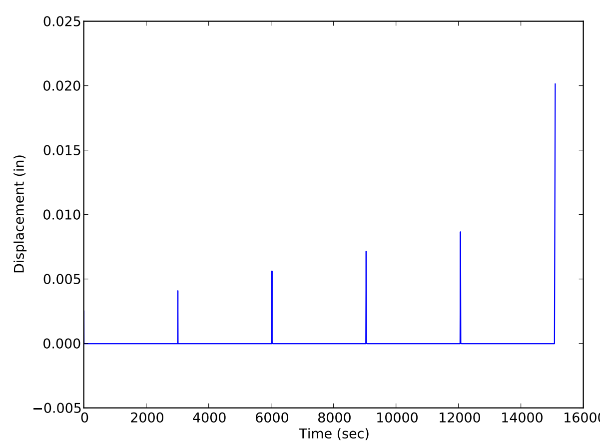

Figure 2: Displacement with 3000 second recovery

Cyclic compression observations

The strain measured during two of these experiments is shown in Figures 3, and 4. A portion of the strain does not recover between cycles in both experiments which may be attributable to plasticity, but much more strain is recovered in the experiments with 3000 seconds recovery time then those with 1 second recovery time so we may conclude that the material recovers viscoelasticly.

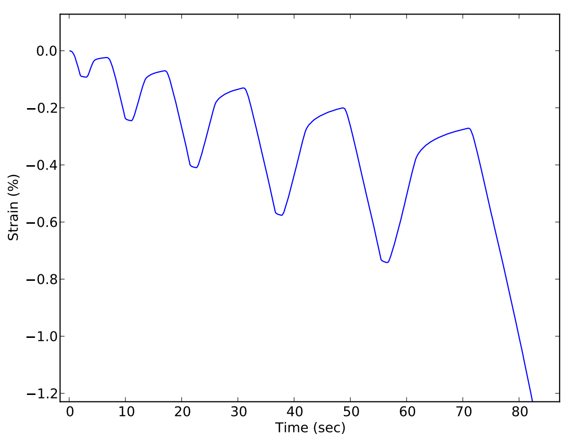

Figure 3: Strain vs. Time with short recovery

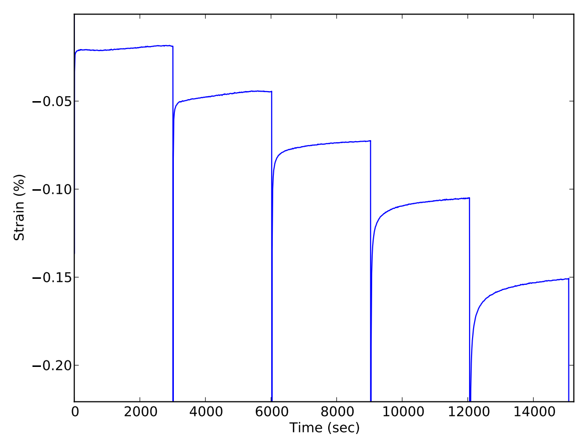

Figure 4: Strain vs. Time with long recovery

In Figure 5 the unloading and recovery stage for each cycle of one of the short recovery experiments is shown. The curves have been shifted vertically to end at zero strain so we can more easily identify the differences between cycles. The knee in the strain curves corresponds to the platens losing contact with the sample, however; the sample is not done recovering when the platen loses contact which again demonstrates a viscoelastic component to the sample strain. Additionally, each cycle requires more time to recover than the preceding cycle. This is likely attributable to the greater load and subsequent viscoelastic strain at each cycle.

Figure 6 shows the recovery stages of each individual cycles for one of the experiments with a long recovery time. Again, these curves have been shifted vertically to highlight the differences between the recovery. There is a small anomaly in the first cycle recovery but overall they appear to be recovering asymptotically. The recovery rates increase with each cycle but they have a steeper slope at the end of the 3000 seconds, which indicates that the samples had not fully recovered.

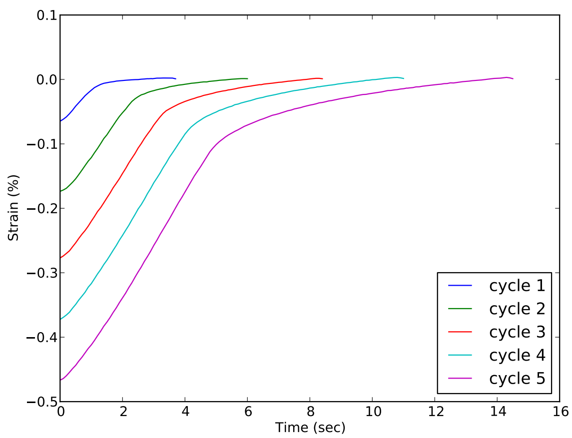

Figure 5: Strain during unloading and short recovery

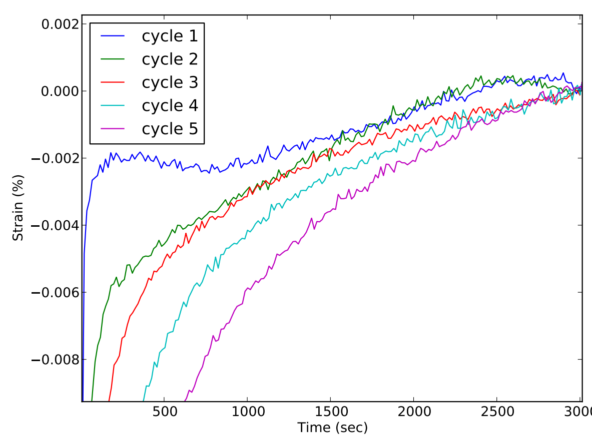

Figure 6: Strain during long recovery

Next, we plot the stress-strain curves for each cycle. Figures 7, and 8 show the stress-strain curves shifted such that the cycles artificially begin at zero strain. In both experiments, the curves follow a similar early path but in the experiment with a long recovery the curves diverge in a non-random way. Above about 1.5 MPa the material appears to be softer with each cycle.

The softening is likely attributable to damage though when the short duration and long duration experiments are plotted on the same axis as in Figure 9 we see that a longer recovery results in less softening of the material as compared to previous cycles. This is contrary to the idea that higher stresses cause more damage. Ignoring for a moment the fact that even the initial cycle for the short recovery experiment appeared to be less stiff I hypothesize that incomplete viscoelastic recovery can mask some softening indicative of damage. Simulations of a pure viscoelastic material were performed and the results are shown in Figure 10. The first stress-strain curves represented is of a new unstressed sample and is marked *No residual stress*. A constant strain rate is applied and then the load is removed at the same strain rate and $\frac{2}{3}$ of the strain is allowed

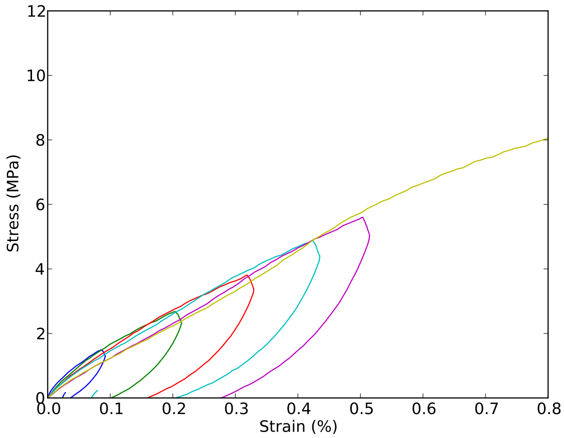

Figure 7: Cyclic stress-strain with short recovery

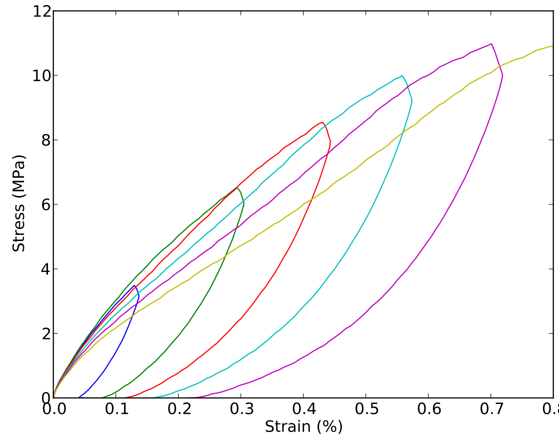

Figure 8: Cyclic stress-strain long recovery

to recover. The next curve is marked *residual stress* and represents a loading at the same strain rate but beginning as soon as the first simulation completely unloads. The final curve is marked *less residual stress* and represents a simulation beginning after the $\frac{2}{3}$ recovery of the first simulation in other words a little more complete recovery. The two simulations with incomplete viscoelastic recovery are shifted to hi-light the apparent increase in stiffness.

These simulations demonstrate that the incomplete recovery may explain the lack of apparent damage in the short recovery experiment though it is more likely that the sample was pre-damaged. In any case it does demonstrate a need to achieve complete viscoelastic recovery between cycles of future experiments in order to truly understand the effect of damage.

Another observed phenomena is that the compressive strain measured by the extensometers continues to grow even while the platens remain stationary. Figure 11 shows the first cycle of one of the short recovery experiments along with an inset zoom of the portion where the platens are stationary. We see an increase in compressive strain of about 40 $\mu\epsilon$ during this time. I hypothesized that this is due friction between the platens and the sample causing a non-uniform state of stress in the sample. This was investigated with a simple viscoelastic model in Abaqus. Figure 12 shows the axial stress at the beginning the hold portion of

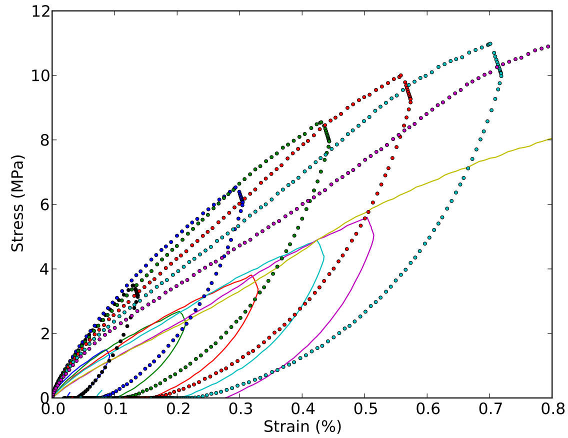

Figure 9: Long and short recovery experiments

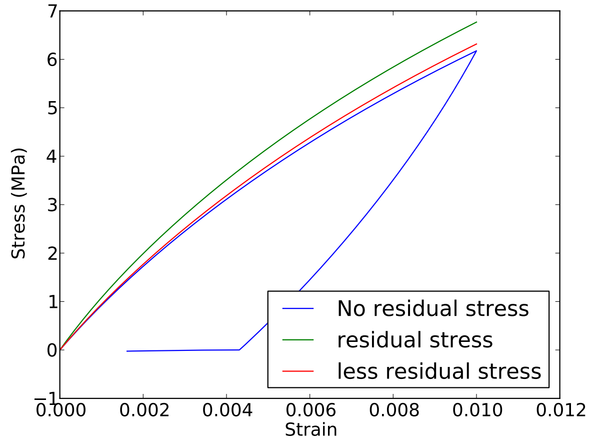

Figure 10: Simulation of incomplete recovery

the Abaqus simulation. As hypothesized, the stresses are not completely uniform though there is obvious signs stress concentrations at the contact which is an artifact of the mesh.

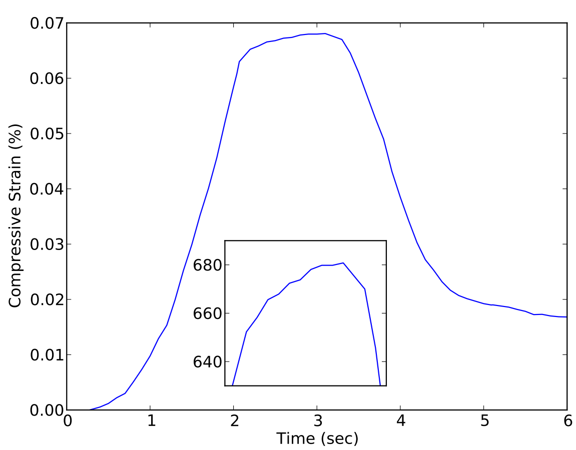

Figure 11: First cycle of 1 second recovery experiment

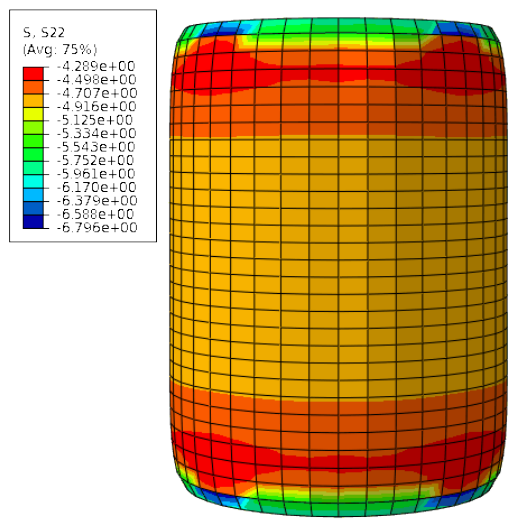

Figure 12: Simulation with friction

Figure 13 shows simulated extensometer readings from the simulation with and without friction. The frictionless model shows no change in compressive strain while the platens are stationary. The model with friction (very high) does show a slight increase in compressive strain. The material model was not fit to all the physics of the material and was not intended to be completely accurate but the simulations to show the trend of increasing compressive strain while the platens are stationary.

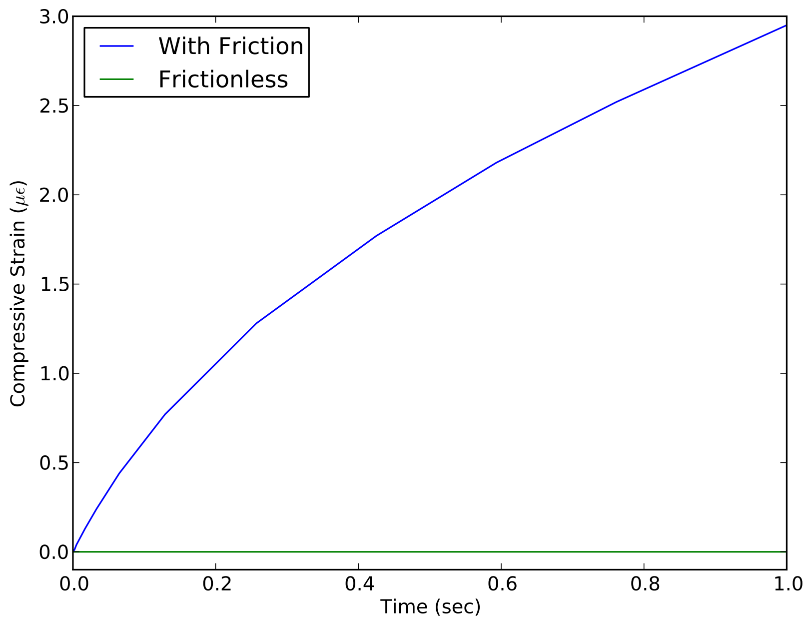

Figure 13: Simulation strain vs. time for a viscoelastic sample with and without friction

The simulated friction may indicate that the experiment could be slightly improved by reduction in friction, but maybe the more relevant observation is that the stress and strain are not uniform during these experiments. Though costs must be considered an ideal experiment would include digital image correlation diagnostics.

Uniaxial monotonic experiments

A series of monotonic-uniaxial tension and compression experiments have been performed by Darla Thompson. A subset of these experiments performed on samples cut from pristine pressings in 2009 is examined in this section.

There are 31 experiments included in this study 14, of them compression and 17 of them tension. All the experiments were performed at 23°C and included 5 nominal strain rates from 1E-6 s^{-1} to 1E-2s^{-1}. The compression samples were1in tall by 0.5 in diameter.

The tension samples were the standard dogbone tensile specimin with a total length of 3 inches, a gage length of 1.5 inches, a gage diameter of 0.5 inches and a 15° taper. The tension samples were first loaded to 3 lbf (approximately 0.1MPa in these samples) to seat the samples in the fixture and then the crosshead was backed off by (some number which Darla will supply) before beginning the test.

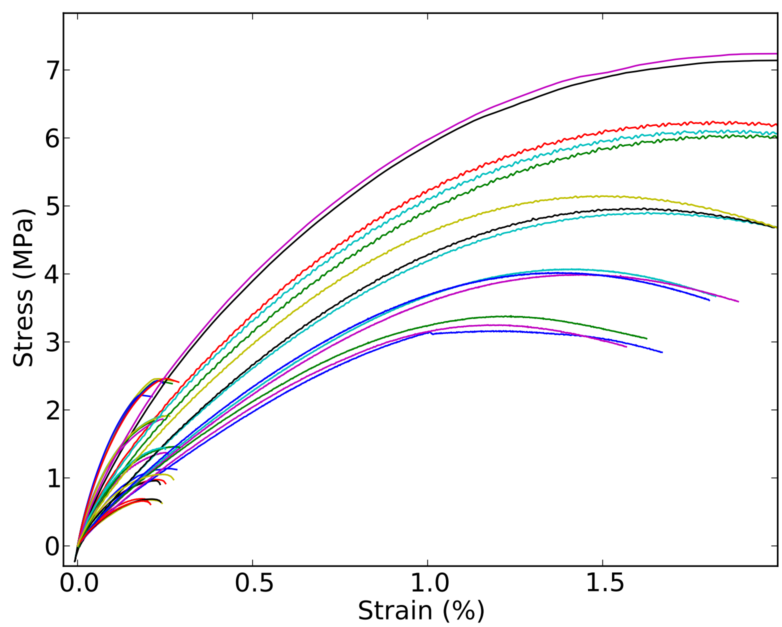

Figure 14: Stress vs. Strain for monotonic uniaxial experiments performed in 2009

Uniaxial data analysis and observations

The first observation we can quickly make is that the behavior is different in compression than in tension. The samples reach much higher stress and strain in compression than in tension. This indicates an I_1 dependance on the behavior. The experiments also lump together by strain rate indicating a rate dependance in the material behavior this is consistent with the viscoelasticity identified in the cyclic experiments discussed above. A puzzling observation is that the material seems to be stiffer in tension than in compression. Some of this may be explained by the slightly higher strain rate used in the tension experiments (a factor of about 1.5) as compared to the compression experiments.

A general viscoelastic model commonly used is a maxwell model. This can be described through a summation

$$G(t) = G_{\infty} + \sum_{i=1}^{N} G_i e^{\frac{-t}{\tau_i}} \tag{1}$$

Where G is the shear modulus as a function of time, G_{∞} is the long term shear modulus, G_i are the individual maxwell moduli, and τ_i are the relaxation time constants associated with the maxwell moduli. We have estimated the deviatoric tangent modulus and plotted that as a function of time for all the tensile data in Figure 15.

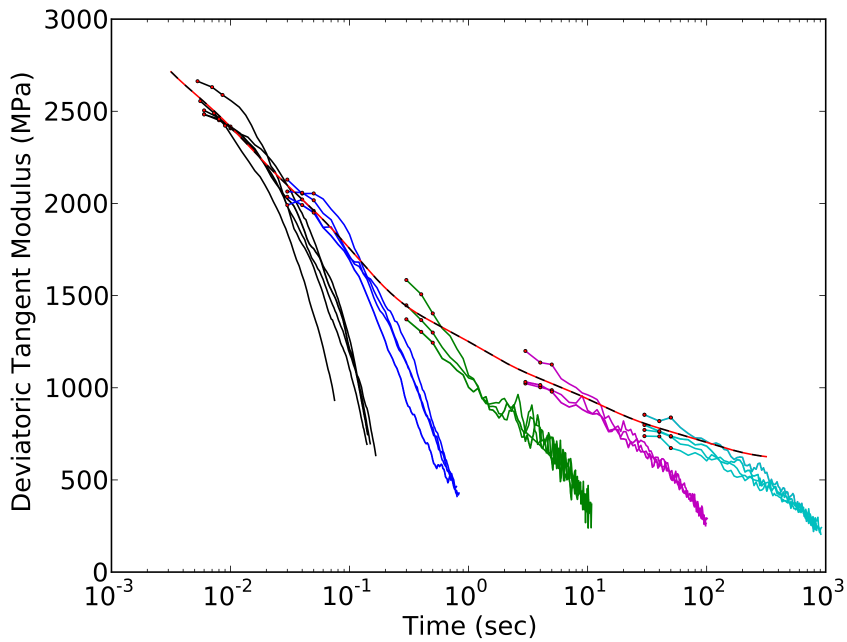

Figure 15: Deviatoric Tangent Stiffness and Fit to Early Data

I say estimated because we only measure uniaxial stress and strain. The leap we take in getting from uniaxial stress and strain to deviatoric stress and strain is that the bulk modulus is a known value. We used 3.5GPa here but that is slightly contested. In the future if we could measure lateral strains as well then we would not have to guess at the bulk modulus. Theoretically the tangent modulus as a function of time for a viscoelastic solid is a rate independant material. The curves shown in Figure 15 are grouped by rate and show a clear rate dependance. We propose that this is because of other phenomena such as plasticity or damage which has been demonstrated earlier in this memo. We developed a crude viscoelastic model by fitting the Prony series to the first few points of each curve under the assumption that significant plasticity or damage is not present in the early data. This Prony series is shown by the striped line going through the early data.

Next we use the viscoelastic model to simulate our experiments providing an estimate of the ideal stress strain curves if damage or plasticity was not present. We then subtract the viscoelastic strain from the measured strain to estimate the non-viscoelastic strain as a function of stress. The measured tension data is reproduced in Figure 16 and the estimated non-viscoelastic strain is shown in Figure 17.

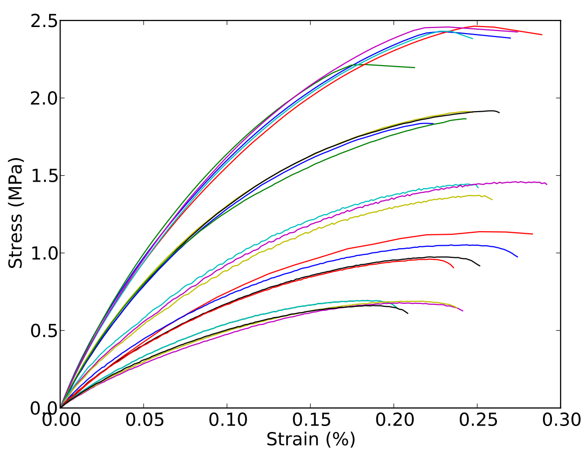

Figure 16: Total stress strain in uniaxial tension

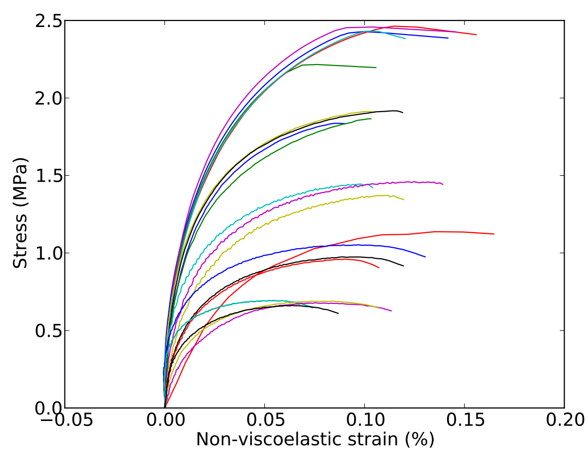

Figure 17: Non-viscoelastic strain vs. stress

The non-viscoelastic curves are much steeper than the experimental curves and at rates of 1E-4S^{-1} and greater it appears there may well be a critical stress for which non-viscoelastic behavior begins. The stress is very low and may be very difficult to measure but we believe that this knowledge will greatly contribute to the choice of model forms as this development moves forward. Additionally, we used the tensile data only for fitting the viscoelastic model. This is because the data was very noisy in the compression experiments in the low stress region. It is possible that the difference in the quality of the low stress data for tension and compression is due to the small preload that was applied to the tension specimen before beginning the test. A good estimate of the critical stress for non-viscoelastic behavior will allow an equivalent preload to be applied to compression tests in the future. The next section outlines the recommended test program for establishing a critical stress limit for non-viscoelastic behavior.

Exploratory test program for identifying threshold stress

The purpose of these tests is to explore the possibility of a critical stress under which the material behaves viscoelastically. We want to perform a very similar test to Darla's previous cyclic test but we want to concentrate on much lower stresses. We should approach 0.1% strain in cyclic compression tests over 10 steps. The loads should be applied through crosshead control and the platen should remain fixed for 1 second at the peak of each cycle. The sample should then be unloaded and allowed 1 hour recovery before the next cycle.

Assuming we use the same sample configuration as Darla's last cyclic test (1.125 in tall 0.5 in diameter) we propose compressive cycles at 0.05 in/min crosshead rate . The cycles will progressively increase their total displacement in increments of 0.000125 in (if this is within Darla's control).

It is not critical that the first cycle produce the full 0.000125 in sample displacement, but it should not exceed it. The long recovery time probably only allows 5 cycles in a work day but it is perfectly acceptable to leave the sample unloaded for longer than 1 hour. I would like to see 10 cycles which would bring us to approximately 0.1% strain.

These first tests can be performed at room temperature. We may want to plan multiple temperatures and rates but we would like to see 3 of these experiments performed and analyzed before we commit to a full test matrix. If this test demonstrates the critical stress, then it should be repeated for tension as well. Given early success the below tests would be requested. They include 3 rates and 3 temperatures and ideally 3 tests under each condition which results in 27 compression and 27 tension specimen. Because we believe we can make good use of these samples as part of this R&D program even if this exploratory test does not show a reliable threshold stress so we may choose to order the samples in advance of the first tests.

- Rates : 1E-4 s^{-1}, 1E-3 s^{-1}, 1E-2 s^{-1}
- Temperatures: -20°C, 20°C, 40°C
- Tension and compression

These requirements were written by an analyst and as such need to be reviewed by Darla and we are very open to changes which may increase the usefulness of the data collected.

Acknowledgements

I would like to thank the Enhanced Surveillance Campaign for supporting the experiments performed by Darla Thompson as well as my analysis of the data she provided.

Distribution

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