Lateral Stress and Bulk Density of Pet Resin with Re-Cycle

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Abstract

Solids conveying depends on the bulk density and the lateral stress of the feed resin. Laboratory measurements show that the addition of re-cycle PET flakes to virgin PET pellet resin feed significantly changes its lateral stress and bulk density. Data for different ratios of re-cycle flake to PET pellets are presented. Also, data for 100% PET pellet feed and 100% PET re-cycle flakes are given for comparison.

Introduction

Extrusion of PET is widely used for packaging and films. PET is also readily re-cycled, and the re-cycle usually is in the form of chips or flakes. When the virgin PET pellets are then mixed to some proportion with the recycled PET, solids conveying performance is affected. Solids conveying has been shown to depend on lateral stress [1-5] and bulk density [3]. Therefore, the desire to extrude PET pellets mixed with re-cycle motivated this laboratory study of the lateral stress and bulk density of mixtures.

Materials

Virgin PET pellets and re-cycle PET flakes are shown in Figure 1. The pellets have an average mass of 0.053 gram, and approximate dimensions of 3.2 x 3.2 x 4.2 mm. The pellets and re-cycle were mixed in proportions of 25%, 50%, and 75% of re-cycle on a total mass basis. The total mass of each mixture sample was 3 to 4 grams, and samples were individually weighed for each test. The mass of each component was measured to 0.01 gram. The lateral stress and the bulk density of the mixtures were then measured as a function of primary compressive stress.

Experimental Equipment

Figures 2 shows the test cell from previous work [2] used to measure the stresses and bulk density of the different mixtures. Load cells record the axial and lateral forces and a linear displacement transducer records the axial strain. The lateral strain is assumed to be zero as in previous work [4], but some minimal lateral strain does occur as a result of the deflection of the load cell. However, it is insignificant in relation to the axial strain. The data taken with the test cell include the axial length of the specimen, the axial or primary load force, and the resulting lateral load force. The dimensions of the test chamber and the piston displacement measurement provide data to calculate the bulk density of the sample as it is compressed and reduced in volume. The two load cells and the dimensions of the test chamber give the needed data to calculate the axial and lateral stresses developed during compression.

“Loose” Bulk Density Data

The “loose” bulk densities of the mixtures of pellets and re-cycle were measured to be a function of the fraction of PET re-cycle. “Loose bulk density” is defined as that at minimal or zero stress, and Figure 3 shows the typical values for the 5 different samples. Pure pellets and pure re-cycle and proportions of 25%, 50%, and 75% of recycle mass/total mass are given. The data were obtained from the test cell before any strain or stress was applied. Figure 3 shows that the loose bulk density of the pellets is significantly greater than that of the re-cycle. Figure 3 also shows that the loose bulk density is reduced in approximate proportion to the mass of recycle that is mixed.

Stratification of re-cycle and pellets is likely to occur in the delivery system of an extruder. Therefore, a sample datum for 50% ratio of re-cycle mass/total mass is shown in Figure 3. The loose bulk density is shown to be nearly the same as for the 50% mixed resin. A slightly lower bulk density might be expected as the void space in the pellet portion is only filled with air for the stratified condition. However, this is shown to not be significant for the 50% stratified mixture of pellets and re-cycle when compared to the 50% sample that is mixed.

Bulk Density vs. Primary Stress Data

Data for the bulk density as a function of primary stress are given in Figure 4. Variation in their value depends on the primary stress as well as the mixture proportion. The matter is complicated by the fact that bulk density of PET pellets will be greater than mixtures at low primary stresses and less than mixtures at high primary stresses. The cross-over point of stress is at a primary stress less than about 15 MPa.

Bulk Density Regression Functions

The curves for bulk density of Figure 4 are modeled with 6th order polynomials, and they are given below. The correlation coefficient was greater than 0.999 for all the functions. The range of validity of primary stress is 0 to 40 MPa. Above 40 MPa error is likely, but a linear extrapolation for stresses moderately above 40 MPa could extend the useful range if need be. The results are given in equation form for easy programming to provide an accurate representation of the density data.

<u>100% Pellets</u>:

$$y= -3.854E\text{-}10x^6 + 5.993E\text{-}08x^5 - 3.605E\text{-}06x^4 + 1.070E\text{-}04x^3 - 1.673E\text{-}03x^2 + 1.858E\text{-}02x + 7.439E\text{-}01 \quad (1)$$

<u>25% Re-cycle</u>:

$$y= -4.663E\text{-}10x^6 + 7.659E\text{-}08x^5 - 5.014E\text{-}06x^4 + 1.681E\text{-}04x^3 -3.050E\text{-}03x^2 + 3.565E\text{-}02x + 6.877E\text{-}01 \quad (2)$$

<u>50% Re-cycle</u>:

$$y= -1.142E\text{-}09x^6 + 1.693E\text{-}07x^5 - 1.018E\text{-}05x^4 + 3.166E\text{-}04x^3 - 5.440E\text{-}03x^2 + 5.932E\text{-}02x + 5.948E\text{-}01 \quad (3)$$

<u>75% Re-cycle</u>:

$$y= 2.679E\text{-}10x^6 - 4.381E\text{-}08x^5 + 2.772E\text{-}06x^4 - 8.067E\text{-}05x^3 + 7.570E\text{-}04x^2 + 2.025E\text{-}02x + 5.889E\text{-}01 \quad (4)$$

<u>100% Re-cycle:</u>

$$y= -1.897E\text{-}09x^6 + 2.557E\text{-}07x^5 - 1.409E\text{-}05x^4 + 4.104E\text{-}04x^3 - 6.817E\text{-}03x^2 + 7.280E\text{-}02x + 5.037E\text{-}01 \quad (5)$$

<u>50% Stratified:</u>

$$y= -1.700E\text{-}10x^6 + 3.106E\text{-}08x^5 - 2.273E\text{-}06x^4 + 8.554E\text{-}05x^3 - 1.887E\text{-}03x^2 + 3.523E\text{-}02x + 5.796E\text{-}01 \quad (6)$$

Lateral Stress vs. Primary Stress Data

Figure 5 shows the lateral stress for PET pellets and re-cycle resin. Data for PET pellets alone (100% pellets) is one basis for comparison with the mixtures of pellets and re-cycle. Another basis is the data for 100% PET re-cycle, and this is shown in Figure 5, also. These two base line functions appear fairly similar. However, the lateral stress for the 100% re-cycle is greater than that of the pellets over the entire range of primary stresses.

The 25% and 50% mixture of re-cycle/total show that lateral stress ratio is less than that for 100% pellets over the entire range of primary stress, whereas 100% recycle has a higher lateral stress than 100% pellets. Therefore, the solids conveying rate with the addition of re-cycle will be affected.

Bulk densities of the mixtures are also lower at low stress, but are greater at higher stress. Therefore, the combined effect of bulk density and lateral stress on solids conveying is subject to the range of stress of the operation.

Lateral Stress Regression Functions

The following are the regression curves for the data of lateral stress versus primary stress shown in Figure 5, and they are shown in Figure 6. A (0,0) intercept is assumed (zero primary stress = zero lateral stress). The trend line consistently used is a 6 th order polynomial. The regression functions between 0 and 40 MPa do accurately portray the data as can be seen comparing the data of Figures 5 with the regression representations of Figure 6. Therefore, the following equations are provided for convenient accurate use of lateral stress data.

<u>100% Pellets</u>:

$$y = -3.053E\text{-}08x^6 + 4.240E\text{-}06x^5 - 2.177E\text{-}04x^4 + 4.994E\text{-}03x^3 - 4.223E\text{-}02x^2 + 2.240E\text{-}01x \quad (7)$$

<u>25% Re-cycle</u>:

$$y = -2.063E\text{-}08x^6 + 2.693E\text{-}06x^5 - 1.312E\text{-}04x^4 + 2.694E\text{-}03x^3 - 9.482E\text{-}03x^2 + 1.123E\text{-}01x \quad (8)$$

<u>50% Re-cycle</u>:

$$y = 3.064E\text{-}08x^6 - 3.677E\text{-}06x^5 + 1.576E\text{-}04x^4 - 2.873E\text{-}03x^3 + 2.747E\text{-}02x^2 - 2.08E\text{-}02x \quad (9)$$

<u>75% Re-cycle</u>:

$$y = 5.359E\text{-}08x^6 - 6.029E\text{-}06x^5 + 2.461E\text{-}04x^4 - 4.280E\text{-}03x^3 + 3.439E\text{-}02x^2 - 2.422E\text{-}02x \quad (10)$$

<u>100% Re-cycle:</u>

$$y = -2.186E\text{-}08x^6 + 2.357E\text{-}06x^5 - 8.911E\text{-}05x^4 + 1.292E\text{-}03x^3 + 2.918E\text{-}03x^2 + 8.592E\text{-}02x \quad (11)$$

<u>50% Stratified:</u>

$$y = -4.167E\text{-}08x^6 + 6.521E\text{-}06x^5 - 3.805E\text{-}04x^4 + 9.753E\text{-}03x^3 - 8.916E\text{-}02x^2 + 3.198E\text{-}01x \quad (12)$$

As with the bulk density regression functions, above primary stress values of 40 MPa, error is likely. Again, a linear extrapolation for primary stresses moderately above 40 MPa could be used to extend the useful range if need be.

Lateral Stress Ratio Functions

Lateral stress ratio [3,4] (the ratio of lateral stress to primary stress) as a function of primary stress [2] is easily obtained from the lateral stress polynomial functions, Equations 7-12. The assumption that the data have an intercept of 0,0 (zero lateral stress at zero primary stress) eliminates a constant term in Equations 7-12. Therefore, Equations 7-12 can be divided by the primary stress (x) and yield a finite result at x=0. This provides a mathematical limit for the lateral stress ratio as primary stress approaches zero. Previous work [2] for other polymers has shown that those with lateral stress ratios of 0.3 or greater at low primary stress correlate with good extrusion performance, and polymers with low lateral stress ratios at low primary stress perform poorly. Therefore, the limit of lateral stress ratio at zero stress is a useful indicator of solids conveying performance.

Figure 7 shows the lateral stress ratio functions so determined from Equations 7-12 with the mathematical limit at zero primary stress (y intercept). The limits of lateral stress ratio values at zero primary stress are unique for the different ratios of pellets and re-cycle. It is highest for the 100% Pellets (~0.22) and stratified 50% re-cycle (~0.32). The mixtures of 25% re-cycle and 100% re-cycle have a limit of lateral stress ratio of about 0.1. Pellets with 50% and 75% re-cycle show a limit near to zero.

The results of Figure 7 clearly indicate that mixing virgin pellets and re-cycle produces non-linear results. Also, the result is dependent on the level of compressive stress. For example, resin with 25 % re-cycle has lateral stress ratio less than that for 100% pellets at primary stresses up to about 5 MPa. At 5 to 10 MPa stress the lateral stress ratio for the mixture is about the same as that for the 100% pellet resin. Above primary stress of 10 MPa, the lateral stress ratio of the 25% mixture is greater than the pure pellets. The non-linearity and the reversing of the effect can make processing difficult to manage and that day to day operation would not be consistent since mixture ratios likely could vary depending on the supply of re-cycle or lack of mixing.

Figure 7 shows that the lateral stress ratio for 50% and 75% re-cycle to always be lower than all other samples, including pure pellets. Also, at zero primary stress each of these two samples had zero lateral stress ratio, whereas all of the other samples had finite values of lateral stress at low primary stress.

Figure 7 also shows that the lateral stress ratio for 50% stratified pellets and re-cycle to have the greatest variability of all the samples. Stratification of the recycle/pellet mixture is inevitable, random, and difficult to detect in the extruder. Stratification will, thereby, make the lateral stress ratio inconsistent, and solids conveying less predictable. Therefore, stratification should be considered when flow instability occurs in the extrusion process of mixtures of PET pellets and re-cycle.

Summary

Extrusion of PET pellet mixed with re-cycle flakes in a single screw extruder is typically more difficult than extruding PET pellets. Lateral stress and density for mixtures of PET pellets and re-cycle flakes have been shown here to depend on mixture fraction of re-cycle and primary stress, and they are major factors in solids conveying in single screw extruders. The dependence has been shown to be non-linear and can depend on the level of primary stress. Stratification is also likely to occur in mixtures of re-cycle flakes and pellets, and this has been shown to be a factor in lateral stress. The data here provide quantitative evidence as to the sources of the difficulty of extruding mixtures of PET pellets and PET recycle. Hopefully, this will improve understanding of this complex phenomenon and assist in the design of better single screws for processing PET pellets with PET recycle.

Conclusions

1. For mixtures of PET pellets and PET re-cycle flakes, the effect on lateral stress, as indicated by the lateral stress ratio, is non-linear and dependent on the level of primary stress. This greatly complicates the solids conveying in single screw extruders and makes consistent processing difficult.
2. The lateral stress of mixtures of PET pellets and PET re-cycle flakes was measured to be a function of the mixture ratio and primary stress.
3. Lateral stress for pure re-cycle flakes was measured to be greater than for pure pellets. However, lateral stress for mixtures with 50% and 75% re-cycle was less than that for 100% pellets.
4. Lateral stress for a 50% stratified combination of pellets and re-cycle flakes resulted in the greatest values of lateral stress and the greatest variability of lateral stress ratio.
5. Loose bulk density was measured to be greatest for the pellets at about 0.75 g/cc. The addition of recycle diminished the loose bulk density in proportion to the amount of re-cycle. Pure re-cycle has a loose bulk density of about 0.5 g/cc.
6. The bulk density of mixtures of PET pellets and PET re-cycle flakes was measured in compression as a function of mixture ratio and primary compressive stress. The bulk density varied between about 0.5 g/cc and 1.2 g/cc.

Acknowledgements

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Key Words

Stress, bulk density, solids conveying, single screw, extrusion, pellets, PET re-cycle, PET, PET scrap, re-cycle

Figure 1. PET Resins. Bottom is re-cycle scrap and the top is virgin PET pellet. Different mixture ratios of these two components were tested. Pellet dimensions are about 3.2 x 4.2 mm.

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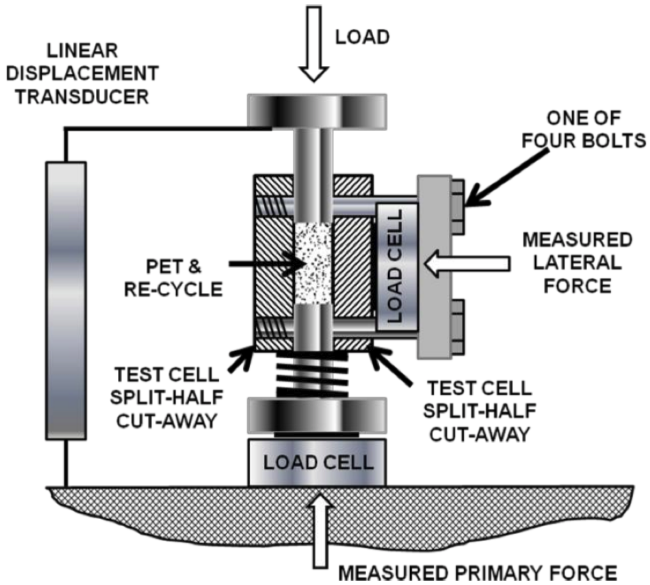

Figure 2. The Test Cell for Measuring the Primary and Lateral Forces During Compression of Bulk Resin Feed as a function of bulk density [1,2]. Diameter of the cylinder is 12.7 mm. The linear displacement transducer records the height of the sample to establish the evolving bulk density value and lateral area of force.

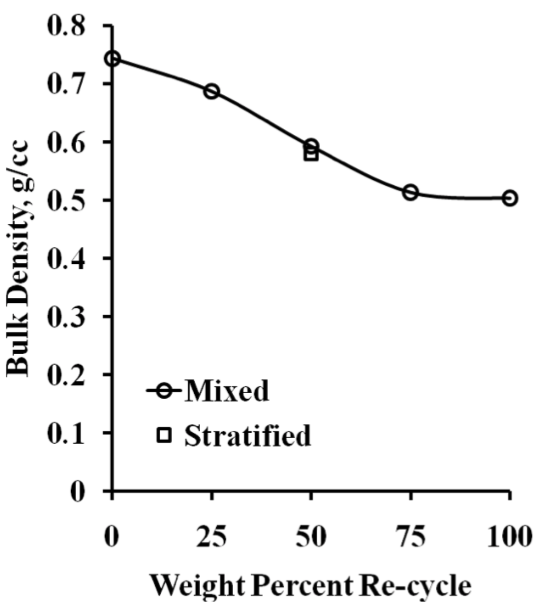

Figure 3. Bulk Density of PET Feed versus percent of Re-cycle Flakes. Values are those measured with the test cell before load is applied.

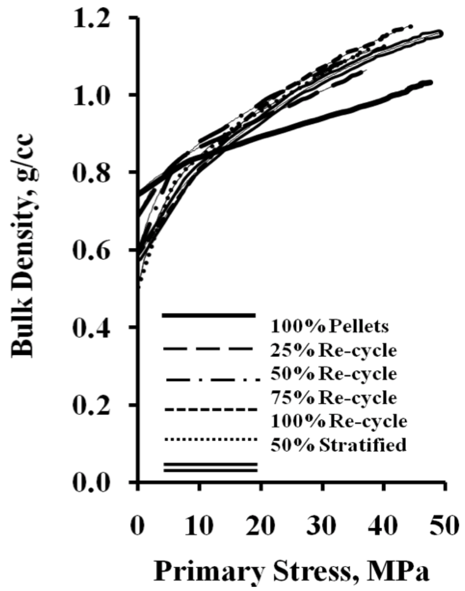

Figure 4. Data for Bulk Density of the Pellet/Re-cycle Mixtures vs. Primary Stress

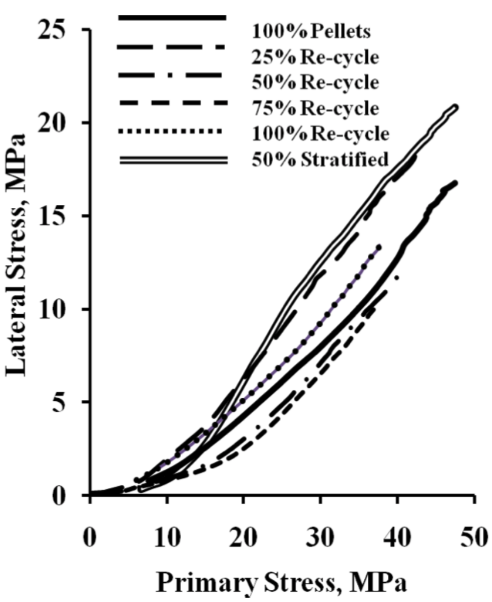

Figure 5. Raw Data for Lateral Stress for PET Pellets with Re-cycle vs. Primary Stress

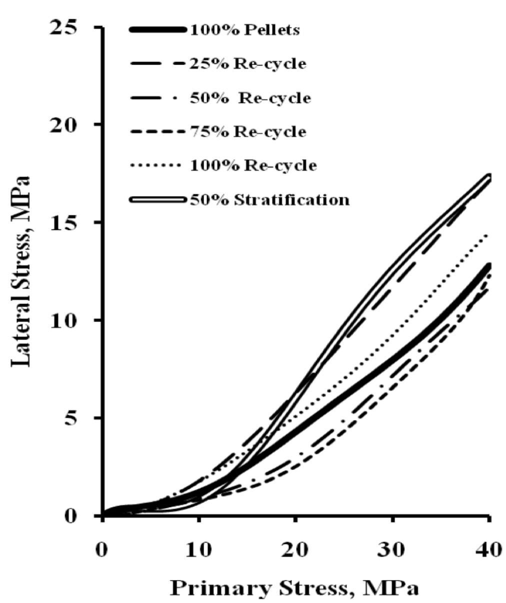

Figure 6. Regression Functions for Lateral Stress versus Primary Stress A 6th order polynomial is used for each set of

data of Figure 5. Regression coefficients are greater than 0.999.

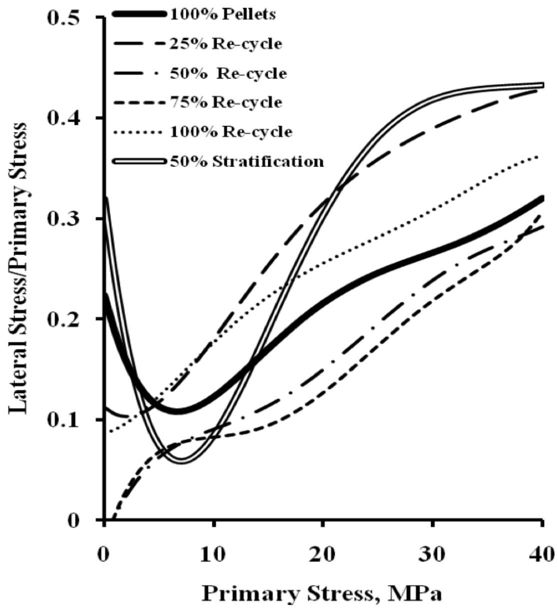

Figure 7. Lateral Stress Ratio Functions for PET/Re-cycle Mixtures

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