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Characterization of Rubber-Modified Polystyrene Blends: Viscosity, Film Morphology and Tensile Properties

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ABSTRACT

This study investigated mechanical properties of rubber-modified polystyrene blends. The research entails the blending of polystyrene (Ṁv = 2.32 x 10^5) with three distinct rubber samples: polyisobutylene PIBmwt, PIBlwt (with Ṁv = 9.88 x 10^5 and 13.5 x 10^5, respectively), and polyisoprene (Ṁv=2.36 x 10^6), with variations in percentage composition. Casting films from these blends facilitated an examination of the film morphology, providing information on structural alterations influenced by the type and concentration of rubber additives. Viscosity measurements were conducted on the blend solutions, leading to the plotting of reduced viscosity against concentration graphs. The resulting limiting viscosity numbers were compared with calculated values, revealing disparities, particularly in the case of polyisoprene (PIR), where experimental values exceeded calculated values. Tensile strength tests were evaluated for mechanical behavior. Stress-strain curves derived from these tests enabled the calculation of Young's modulus, a parameter indicative of stiffness. The analysis of viscosity, film morphology, and tensile tests indicate that the blend containing PIBmwt exhibited superior compatibility and enhanced mechanical properties compared to conventional one. These findings suggest promising applications across a broad spectrum of industrial contexts. The research contributes valuable insights into tailoring rubber-modified polystyrene blends for optimized mechanical performance, thereby advancing the field of polymer science and material engineering.

Keywords: Rubber-modified polystyrene, polyisobutylene blends, film morphology, viscosity analysis, tensile strength.

INTRODUCTION

The contemporary era is described as a polymer age. The global production of plastics has witnessed growth, steadily replacing traditional materials such as glass and metals across diverse industries. Among the plethora of plastics, polystyrene emerges as a highly versatile and widely utilized thermoplastic, contributing to polymer applications. Polystyrene, characterized by its transparent nature and thermoplastic properties, demonstrates versatility by softening at temperatures just above 100 °C. Renowned for its durability, resistance to biodegradation, stiffness, and ease of synthesis, polystyrene has become a cornerstone in various industrial sectors [1-6]. In spite of its advantages, polystyrene does exhibit limitations such as vulnerability to hydrocarbon solvents, poor resistance to UV radiation, and brittleness at temperatures below its glass transition temperature (Tg) of 100 °C [2, 7, 8]. The mechanical properties of plastic materials, including polystyrene, are linked to structural parameters such as molecular weight, branching in molecular chains, intrinsic flexibility of polymer chains, crystallinity, crystal arrangement, and intermolecular forces [9-11]. These properties form the basis for the mechanical behavior and performance of polymers in a variety of applications.

Polyblends is a fusion of two or more polymers that are not covalently bonded. This blending technique presents an avenue for modifying the mechanical properties of polymers, exploring the compatibility between different polymers. Unlike chemical modifications, polyblends leverage physical interactions, ensuring that the imparted properties resist degradation even under exposure to heat and radiation. The compatibility of polyblends becomes a pivotal metric, reflecting the degree of interaction between polymers during mixing. Achieving a homogeneous phase in a blend indicates compatibility, while phase separation signifies incompatibility [12-15]. This understanding of compatibility is necessary for investigating the advantages of plastics on the incorporation of rubber.

Rubber modification, a prevalent practice in polymer engineering, serves for enhancing the impact resistance of materials [16-18]. In rubber-modified polystyrene, rubber is introduced as discrete particles within the polymer matrix. Notably, there is often grafting of monomers onto rubber particles, effectively reducing crack propagation through the polystyrene matrix. This mechanism terminates or slows down crack propagation, contributing to improved material toughness [15, 19-21]. The advantages of rubber modification extend beyond enhanced impact strength. Rubber-modified polystyrene grades exhibit conductivity, as indicated by increased elongation at break [22]. The introduction of rubber particles alters the mechanical response to stress, introducing characteristics such as improved toughness and crack resistance [23-25]. The characterization of rubber-modified polystyrene and its polyblends, provides information on the durability, impact resistance, and overall performance of polymers in contemporary applications [26-29].

The aim of this study is to investigate the physical properties of rubber-modified polystyrene. The objectives are to investigate the impact of varying percentages of rubber on key parameters. These include the changes in solution viscosity, film morphology, and overall mechanical properties as a function of different rubber concentrations. Also to explore how solution viscosity evolves when different rubber types are introduced at a fixed percentage concentration.

MATERIALS AND METHODS

Commercial samples of polystyrene and rubber (PIBmwt and PIBlwt) were obtained from Sigma-Aldrich and utilized without purification. Toluene, an Instron tensile machine model 1206 was used to conduct the tensile tests.

Preparation of Solution

A 2 percent polystyrene solution was prepared by dissolving 10 g of polystyrene in a 500 cm^3 volumetric flask.

Viscosity Measurement for the 2 Percent Solution

Hardness in plastics reflects fracture and deformation characteristics. Thermoset plastics generally exhibit greater hardness than thermoplastics.

Tensile strength is the ability to resist a pulling force. Polystyrene achieves tensile strength in the range of 5,000 – 12,000 psi, distinct from metals like aluminum (25,000 psi) and steel (100,000 psi).

Ultimate Elongation is a measure of a material's stretchability before breaking. Polystyrene exhibits elongation of 1.0 – 7.5%, a noteworthy contrast to materials like rubber, which elongates 300 – 400%.

Compressive strength is the resistance to crushing under squeezing force. Polystyrene's compressive strength ranges from 20,000 – 25,000 psi, with variations influenced by temperature. Impact strengths is a measure of a material's ability to resist sharp blows or shocks. Polystyrene's impact strength, while moderate (0.25 to 0.40 ft/lb/in), contrasts with highly impact-resistant materials like flexible vinyl and polyethylene.

A constant temperature bath at 25 °C housed a ubbelode viscometer, rinsed with toluene. Toluene (10 cm^3) was pipetted into the viscometer, equilibrated, and efflux times recorded for varying concentrations. Relative viscosity (η_rel), specific viscosity (η_sp), and reduced viscosity (η_red) were calculated from the obtained efflux times.

This procedure was repeated for each 2 percent solution of the rubber samples, and results were tabulated.

Linear graphs of reduced viscosity against concentration were plotted for each polymer, extrapolated to zero concentration for determining the limiting viscosity number. The average viscosity molecular weight was calculated using Huggin’s equation.

Solution Viscosity Measurement for Polymer Rubber Blend

Viscosity of polymer solutions, a critical property, is assessed through relative viscosity, specific viscosity, reduced viscosity, and limiting viscosity number. These measurements contribute to understanding how a polymer solution influences the flow of a liquid.

Volumes of PS and PIBmwt were taken from the 2 percent solution, blended at different compositions (95/5, 90/10, 85/15, and 80/20), and viscosity measurements were conducted. Results were tabulated, and graphs of reduced viscosity against concentration were plotted for each blend, determining limiting viscosity numbers by extrapolation. These values were compared with those calculated using a modified form of Krigbum and Wall equation.

Film Casting

Twenty centimeters cubed of 2 percent PS, PIBmwt, and PIBlwt were cast in petri dishes, allowing solvent evaporation for 24 hours. Films were immersed in distilled water, observed for transparency, and the extent of rubber particle dispersion was noted. Dried films were used for subsequent tensile tests.

Tensile Test

The tensile test was conducted using the Instron machine model 1026, employing the following parameters:

- Maximum Load: 2000g
- Chart Speed: 50cm/minute
- Cross Head Speed: 12.5cm/minute
- Chart Magnification Factor: 4:1
- Gauge Length: 2.5cm
- Cross-Sectional Area of Film: 0.02 x 10^-3m^2
- Actual Extension: (Chart Extension)/4
- % Strain: (Actual Extension)/4 x 100%
- Strain Formula: Force/(Cross-Sectional Area of Film) = (Load x Acceleration due to Gravity (9.8 m/s^2))/(0.02 x 10^(-3) m^2)

These parameters were chosen to ensure accurate and reproducible tensile test results for all films. The applied forces, extension rates, and strain calculations were standardized to facilitate l comparison of mechanical properties across different films.

RESULTS AND DISCUSSION

Table 1 presents data from viscosity measurements for a 2 percent solution of polystyrene at various concentrations (g/100cm^3), along with corresponding time values, relative viscosity (η_rel), specific viscosity (η_sp), and reduced viscosity (η_red) in cm^3/g.

Table 1: Viscosity measurement for 2% PS/2% PIB_{mwt}, 2% PIB_{lwt} and 2% PIR.

(a) 2% PS $t_0 = 151$seconds

Concentration (g/100cm^3)	Time (seconds)	η_{rel}	η_{sp}	η_{red} (cm^3/g)
1.00	231	1.53	0.53	0.53
0.80	214	1.42	0.42	0.53
0.67	205	1.36	0.36	0.53
0.57	196	1.30	0.30	0.52
0.50	190	1.26	0.26	0.52

The concentration levels of the polystyrene solution, ranges from 1.00 to 0.50 g/100 cm³. Each concentration represents a different formulation of the solution.

The efflux time in seconds for each concentration reflects the time taken for a specific volume of the solution to flow through the viscometer, providing insights into the viscosity of the solution. It range from 1.26 to 1.53η_{rel}

Relative viscosity (η_rel) is the ratio of the efflux time of the solution to that of the pure solvent (toluene). It serves as an indicator of how much the viscosity of the solution has increased compared to the solvent. As the concentration decreases, η_rel generally decreases, indicating lower viscosity relative to the solvent.

Specific viscosity (η_sp) represents the increase in viscosity due to the distribution of polymers in the solvent. It is calculated as η_sp = η_rel - 1. The values in this study show how much the viscosity has increased relative to the pure solvent. Similar to η_rel, η_sp tends to decrease as concentration decreases.

Reduced viscosity (η_red) is the ratio of η_sp to the concentration (c). It provides information on the ability of the polymer to increase the viscosity of the solvent. The values in this study demonstrate the concentration-dependent behavior of reduced viscosity [30, 31].

Table 2 illustrates the variation in viscosity-related parameters with changing concentrations of the polystyrene solution. The decreasing trend in η_rel, η_sp, and η_red as the concentration diminishes suggests that the viscosity of the solution decreases with a reduction in polymer concentration. This observation is crucial for understanding the rheological behavior of the polymer solution, which, in turn, is vital for further analyses and applications in polymer science [3, 4].

Table 2: Variation in viscosity-related parameters (b) 2% PIB_{mwt} t_o = 151 seconds

Concentration (g/100cm^3)	Time (seconds)	η_{rel}	η_{sp}	η_{red} (cm^3/g)
1.00	399	2.64	1.64	1.64
0.80	344	2.28	1.28	1.60
0.67	313	2.07	1.07	1.60
0.57	284	1.88	0.88	1.54
0.50	269	1.78	0.78	1.56

Table 2 presents the variation in viscosity-related parameters for a 2% concentration of PIBmwt polymer solution over a range of concentrations. As the concentration of PIBmwt increases from 0.50 g/100cm³ to 1.00 g/100cm³, the viscosity-related parameters exhibit consistent trends. The viscosity (η_rel) increases from 1.78 to 2.64, indicating a proportional relationship with concentration. Similarly, the specific viscosity (η_sp) and reduced viscosity (η_red) also increase with concentration, reflecting the polymer's ability to increase viscosity in solution. However, the increase in viscosity-related parameters slows down as the concentration approaches higher values, suggesting a saturation effect[4, 5, 32].

Table 3 displays the variation in viscosity-related parameters for a 2% concentration of PIBlwt polymer solution.

Table 3: Variation in viscosity-related parameters 2% PIB_{lwt} t_o = 151 seconds

Concentration (g/100cm^3)	Time (seconds)	η_{rel}	η_{sp}	η_{red} (cm^3/g)
1.00	362	2.40	1.40	1.40
0.80	313	2.07	1.07	1.34
0.67	282	1.87	0.87	1.30
0.57	263	1.74	0.74	1.30
0.50	243	1.64	0.64	1.28

In Table 3, as the concentration increases from 0.50 g/100cm³ to 1.00 g/100cm³, the viscosity-related parameters follow a consistent trend of increasing values. However, the magnitude of increase in viscosity-related parameters for PIBlwt is slightly lower compared to PIBmwt at equivalent concentrations. This difference in behavior may be due to variations in the molecular weight or structural characteristics of the polymers. Additionally, the specific and reduced viscosity values for PIBlwt are marginally lower compared to PIBmwt at corresponding concentrations, indicating differences in solution behavior between the two polymer types [9, 13, 16].

Table 4 summarizes the results of the film morphology study for blends of polystyrene (PS) with rubber, categorized by blend composition percentage and the observed characteristics of transparency and rubber dispersion over the film.

Table 4: film morphology study (visual observation) for polystyrene-rubber blends

Blend Type	Blend Composition %	Transparency	Rubber Dispersion Over the film
Pure PS	100	A	No rubber
PS/PIS$_{mwt}$	95/5	A	$\bar{B}$
	90/10	B	$\bar{B}$
	85/15	C	$\bar{C}$
	80/20	D	$\bar{D}$
PS/PIB$_{lwt}$	95/5	A	$\bar{B}$
	90/10	B	$\bar{B}$
	85/15	D	$\bar{D}$
	80/20	D	$\bar{D}$

Key

A – Quiet transparent
B – Transparent
C – Fairly transparent
D – Translucent

$\bar{A}$ – Highly dispersed
$\bar{B}$ – Dispersed
$\bar{C}$ – Fairly dispersed
$\bar{D}$ – Poorly dispersed

For the blends containing PS with PISmwt (Polyisoprene molecular weight type), as the proportion of PISmwt increases from 5% to 20%, there is a transition in both transparency and rubber dispersion. At lower concentrations (95/5 and 90/10), the films exhibit good transparency (A and B ratings) with relatively well-dispersed rubber (B rating). However, as the proportion of PISmwt increases to 15% and 20%, transparency decreases (C and D ratings), and rubber dispersion becomes less uniform (C and D ratings), indicating a reduction in film quality and dispersion homogeneity [2, 3, 7, 8]. Similarly, for blends containing PS with PIBlwt (Polyisoprene low molecular weight type), transparency and rubber dispersion show a similar trend. Films with lower concentrations of PIBlwt (95/5 and 90/10) exhibit good transparency (A and B ratings) and well-dispersed rubber (B rating). However, as the proportion of PIBlwt increases to 15% and 20%, transparency decreases (D rating), and rubber dispersion becomes less uniform (D rating), indicating a decline in film quality and dispersion homogeneity similar to the PISmwt blends.

Overall, the results suggest that increasing the proportion of rubber in the PS blends leads to decreased transparency and poorer dispersion of rubber within the film, highlighting the importance of blend composition in determining film morphology and properties [4, 5, 12, 32].

Figure 1 illustrates results of tensile tests conducted on two different compositions: a 2% Polystyrene solution and a blend of Polystyrene with PIBmwt (Polyisobutylene molecular weight type).

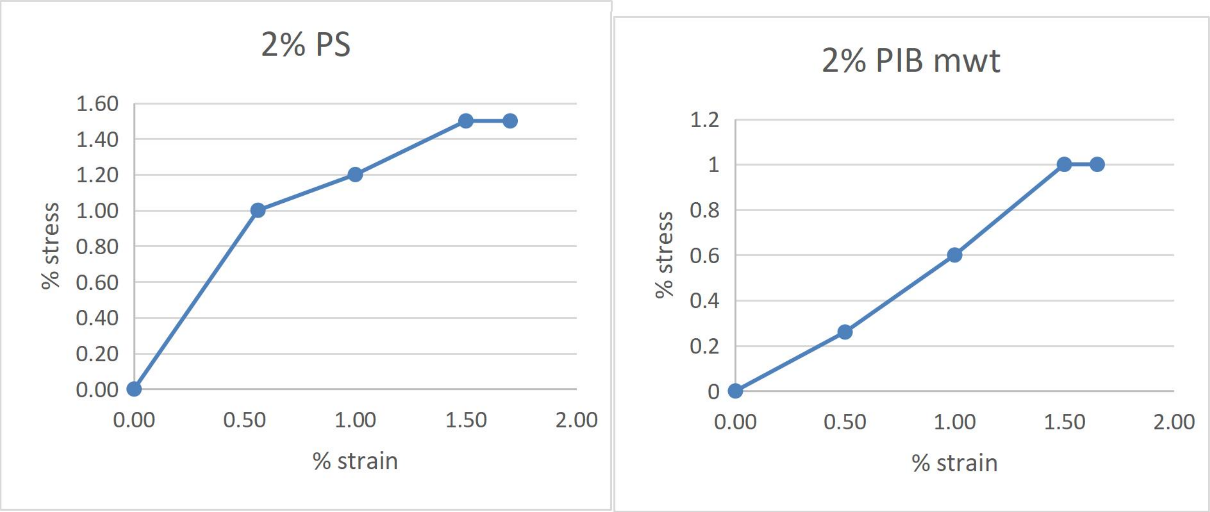

Figure 1: Results of tensile test for 2% PS and PS/PIB_{mwt} blend compositions ,2% (PS)

Table 5 compares the calculated and graphical values of viscosity for blends of polystyrene (PS) with two types of rubber: PIBmwt (Polyisobutylene molecular weight type) and PIBlwt (Polyisobutylene low molecular weight type).

Table 5: Comparison of calculated and graphical values of viscosity of polystyrene-rubber blends.

Blend type	Calculated viscosity	Graphical
PS/PIB_{mwt}		
95/5	0.95(0.52) + 0.05(1.5) = 0.569	0.555
90/10	0.90(0.52) + 0.10(1.5) = 0.648	0.622
85/15	0.85(0.52) + 0.15(1.5) = 0.667	0.632
80/20	0.80(0.52) + 0.20(1.5) = 0.776	0.745
PS/PIB_{lwt}		
95/5	0.95(0.52) + 0.05(1.25) = 0.557	0.553
90/10	0.90(0.52) + 0.10(1.25) = 0.593	0.580
85/15	0.85(0.52) + 0.15(1.25) = 0.629	0.615
80/20	0.80(0.52) + 0.15(1.25) = 0.668	0.645

Limiting viscosity of polystyrene = 0.52

For the PS/PIBmwt blends, the calculated viscosity values are obtained using a weighted average formula based on the blend composition percentages and the respective viscosities of PS and PIBmwt. Graphical values are determined experimentally or through graphical methods.

Across all blend compositions (95/5, 90/10, 85/15, and 80/20), the calculated viscosities generally align closely with the graphical values, indicating good agreement between the two methods. For the PS/PIBlwt blends, the calculated viscosities are determined using a weighted average formula based on the blend composition percentages and the respective viscosities of PS and PIBlwt.

There is overall consistency between the calculated and graphical viscosities for the different blend compositions (95/5, 90/10, 85/15, and 80/20), indicating a reasonable agreement between the two approaches.

The comparison between calculated and graphical values provides validation for the viscosity prediction methods employed, suggesting that the calculated values represent the experimental data obtained through graphical analysis[9, 13, 14, 16].

In the 2% PS composition, as the applied load increases from 0 to 340 grams, there is a corresponding rise in chart extension, actual extension, stress, and percent strain, showcasing the material's linear elastic behavior. Similarly, for the PS/PIBmwt blend compositions, increasing loads lead to proportional increases in chart extension, actual extension, stress, and percent strain, suggesting comparable mechanical properties to the 2% PS solution and indicating the blend's potential for various applications requiring tensile strength assessment.

A comparison between the results of tensile tests for the 2% Polystyrene (PS) solution and the Polystyrene/Polyisobutylene molecular weight type (PS/PIBmwt) blend compositions reveals notable similarities and differences in their mechanical behavior under increasing loads. In both cases, as the applied load gradually increases, there is a corresponding rise in chart extension, actual extension, stress, and percent strain. This consistent trend suggests that both the pure PS solution and the PS/PIBmwt blends exhibit typical linear elastic behavior.The material deforms proportionally to the applied load within the elastic limit [2, 7, 8, 33]. However, slight variations emerge between the two compositions. The stress values for the PS/PIBmwt blends are lower than those for the 2% PS solution at equivalent loads, indicating a potential decrease in the material's ability to withstand deformation under stress when blended with PIBmwt. The percent strain values follow a similar pattern for both compositions, with slight differences in the magnitude of elongation, suggesting subtle alterations in the material's flexibility and stretchability. Overall, while the mechanical properties of the PS/PIBmwt blends exhibit similarities to the 2% PS solution, particularly in their linear elastic response to increasing loads.

The addition of PIBmwt may impart minor modifications to the material's tensile behavior, warranting further investigation into the blend's suitability for specific applications requiring tensile strength assessment [2, 3, 5, 8].

Figure 2 shows the results of tensile tests for an 80/20 blend of Polystyrene (PS) with Polyisobutylene molecular weight type (PIBmwt) under increasing loads.

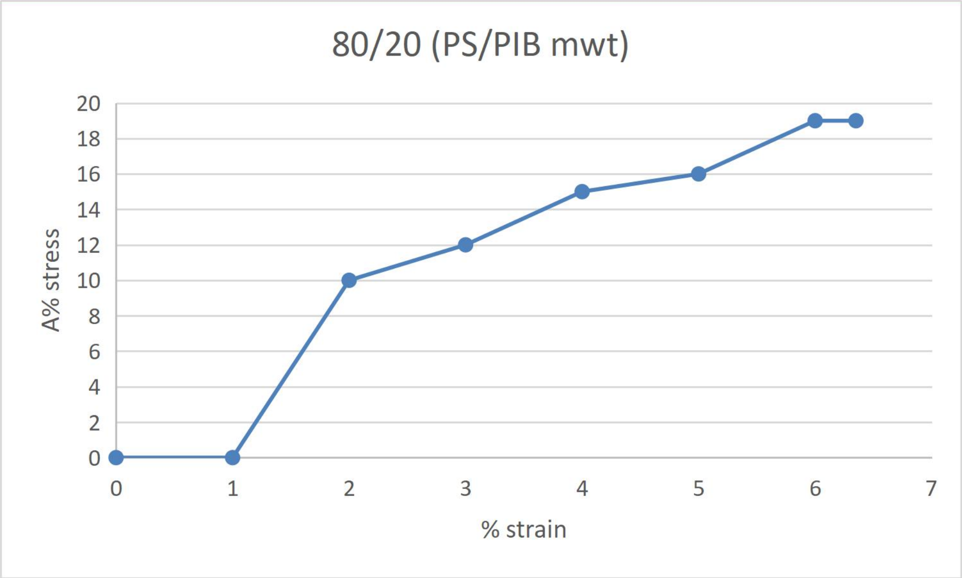

Figure 2: 80/20 (PS/PIB$_{mwt}$)

As the load increases from 0 to 1270 grams, there is a corresponding increase in chart extension, indicating the material's elongation under stress. This demonstrates the blend's ability to deform in response to applied loads.

The actual extension of the material also increases with the load, following a similar trend to the chart extension. This confirms the material's ability to stretch under stress, consistent with its linear elastic behavior.

The stress values, calculated based on the load and cross-sectional area, increase linearly with the applied load. This indicates the increasing force per unit area that the material experiences as the load increases, highlighting its resistance to deformation.

The percentage strain values represent the degree of deformation relative to the material's original length. % strain increases with the applied load, reflecting the material's increasing elongation under stress.

The load-extension relationship follows a linear pattern, with extension increasing proportionally with the applied load up to a certain point. Beyond a load of 400 grams, the % strain begins to rise significantly, indicating the material's transition into a region of plastic deformation where permanent changes occur.

Overall, the tensile test results demonstrate the mechanical behavior of the 80/20 PS/PIBmwt blend, showing its ability to withstand increasing loads while undergoing elastic deformation. The data provides valuable insights into the material's tensile properties, aiding in its characterization and potential application in various industries[2, 3, 5, 8, 34, 35].

Figure 3 presents the results of tensile tests for an 85/15 blend of Polystyrene (PS) with Polyisobutylene molecular weight type (PIBmwt) under increasing loads.

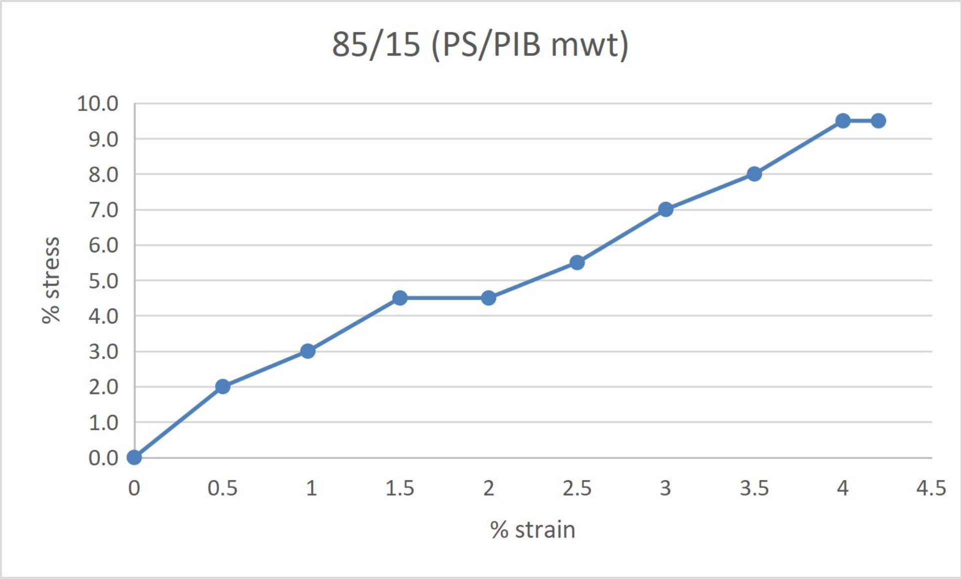

Figure 3: 85/15 (PS/PIB$_{mwt}$)

As the load increases from 0 to 840 grams, there is a corresponding increase in chart extension, indicating the material's elongation under stress. This demonstrates the blend's ability to deform in response to applied loads.

The actual extension of the material also increases with the load, following a similar trend to the chart extension. This confirms the material's ability to stretch under stress, consistent with its linear elastic behavior.

The stress values, calculated based on the load and cross-sectional area, increase linearly with the applied load. This indicates the increasing force per unit area that the material experiences as the load increases, highlighting its resistance to deformation.

The percentage strain values represent the degree of deformation relative to the material's original length. As expected, % strain increases with the applied load, reflecting the material's increasing elongation under stress.

The load-extension relationship follows a linear pattern, with extension increasing proportionally with the applied load up to a certain point. Beyond a load of 400 grams, the % strain begins to rise more steeply, indicating the material's transition into a region of plastic deformation where permanent changes occur.

Overall, the tensile test results provide valuable insights into the mechanical behavior of the 85/15 PS/PIBmwt blend, showing its ability to withstand increasing loads while undergoing elastic deformation. The data aids in characterizing the material's tensile properties, which are crucial for understanding its performance in various applications[2, 3, 5, 8, 34, 35].

Figure 4 displays the outcomes of tensile tests conducted on a blend composition of 90% Polystyrene (PS) and 10% Polyisobutylene molecular weight type (PIBmwt) under varying loads.

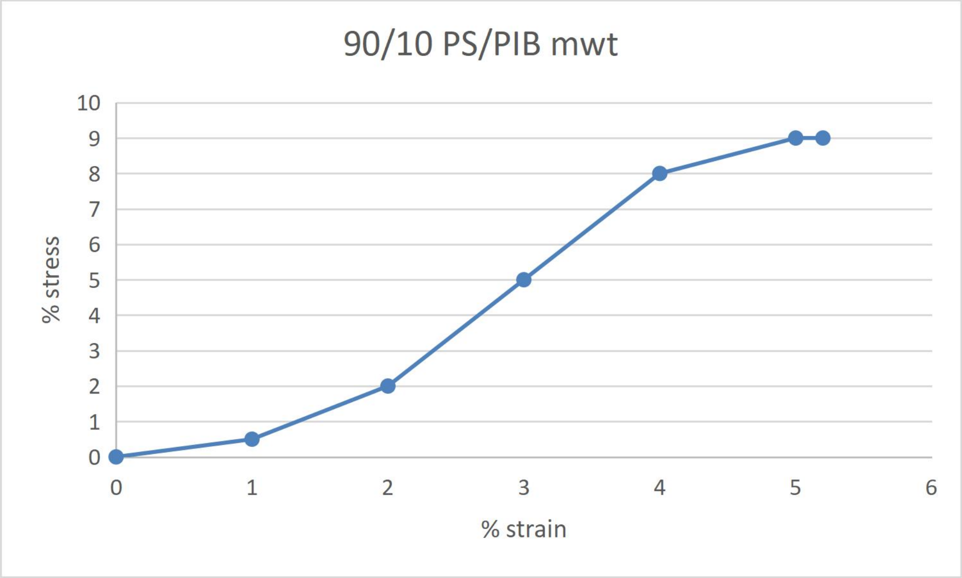

Figure 4 :_90/10 (PS/PIB$_{mwt}$)

Figure 4 illustrates how the chart extension increases as the load is incremented from 0 to 1040 grams. This suggests that the material undergoes elongation in response to increasing applied loads. Similarly, the actual extension of the material follows a similar trend, increasing as the load increases. This confirms the material's ability to stretch under stress, which is indicative of its linear elastic behavior.

The stress values, calculated based on the load and cross-sectional area, exhibit a linear increase with the applied load. This indicates the material's resistance to deformation, with higher loads leading to higher stress levels.

The percentage strain values represent the degree of deformation relative to the material's original length. As observed, % strain increases with the applied load, indicating the material's increasing elongation under stress.

The relationship between load and extension appears to be linear, with extension increasing proportionally with the applied load. However, beyond a load of 600 grams, the % strain begins to rise more rapidly, indicating the material's transition into a region of plastic deformation.

Overall, the tensile test results for the 90/10 PS/PIBmwt blend as presented in Figure 4 provide insights into its mechanical behavior, demonstrating its ability to withstand increasing loads while undergoing elastic deformation. These findings contribute to the characterization of the material's tensile properties, essential for evaluating its suitability for various applications [2, 3, 5, 8, 34, 35].

CONCLUSION

Based on the results obtained for different blend compositions of Polystyrene (PS) and Polyisobutylene molecular weight types (PIBmwt) under tensile test, it was observed that across all blend compositions (80/20, 85/15, and 90/10 PS/PIBmwt), the materials exhibit linear elastic behavior under increasing loads. This is evidenced by the linear relationship between applied load and both chart extension and actual extension, indicating that the materials deform elastically in response to applied stress up to a certain point. As the load increases, there is a corresponding increase in stress and strain for all blend compositions. This demonstrates the materials' ability to withstand higher levels of stress and elongate further under increasing loads, highlighting their mechanical resilience. Beyond a certain load threshold, typically around 600-800 grams depending on the blend composition, the materials begin to exhibit signs of plastic deformation. This is evident from the more rapid increase in strain compared to lower loads, indicating that permanent changes are occurring in the material structure. When comparing the mechanical properties of different blend compositions, subtle variations are observed. While all compositions demonstrate similar linear elastic behavior, slight differences in stress and strain values may be noted, reflecting variations in material composition and blend ratios. The tensile test results provide valuable insights into the mechanical behavior of PS/PIBmwt blend compositions, demonstrating their ability to withstand loads and deform elastically under stress. These findings are crucial for understanding the materials' performance and suitability for various applications in industries such as packaging, automotive, and construction. Further studies can explore optimizing blend ratios to enhance specific mechanical properties based on application requirements.

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