Low Density Polyethylene, Expanded Polystyrene and Expanded Polypropylene: Strain Rate and Size Effects on Mechanical Properties

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Submitted to: Journal of Polymer Testing

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Word Count: 3841 (Introduction to Conclusions)

Acknowledgements: The authors would like to thank DRDC Valcartier Research Center for financially supporting this research. The authors gratefully acknowledge the assistance of Jeff Wemp and Jeff Moulton in the material testing.

Abstract

Polymeric foam materials may be used as energy absorbing materials for protection in impact scenarios, and design with these materials requires the mechanical properties of foams across a range of deformation rates, where high deformation rate testing often requires small samples for testing. Owing to their cellular macrostructure, and the large deformations that occur during loading of foams, the measured stress-strain response of a foam material may be influenced by the sample size. In this study, the mechanical properties of three closed-cell polymeric foams (Low Density Polyethylene, Expanded Polystyrene and Expanded Polypropylene) at two different densities were investigated over a range of deformation rates from 0.01 s^{-1} to 100 s^{-1}. For each foam material, three different nominal sample sizes (10mm, 17mm and 35 mm) were tested. On average, the polymeric foam materials exhibited increasing stress with increasing deformation rate, for a given amount of strain.

Density variation was identified at the sample level, with smaller samples often exhibiting lower density. Expanded Polystyrene demonstrated the highest variability in sample density and corresponding variability in mechanical response, qualitatively supported by observed variations in the macrostructure of the foam. Expanded Polypropylene exhibited variability in density with sample size, and observable variability in the material macrostructure; however, the dependence of the measured mechanical properties on sample size was modest. Low Density Polyethylene was found to have a relatively consistent cell size at the macrostructure level, and the material density did not vary significantly with sample size. In a similar manner, the dependence of measured mechanical properties on sample size was modest. The effect of sample size was identified to be material specific, and it is recommended that this be assessed using sample-specific density measurements and considering different sized samples when testing foam materials.

Keywords: deformation rate effects; macrostructure; sample size; Low Density Polyethylene; Expanded Polystyrene; Expanded Polypropylene

Introduction and Background

Polymeric foam materials are widely used as energy absorbing or energy management materials for enhanced protection of the human body in impact scenarios such as vehicle crash, sports protection equipment, and military applications [1]. Important properties of polymeric foams include a low density and high specific energy absorption, where the absorbed energy per unit volume is approximated as the area beneath the stress-strain curve [2]. Using polymeric foams for protection applications, and implementation into Computer Aided Engineering (CAE) requires a good understanding of foam mechanical properties, the dependency on deformation rate, and variability of the material properties. In general, the mechanical properties of foams can be modified by changing the foam density for a given material [2]. Deformation rates in impact events for packaging, sports equipment and protective headwear may range from 10^0 s^{-1} to 10^2 s^{-1} while deformation rates in military applications can exceed 10^3 s^{-1} [1], with the typical mode of loading being compression of the foam.

The mechanical response of closed-cell foam can be characterized by three phases of deformation [2]. Under small deformations (strains less than approximately 5%), a linear elastic response occurs where the cell walls bend or distort to accommodate deformation. The second phase of deformation is the plateau region, where large plastic or elastic deformations occur at modestly increasing stress levels, primarily related to cell wall buckling, and corresponding to a large portion of the material energy absorption in impact scenarios. The third stage of deformation is known as densification, occurring as the foam cells are compacted leading to a dramatic increase in material stiffness and stress levels. It is important to note that densification does not initiate when all the voids in the foam are eliminated. Cell edges and walls can interact prior to reaching the theoretical value of zero void volume. The onset of densification can occur at compressive engineering strains as low as 60%, where the stress in the material begins to increase dramatically until the zero void ratio is approached. Many of the important characteristics of foam material behaviour can be related to the foam material density. Gibson and

Ashby [2] provide several relationships to describe the plateau stress and densification as a function of material density. In general, the material elastic modulus and plateau stress increase with increasing density while the strain to densification decreases with increasing density [3].

Most polymeric foams exhibit sensitivity to strain rate [1,4,5,6], which may be observed as creep or relaxation response at low deformation rates and as an increase in the modulus, an increase in the plateau stress level, and a decrease of the densification strain under increasing deformation rate compressive loading. The sensitivity of a material to deformation rate may also depend on the material density [2,7]. The rate dependency of polymeric foams is attributed to the viscoelastic properties of the base material, cell collapse or rupture, locking mechanisms that may occur between adjacent deforming cells, movement of gas (air) within the foam, and frictional forces. The change in densification strain is attributed to deformed cell orientations and their inability to re-orient at high deformation rates to minimize the volume of the compressed material.

Polymeric foam materials may also exhibit local variability in density, owing to the method of manufacture and resulting material structure, and therefore potentially exhibit variability in mechanical response. Polymeric foams exhibit a wide variety of macrostructures including open cells, partially open cells, and closed cells. Three common polymeric foams include Low-Density Polyethylene (LDPE), Expanded Polystyrene (EPS) and Expanded Polypropylene (EPP). Low-Density Polyethylene foam can be manufactured as a closed-cell elastomeric foam using an extrusion or cross-linking process, often with a resulting local variability in density. Expanded polystyrene is a closed-cell elasto-plastic foam made from beads of material, which are expanded by entrapped pentane gas and are then moulded into solid form using steam and pressure. Expanded Polypropylene is also an elastomeric closed-cell bead foam, with some level of plasticity, that is moulded using heat and pressure. Since the pre-process beads vary in size for EPS and EPP, so does the final cell structure of the foam.

Measuring the mechanical response of polymeric foams at low or quasi-static deformation rates (~0.01 s^{-1}) is relatively straightforward [1], allowing for a variety of sample dimensions and uniform loading of the foam. At quasi-static deformation rates, the maximum sample size is often determined by the load cell capacity and desired maximum strain. High resolution is required to measure response in the elastic and plateau regions, while high load capacity is required when the foam reaches densification. Intermediate deformation rates, on the order of 100 s^{-1}, are achieved through high inertia devices and impact loading of test materials, such as a drop tower or pendulum impact test apparatus. At intermediate loading rates, the sample size is limited by the requirement to overwhelm the sample and achieve uniform deformation. In the current study, the range of sample sizes was selected based on the quasi-static and intermediate deformation test requirements. High deformation rate loading of low impedance materials, such as polymeric foams, can present challenges with respect to sample size and the achievement of uniform deformation during the test, owing to the characteristically low wave speed and correspondingly low impedance of these materials [8]. The most widely used method for measuring material properties at high deformation rates is the Split Hopkinson Pressure Bar (SHPB) or Kolsky bar apparatus [9]. Originally proposed by Kolsky [10], the method was developed for high deformation rate testing of metallic materials. This method has more recently been adapted for low impedance materials using two principal methods: incorporation of pulse shaping to increase the rise time of the incident wave to achieve equilibrium [11, 12] and the use of low impedance bars to decrease rise time and improve the signal to noise ratio of the output [13-15]. However, one challenge with many methods is that relatively small samples are required for testing, on the order of 6-12 mm in diameter and 3 to 6 mm in length, are required. A non-uniform compaction wave may be observed in larger samples [16] and anisotropy may be present [17] depending on the material type and manufacturing methods.

Given that foam materials are cellular in nature, and the size of the cells as well as potential voids in the material may vary, a dependency on sample size may occur, along with corresponding variation in

mechanical properties of the foam. The aim of this study was to measure the mechanical properties of three polymeric foam materials, at two different densities, for low to intermediate deformation rates, and evaluate the effect of sample size on the mechanical response and deformation rate sensitivity.

Methods

Compressive mechanical testing was undertaken on two different densities of Low-Density Polyethylene (LD45, LD70), Expanded Polystyrene (EPS35, EPS44) and Expanded Polypropylene (EPP35, EPP44) (Table 1). The materials were received in sheet form, with varying thickness from 20 to 25 mm. The as-received sheet dimensions were measured, taking care not to deform the material and the material was weighed to calculate the sheet material density (Table 2) using an average of 8 thickness measurements. It was found that the material thickness was relatively consistent within the material sheets, but did vary between the material sheets. The highest variability in thickness was 0.113 mm (standard deviation, LD70), while the largest variability in sheet density was 1.52 kg/m^3 (standard deviation, EPP44) for Expanded Polypropylene. It should be noted that the sheet densities did not quantify density variations, if any, within the material sheet. This aspect was addressed by calculating density for individual samples.

The structure of three foam materials with similar nominal densities of 70 kg/m^3 (LD70, EPP44 and EPS44) was investigated using a Scanning Electron Microscope for qualitative evaluation of the macrostructure.

Sample Preparation

Samples were removed from the material sheets away from the edges to avoid edge effects (Fig. 1), with 3 repeats and 3 sample sizes used in the quasi-static study (9 samples per material), and 5 repeats for 3 samples sized used in intermediate rate tests (15 samples per material) (Table 1). Several methods of sample manufacture were investigated. The final method that provided consistent results was to use

a hole saw without an arbour to core out samples of the desired diameter. Three nominal sample diameters were considered in the study: 10mm (small), 17 mm (medium) and 35 mm (large) (Fig. 2), with the axis of the cylinder oriented in the through-thickness direction. In some cases, the sample diameter was adjusted based on a series of initial tests to maximize the diameter without exceeding the load capacity of the quasi-static test apparatus due to foam densification, and to meet the size requirements for the dynamic tests. Sample sizes were selected to ensure the load limit of the low rate test frame load cell was not exceeded and so that the pendulum apparatus could overwhelm the samples to maintain a constant strain rate for the dynamic tests. Each sample was weighed using a scale accurate to +/-0.005 grams. The diameter and length of each sample was recorded and the individual samples were provided with an identification number. Samples were cut to length using a custom fixture (Figure 1) to ensure the ends remained parallel and to minimize distortion of the samples when cutting.

Mechanical Testing

Low deformation rate compression testing (0.01 s^{-1}, 1.0 s^{-1}, and 10 s^{-1}) was undertaken using a hydraulic driven compression frame operated under displacement control using a MTS 407 controller (MTS). Displacement was measured using a LVDT displacement transducer and load was measured using a load cell (Omegadyne, 500 lb or 2224 N max load). This load cell provided a good balance in terms of accurate measurement of the initially small loads at low deformations, and the foam consolidation response, which generated much higher loads. Data was acquired using National Instruments Daqpad-6015 and Labview Version 8.0 software (National Instruments). Prior to testing, the load cell calibration was confirmed with a static weight, and the LVDT calibration was verified with a micrometer.

Intermediate rate dynamic testing (~100 s^{-1}) was undertaken using a pendulum test apparatus (Fig. 3). Loads were measured using a Quartz Load Washer (Kistler type 9051A) with a Dual Mode Amplifier (Kistler type 5010), and displacements were measured using a Laser Displacement System (LDS) [18].

The load cell and amplifier were capable of measuring loads up to 120kN. The test strain rate was controlled by the drop height of the pendulum and data acquisition was initiated using an optical trigger. The mass of the pendulum head was sufficient to overwhelm the samples and achieve a constant strain rate up to high levels of strain (>90%) for the foam samples. The LDS was aligned and then calibrated using custom calibration blocks and a micrometer. The calibration of the load washer was verified using a standard calibrated load cell.

Results and Discussion

Foam Density

As noted in the background section, foam density is correlated with mechanical properties [2] and it is important to evaluate the material density, and any variations that may be present, to interpret the measured mechanical data. A summary of the sheet density (Table 2) compared to the individual sample density is shown in Fig. 4. The average sheet density differed from the average density of the low deformation rate samples. Two important findings were that the sheet-to-sheet densities for a given material were consistent with coefficients of variation (COV) ranging from 0.0004 to 0.0225; whereas the coefficients of variation for the samples ranged from 0.032 to 0.177. The ratio of coefficients of variation for the samples to the sheet materials ranged from 3.78 (EPS35) to 88.79 (LD45), demonstrating differences between the sheet and sample density. The EPS and EPP foam materials exhibited a large variability in sample density, while the LD materials generally displayed smaller variability. One significantly higher density sample was identified in the LD45 material (Fig. 4), resulting in a higher standard deviation and demonstrating the possibility for large density variations within a material. This specific sample was investigated and was confirmed to be from the LD45 sheet.

Plotting the measured sample volume as a function of the measured density for the LD materials (Fig. 5) demonstrated a relatively consistent density for the different sample sizes, indicated by the linear fit to the data with a near horizontal slope (-6e-5 $kg/m^3/m^3$ for LD70 and -8e-5 $kg/m^3/m^3$ for LD45). Variability in the material density was higher for the small samples, and similar for the medium and large samples (Fig. 5). In contrast, the EPS materials (Fig. 6) demonstrated a positive slope (0.0005 $kg/m^3/m^3$ for EPS35 and 0.0012 $kg/m^3/m^3$ for EPS44), identifying an increase in density with increasing sample volume. Similarly, the EPP materials (Fig. 7) demonstrated a positive slope (0.0011 $kg/m^3/m^3$ for EPP35 and 0.0007 $kg/m^3/m^3$ for EPP44).

Considering all of the samples in three groups (small, medium and large), single factor analysis of variance (ANOVA) was applied to the measured sample density (Table 3). All materials, with the exception of LD45, were identified to have a significant variation in density with respect to sample size. A two-tailed, paired, equal variance T-Test was undertaken to compare the sample sizes (Table 3) and identified variation between all sample sizes for the EPS44 and EPP35 materials. The large EPS35 samples were significantly different from the medium and small, while the small EPP44 samples were significantly different from the medium and large samples. A difference between the medium and large samples for LD70 material was identified.

It should be noted that the samples were cored or cut from the sheets in sequence and therefore, a given sample size was removed from a similar location in a given sheet. The location was not randomized since such significant differences in density were not anticipated at the outset of the study. Considering the distribution of the density for the three sample sizes or volumes, the LDPE materials show much higher variability for the small samples, relative to the medium and large samples. In contrast, the variability in density was high at all levels for the EPS and EPP materials. Importantly, it was

found that the sheet material density and nominal material density differed from the local or sample density. It is recommended that the actual sample density be measured when testing foam materials.

The structure of the three materials with similar nominal density (LD70, EPS44, EPP44) were prepared with a standard gold coating and investigated using a scanning electron microscope (low vacuum ESEM). The LD70 material (Fig. 8) demonstrated relatively good regularity in terms of cell size and distribution at the millimeter scale. This regular structure is reflected in the lower variability of sample density for this material (Table 2, Figs 4 and 5). The EPS material (Fig. 9) had a larger dual macrostructure comprised of grains and inner-grain cells. Voids were identified throughout the material and varied in size, explaining the higher variability in sample density (Table 2, Figs 4 and 6). Similarly, the EPP material (Fig. 10) exhibited an irregular multi-scale structure with a variation in cell size within variable size grains, and the presence of inter-grain voids corresponding to higher variability in material density (Table 2, Figs 4 and 7). In the case of EPS and EPP foams, variation in the macrostructure was on the order of millimeters, and was expected to become significant for smaller samples (e.g. the small samples in the present study). This is an important consideration when testing foams at high deformation rates (e.g. ~ 1000 s^{-1}) where sample size is typically smaller than the small samples in the present study. It is hypothesized that the dependence of sample density on sample size is attributed to two effects. For a cylinder, the ratio of volume to surface area increases with increasing size, and this ratio is linear with respect to the sample dimensions. Firstly, sample manufacture using a coring tool can result in transection of cells, and some tearing of the cut surface leading to removal of additional material, potentially higher variability in sample mass. This can be considered a surface area effect. Secondly, the EPP and EPS materials exhibited voids as observed in the SEM analysis. Although these voids may vary in size, on average they are a fraction of the cell size and represent an overall reduction in mass. This can be considered a volume effect and, for a given average void size, would have a more significant effect on smaller samples.

Low Deformation Rate Testing

Low deformation rate testing was undertaken to evaluate variability in the mechanical response for different sample sizes at a deformation rate of 0.01 s^{-1}. The results of the 0.01 s^{-1} testing (Fig. 11) include three repeats of three different sample sizes (10 mm, 17 mm and 35 mm). Within a given sample size, the EPS materials exhibited the largest differences in stress-strain response. The EPP materials demonstrated a modest amount of variability and the LD materials generally had low variability for all sample sizes. The LD45 was very consistent except for one sample, which demonstrated a significantly higher stiffness and corresponded to the high-density sample in Fig. 4.

Effect of Deformation Rate

Low to intermediate strain rate testing (0.01 to 100 s^{-1}) was undertaken and all materials demonstrated increasing plateau strength and reduced strain to densification with increasing strain rate. When considering the measured stress at two specific strain levels (0.2 mm/mm Fig. 12 and 0.5 mm/mm Fig. 13), a positive slope of stress versus the log of strain rate was found for all materials, on average. However, high variability in stress was identified for the EPS and EPP materials. Results were similar at other strain levels within the crush plateau of the foams.

In general, the EPP 35 and EPP 44 materials demonstrated high variability in the data but did not show much size effect with respect to deformation rate. The EPS 35 and EPS 44 materials exhibited high variability in the data and showed some size effect. Even though there was high variability in the LD45 data, the data points for all sizes overlapped one another, so it was considered to have no size effect for the number of samples tested. The LD 70 showed a small size effect for the 20% strain values, but not for the 50% strain values. These results were supported by an analysis of variance (ANOVA) and T-Test investigating stress levels for three different sample sizes at each strain rate (Table 4).

The sample geometry was evaluated qualitatively based on the amount of recovery of the post-test sample and observable damage or ejection of material from the sample. The deformation was classified as 'recovered' (R) if the resulting permanent deformation was less than 20% strain, 'plastic' (P) if the permanent deformation of the sample exceeded 20%, and 'fragmented' (F) if the sample was fragmented or material was ejected from the sample (Table 5, Fig. 14). The LD and EPP materials demonstrated recovery for all sample sizes up to deformation rates of 10 s^{-1}, while the EPS material consistently demonstrated different post-test appearance for the small samples compared to the medium and large samples. At a rate of 100 s^{-1}, the EPS material exhibited different response for all three sample sizes, with material ejected from the small samples.

Some limitations were identified in this study. The sample macrostructures were only qualitatively evaluated since only one sample from each material was investigated. Future studies should consider relating macrostructure parameters such as grain size and void volume to sample density, possibly using three-dimensional imaging techniques. The removal locations of the individual samples were not randomized within material sheets for this study. However, samples were removed away from the edges of the sheets to minimize edge/skin effects.

Three polymeric foam materials demonstrated differing levels of dependence on sample size, with the EPS and EPP materials having lower density for smaller size samples. The level of variability in the macrostructures was observed to be consistent with the measured variability in sample density. The EPS material exhibited the highest variability in measured stress-strain response, with a dependence on sample size. Although the EPP materials demonstrated variability in density, as a function of sample size, the dependence of the measured stress-strain response on sample size was modest, evaluated using the T-Test. The LD materials demonstrated low or no dependence of density on sample size, consistent with the macrostructural observations. This was also apparent in the measured stress-strain-strain rate

response of the LD45 and LD70 materials. Within a given strain rate, there was low variability in the measured response for the LD45, and some dependence on sample size for the LD70. The results generally followed the same trend with increasing strain rate.

The results from this study provide guidance on the testing of foam materials and the effects of sample size, which are particularly important for dynamic testing of materials that often requires small samples for test purposes. It is recommended that individual samples should be weighed and measured to determine the actual sample density and identify any variations in density. Multiple sample sizes should be undertaken, at least at quasi-static levels, including sample sizes that may be considered for high rate or dynamic testing.

Conclusions

Six foam materials (LD45, LD70, EPS33, EPS44, EPP33, and EPP45) demonstrated a typical foam mechanical response comprising an elastic region, crush plateau, and densification region.

A variation in density was identified at the sample level, which was not apparent in the measured sheet material density. The variation in sample density was reflected in the measured quasi-static stress-strain curves. Further, the variation in density was observable in the sample macrostructure, particularly for the EPS and EPP materials.

The EPS and EPP foam materials exhibited a large variability in sample density, and this variability was correlated with sample size. Smaller samples, on average, had a lower density. It was hypothesized that this could be due to voids present in the material (volume effect) and material loss from sample manufacture (surface area effect). The LD45 and LD70 materials generally displayed smaller variability in density and mechanical properties, and did not exhibit a significant difference in density with sample size. These findings were supported by ANOVA of the material density for three different sample sizes.

On average, the polymeric foam materials exhibited increasing stress with increasing deformation rate, for a given amount of strain. Small samples demonstrated lower stress values at a given strain rate and deformation for the EPS materials, with lesser effects for the EPP and LD materials. A qualitative assessment of the post-test permanent deformation demonstrated size effects for the EPS, while LD and EPP materials generally exhibited some recovery. A quantitative ANOVA identified sample size effects for all materials, with the most significant effects found in EPS, and lesser effects for the EPP and LD materials.

The effect of sample size on the mechanical response of the polymeric foams is material specific. Sample size should be evaluated at the quasi-static level, along with density measurements of individual samples, to evaluate potential variability in the mechanical response of these materials.

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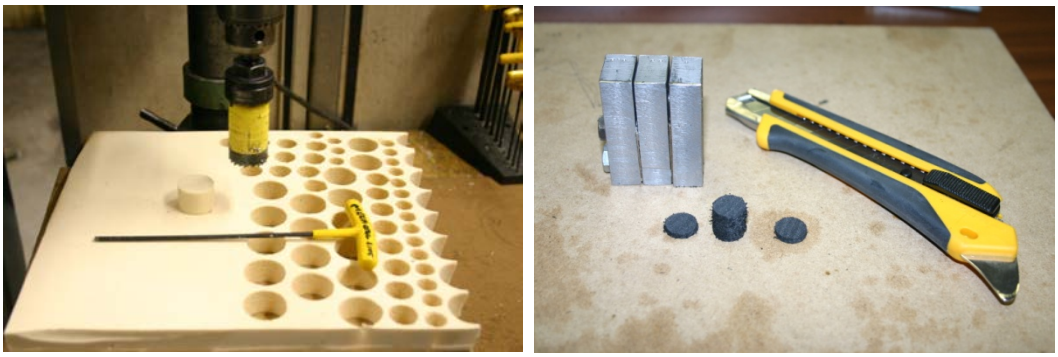


Figure 1: Sample coring from sheets [L] and custom fixture for cutting samples to length [R]

Figure 2: Test samples before and after quasi-static testing (large [L], medium [C], small [R])

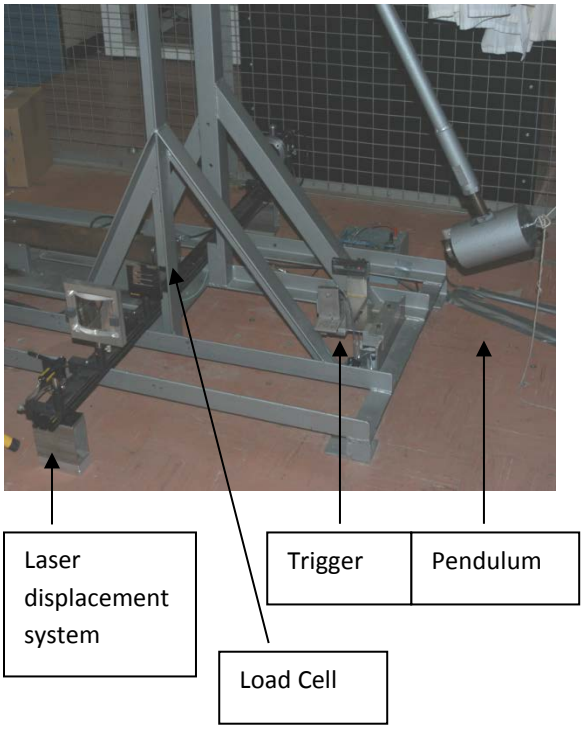


Figure 3: Pendulum test apparatus for intermediate rate compression testing

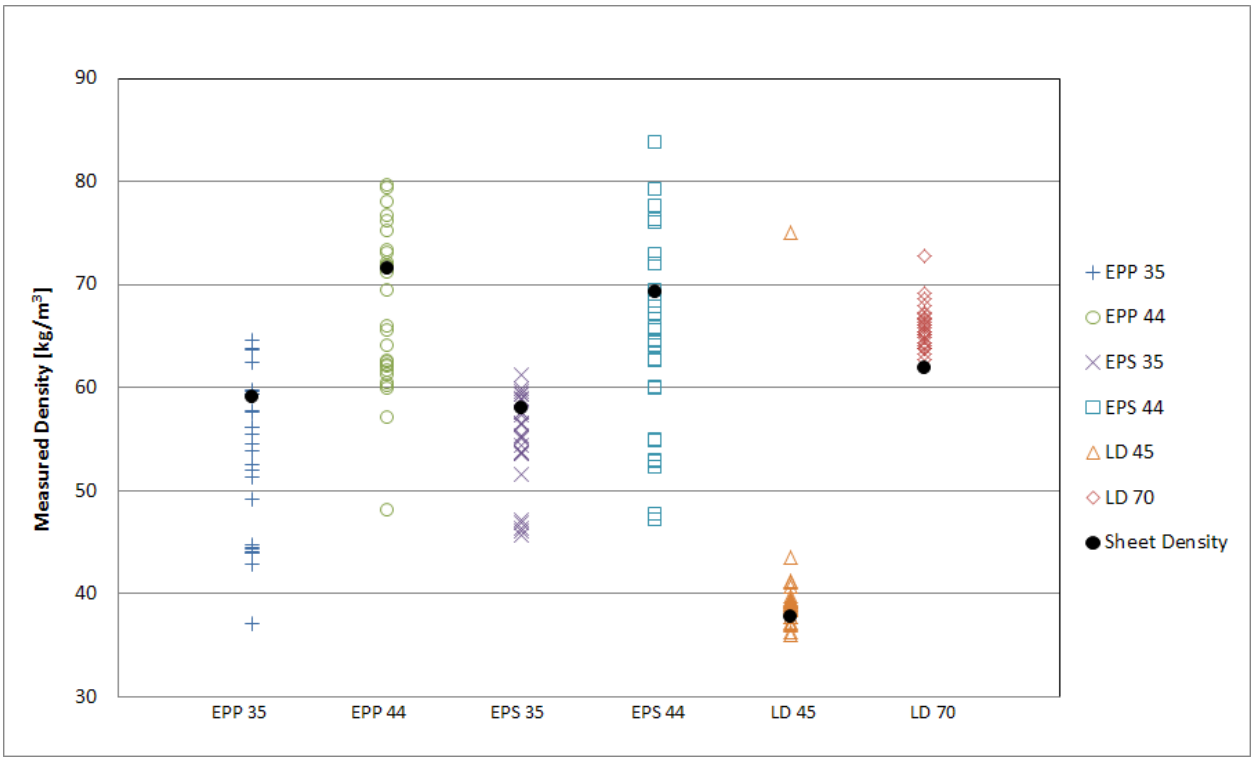


Figure 4: Measured sheet material density and low deformation rate test sample material density

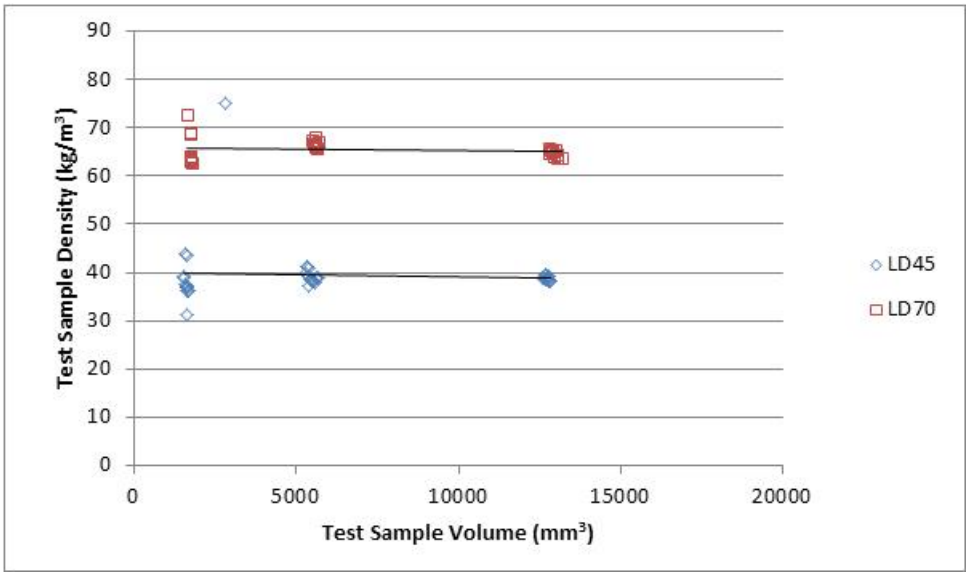


Figure 5: Measured material density versus test sample volume (LD materials)

LD45 ρ=-6.0e-05xVolume+65.9 r^2=0.022

LD70 ρ=-8.0e-05xVolume+39.9 r^2=0.004

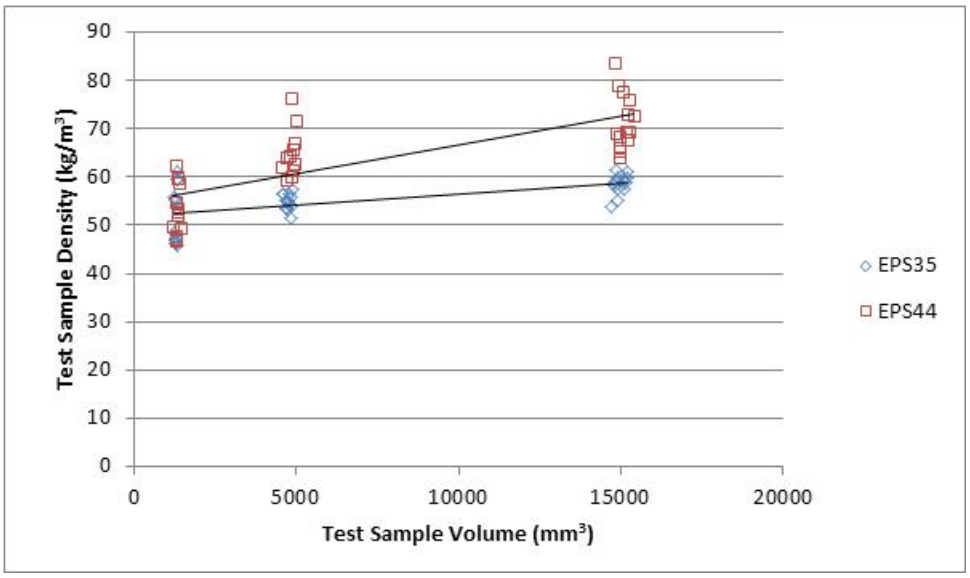


Figure 6: Measured material density versus test sample volume (EPS materials)
EPS35 ρ=0.0012xVolume+54.8 r^2=0.585
EPS44 ρ=0.0005xVolume+51.9 r^2=0.360

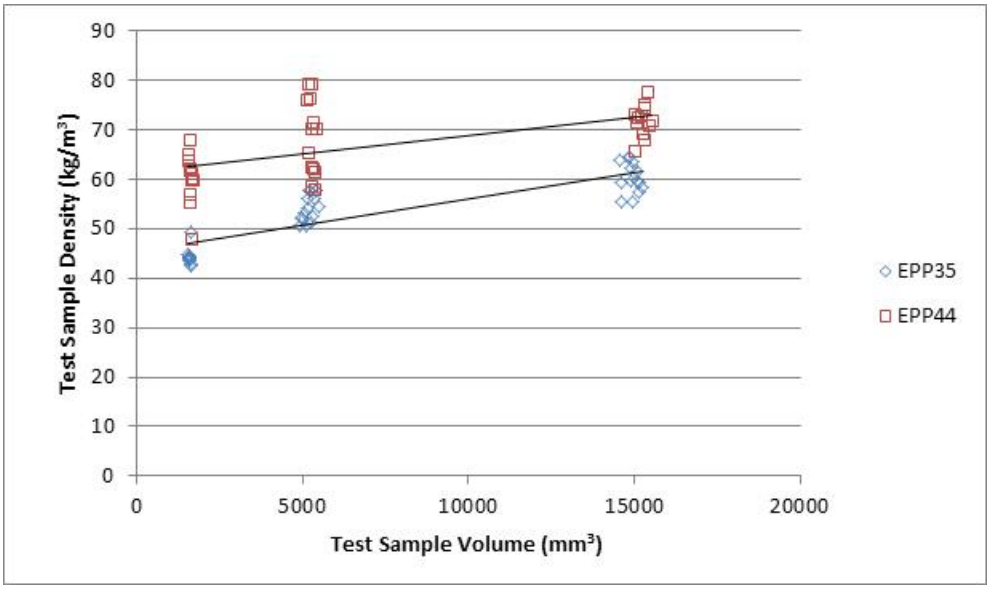


Figure 7: Measured material density versus test sample volume (EPP materials)
EPP35 ρ=0.0007xVolume+61.4 r^2=0.350
EPP44 ρ=0.0011xVolume+45.4 r^2=0.734

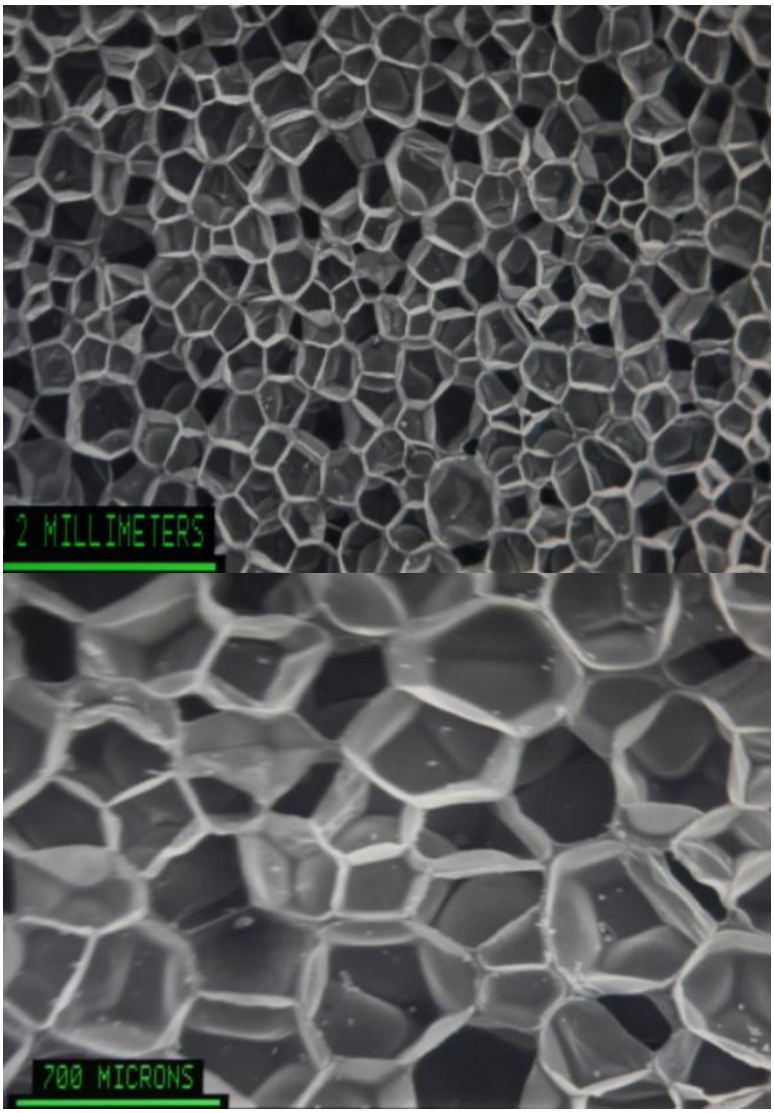


Figure 8: LD70 material, SEM imaging

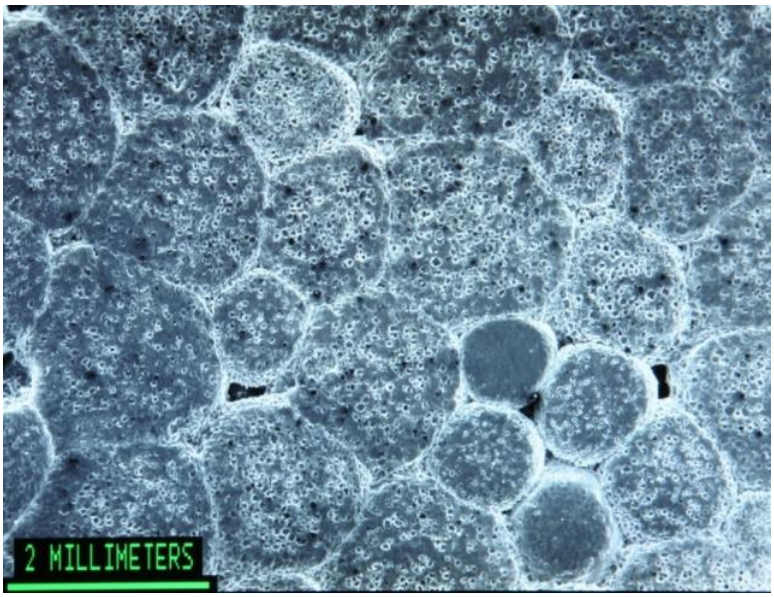


Figure 9: EPS44 material, SEM imaging

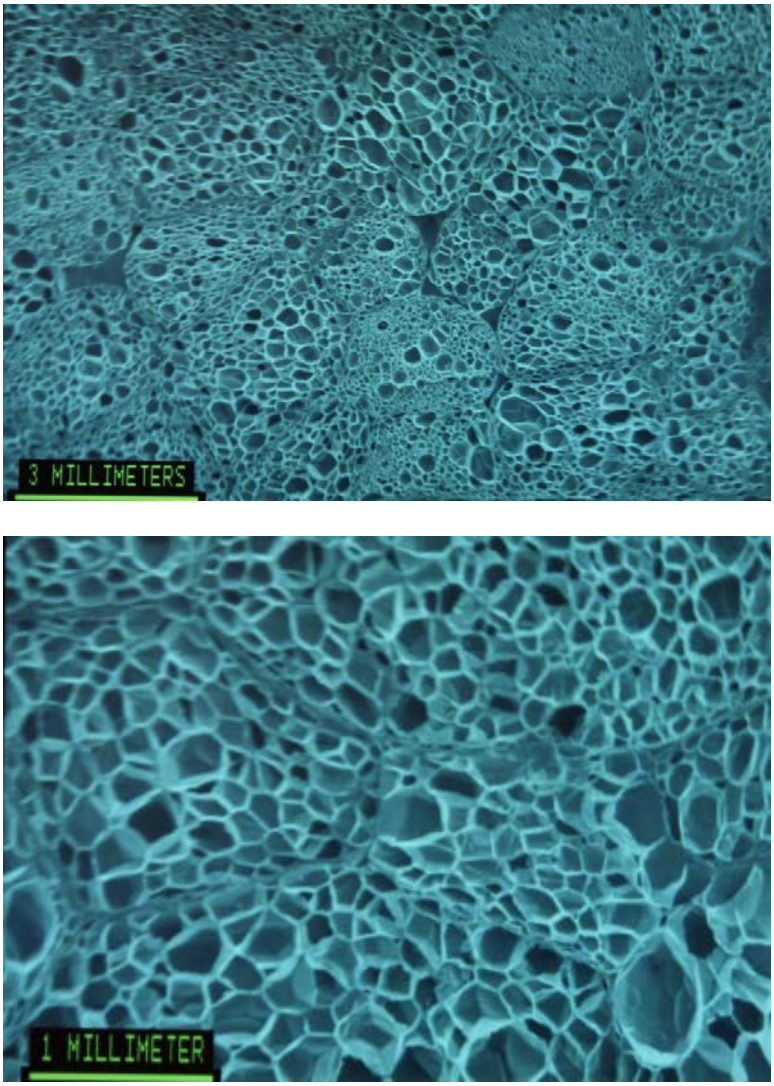


Figure 10: EPP44 material, SEM imaging

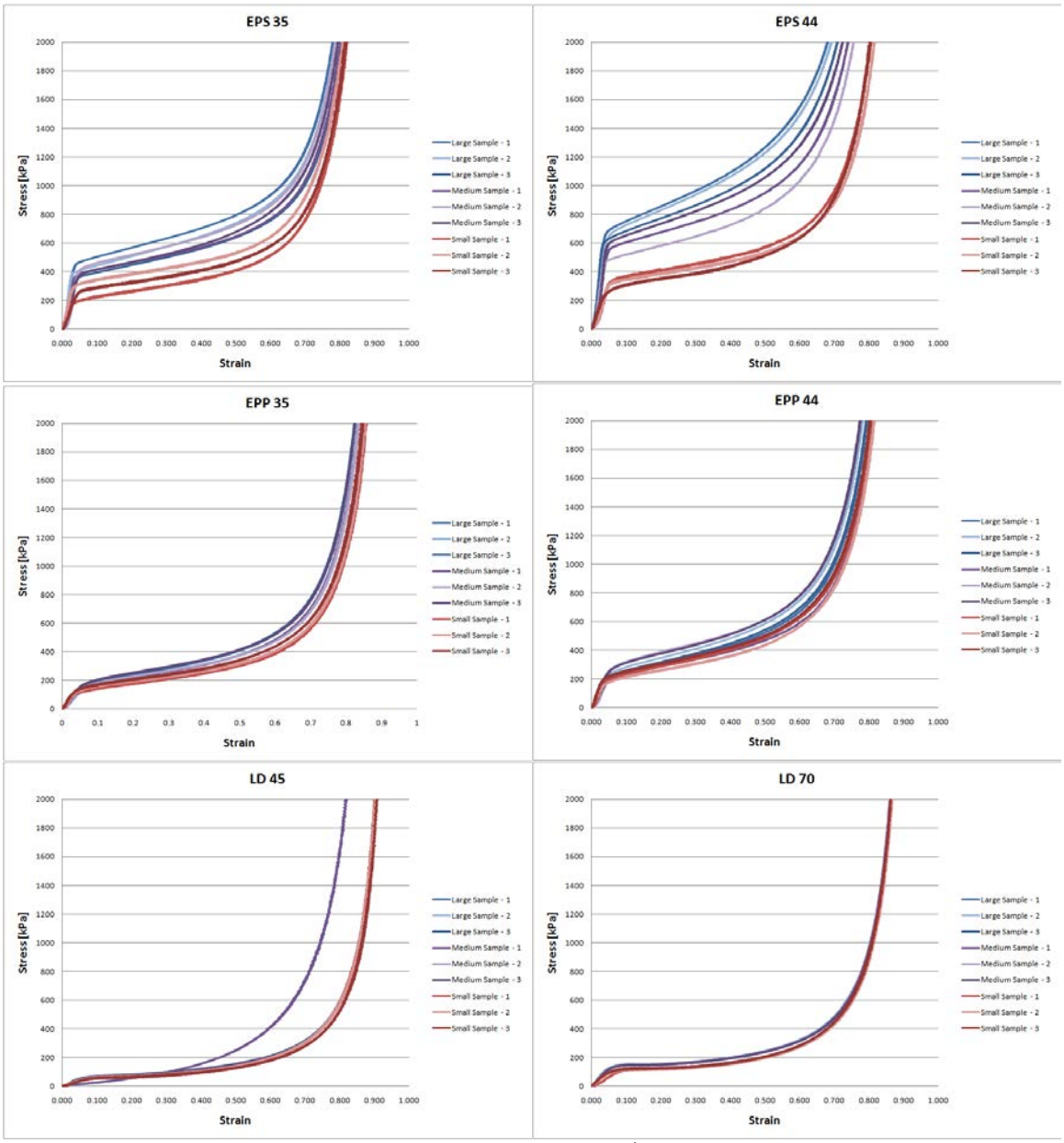


Figure 11: Foam material response and size effect (0.01 s^{-1})

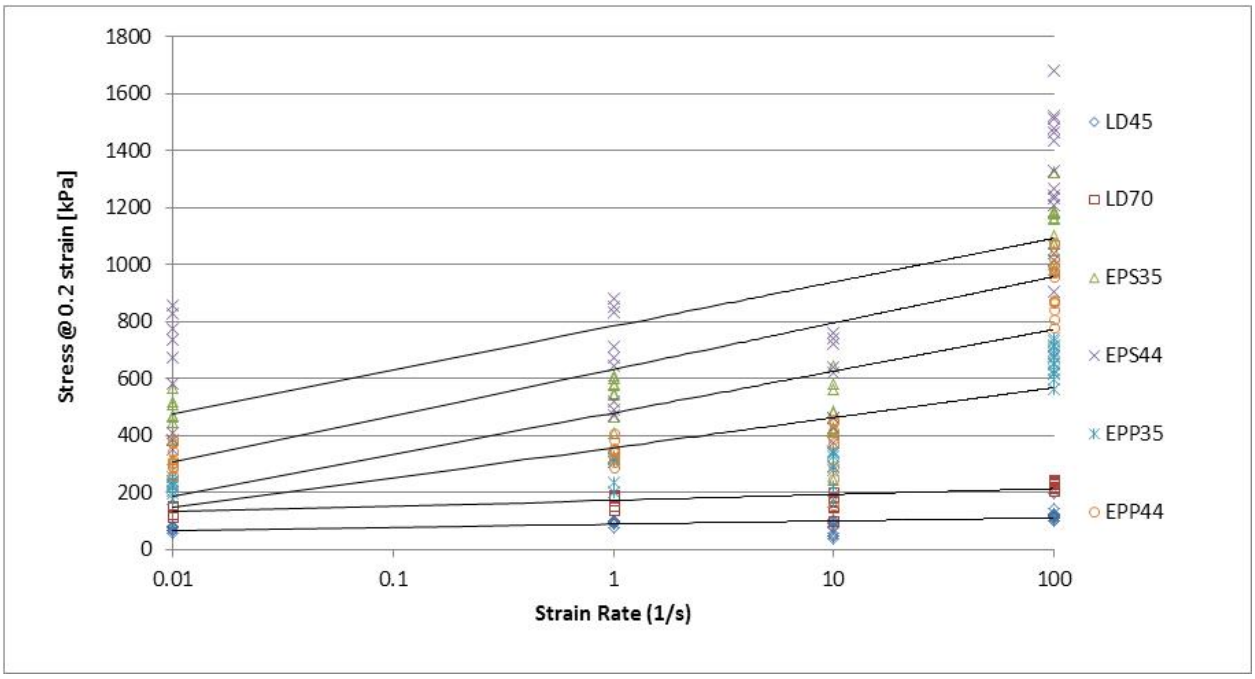


Figure 12: Deformation rate effect plotted at a strain of 0.2 mm/mm

LD45 $\sigma = 4.72\ln(\dot{\varepsilon}) + 88.7$ $r^2 = 0.322$

LD70 $\sigma = 8.90\ln(\dot{\varepsilon}) + 172$ $r^2 = 0.528$

EPS35 $\sigma = 70.5\ln(\dot{\varepsilon}) + 633$ $r^2 = 0.552$

EPS44 $\sigma = 66.8\ln(\dot{\varepsilon}) + 784$ $r^2 = 0.393$

EPP35 $\sigma = 45.8\ln(\dot{\varepsilon}) + 357$ $r^2 = 0.642$

EPP44 $\sigma = 63.6\ln(\dot{\varepsilon}) + 478$ $r^2 = 0.563$

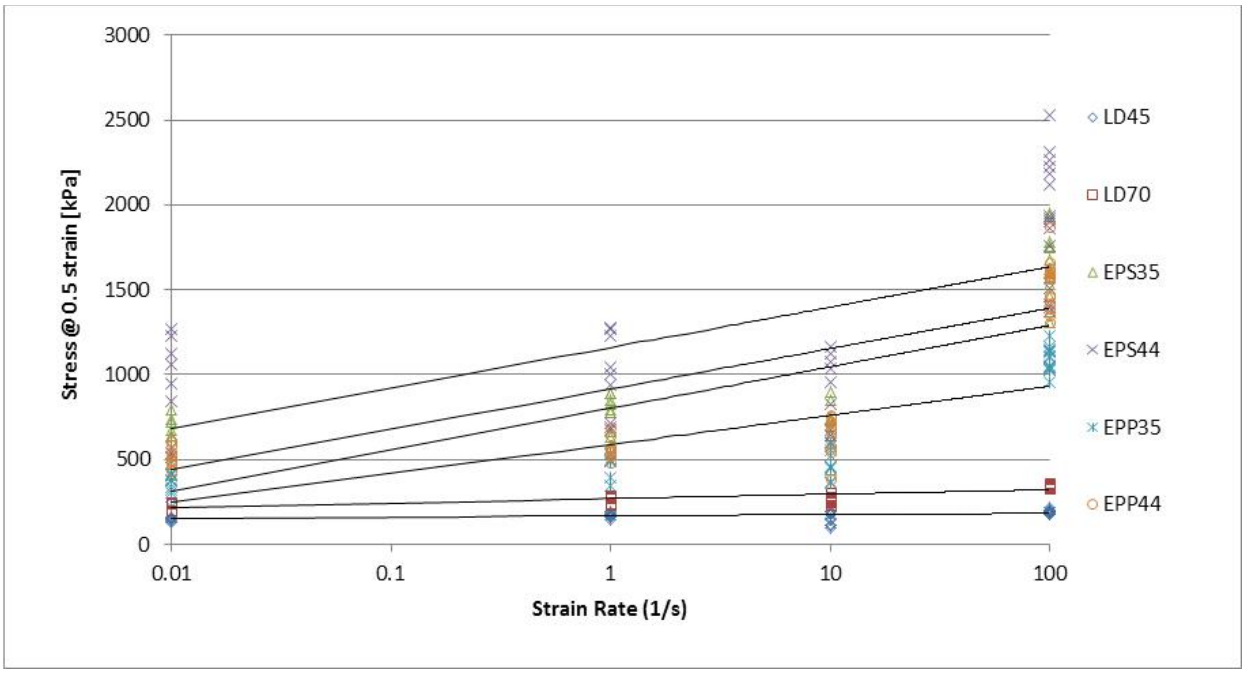


Figure 13: Deformation rate effect plotted at a strain of 0.5 mm/mm

LD45 $\sigma = 3.03\ln(x) + 167$ $r^2 = 0.131$

LD70 $\sigma = 11.0\ln(\dot{\varepsilon}) + 269$ $r^2 = 0.708$

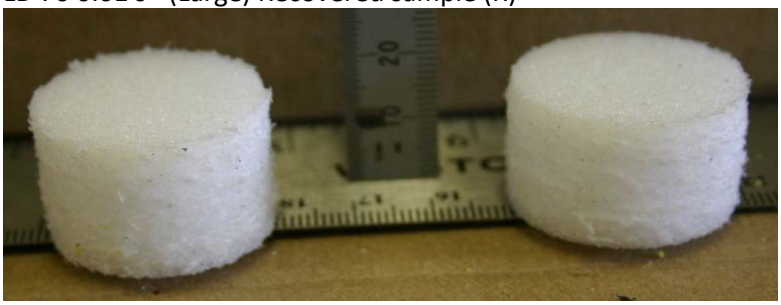
EPS35 $\sigma = 103\ln(\dot{\varepsilon}) + 916$ $r^2 = 0.570$

EPS44 $\sigma = 103\ln(\dot{\varepsilon}) + 1160$ $r^2 = 0.414$

EPP35 $\sigma = 74.5\ln(\dot{\varepsilon}) + 588$ $r^2 = 0.650$

EPP44 $\sigma = 63.6\ln(\dot{\varepsilon}) + 479$ $r^2 = 0.563$

LD 70 0.01 s^{-1} (Large) Recovered sample (R)



EPS 35 100 s^{-1} (Medium) Permanent deformation (P)

EPS 35 100 s^{-1} (Small) Fragmented sample (F)

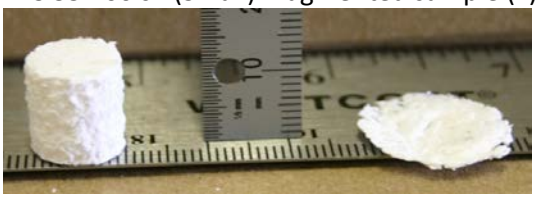


Figure 14: Examples of deformed samples and qualitative descriptions