Investigating Tensile & Impact Properties of Recycled Polypropylene, Polyvinyl Chloride, Polyamide & Polyethylene

Investigación de las propiedades de tracción e impacto del polipropileno, cloruro de polivinilo, poliamida y polietileno reciclados

Investigação das propriedades de tração e impacto de polipropileno, cloreto de polivinila, poliamida e polietileno reciclados

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Summary. - Although Pakistan has an abundance of natural resources, it also faces a significant challenge with plastic waste, producing 3.3 million tons annually. This environmental issue demands immediate action, especially due to the increased demand for personal protective equipment (PPE) during the pandemic. Our research aims to make thermoplastics more environmentally friendly by focusing on the properties of recycled polypropylene (PP) enhanced with elastomers and calcium carbonate. Despite a modest loss in tensile properties and impact strength, recycled PP retains key characteristics. Adding calcium carbonate notably increases density, from 908 kg/m³ for stabilized recycled PP to 1029 kg/m³ for a 20% calcium carbonate blend. The total deformation analysis of both recycled and virgin PVC further supports our findings, revealing higher deformation in recycled PVC, which indicates its superior ductility. Additionally, this study examined the effects of aramid short fibers and thermoplastic polyurethane (TPU) additives on recycled polyamide-12 (PA-12). The inclusion of TPU decreased the modulus while increasing tensile strain and energy at break, whereas aramid fibers increased the modulus. Deformation analysis revealed significant strain concentrations in the central sections of these specimens, underscoring the impact of these additives on mechanical behavior. For example, PA-12 with 20% TPU exhibited higher maximum deformation, reflecting its enhanced tensile properties. Moreover, our deformation studies on Poly Butylene terephthalate with 0% HDPE and a blend containing 10% HDPE demonstrated the influence of HDPE content on elastic strain distribution and total deformation. The findings showed that the central region experiences substantial elastic deformation, which is critical for understanding stress distribution in these materials.

Keywords: Environmental sustainability, Thermoplastics, Elastomers, Mechanical Behaviors, Resource Conservation, Technological applications.

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Resumen. - *Aunque Pakistán cuenta con abundantes recursos naturales, también enfrenta un importante desafío con los residuos plásticos, generando 3,3 millones de toneladas anuales. Este problema ambiental exige medidas inmediatas, especialmente debido al aumento de la demanda de equipos de protección personal (EPP) durante la pandemia. Nuestra investigación busca lograr que los termoplásticos sean más ecológicos, centrándonos en las propiedades del polipropileno (PP) reciclado mejorado con elastómeros y carbonato de calcio. A pesar de una ligera disminución en las propiedades de tracción y resistencia al impacto, el PP reciclado conserva características clave. La adición de carbonato de calcio aumenta notablemente la densidad, de 908 kg/m³ para el PP reciclado estabilizado a 1029 kg/m³ para una mezcla con un 20 % de carbonato de calcio. El análisis de deformación total del PVC reciclado y virgen respalda aún más nuestros hallazgos, revelando una mayor deformación en el PVC reciclado, lo que indica su mayor ductilidad. Además, este estudio examinó los efectos de las fibras cortas de aramida y los aditivos de poliuretano termoplástico (TPU) en la poliamida-12 (PA-12) reciclada. La inclusión de TPU disminuyó el módulo, pero aumentó la deformación por tracción y la energía de rotura, mientras que las fibras de aramida incrementaron el módulo. El análisis de deformación reveló concentraciones significativas de deformación en las secciones centrales de estas muestras, lo que subraya el impacto de estos aditivos en el comportamiento mecánico. Por ejemplo, el PA-12 con un 20 % de TPU presentó una mayor deformación máxima, lo que refleja sus mejores propiedades de tracción. Además, nuestros estudios de deformación en tereftalato de polibutileno con un 0 % de HDPE y una mezcla con un 10 % de HDPE demostraron la influencia del contenido de HDPE en la distribución de la deformación elástica y la deformación total. Los resultados mostraron que la región central experimenta una deformación elástica sustancial, lo cual es fundamental para comprender la distribución de tensiones en estos materiales.*

Palabras clave: *Sostenibilidad ambiental, termoplásticos, elastómeros, comportamiento mecánico, conservación de recursos, aplicaciones tecnológicas.*

***Resumo*. -** *Embora o Paquistão possua abundância de recursos naturais, também enfrenta um desafio significativo com o lixo plástico, produzindo 3,3 milhões de toneladas anualmente. Essa questão ambiental exige ação imediata, especialmente devido ao aumento da demanda por equipamentos de proteção individual (EPI) durante a pandemia. Nossa pesquisa visa tornar os termoplásticos mais ecológicos, concentrando-se nas propriedades do polipropileno (PP) reciclado, aprimorado com elastômeros e carbonato de cálcio. Apesar de uma pequena perda nas propriedades de tração e resistência ao impacto, o PP reciclado mantém características importantes. A adição de carbonato de cálcio aumenta notavelmente a densidade, de 908 kg/m³ para o PP reciclado estabilizado para 1029 kg/m³ para uma mistura com 20% de carbonato de cálcio. A análise da deformação total do PVC reciclado e do PVC virgem corrobora nossos resultados, revelando maior deformação no PVC reciclado, o que indica sua ductilidade superior. Além disso, este estudo examinou os efeitos de fibras curtas de aramida e aditivos de poliuretano termoplástico (TPU) na poliamida-12 (PA-12) reciclada. A inclusão de TPU diminuiu o módulo de elasticidade, ao mesmo tempo que aumentou a deformação por tração e a energia de ruptura, enquanto as fibras de aramida aumentaram o módulo. A análise de deformação revelou concentrações significativas de deformação nas seções centrais dessas amostras, ressaltando o impacto desses aditivos no comportamento mecânico. Por exemplo, o PA-12 com 20% de TPU apresentou maior deformação máxima, refletindo suas propriedades de tração aprimoradas. Além disso, nossos estudos de deformação em poli(tereftalato de butileno) com 0% de HDPE e em uma mistura contendo 10% de HDPE demonstraram a influência do teor de HDPE na distribuição da deformação elástica e na deformação total. Os resultados mostraram que a região central sofre deformação elástica substancial, o que é crucial para a compreensão da distribuição de tensões nesses materiais.*

Palavras-chave: *Sustentabilidade ambiental, Termoplásticos, Elastômeros, Comportamento mecânico, Conservação de recursos, Aplicações tecnológicas.*

1. Introduction. - Plastic, which first emerged in the mid-20th century, has become a cornerstone of our modern economy, growing from a novel material to an indispensable component in countless applications [1]. A study performed to evaluate blends of post-consumer recycled polypropylene (PPr) and virgin PP (PPv) at 25%, 50%, 75%, and 100% PPr to assess processability, thermal stability, oxidative resistance, and mechanical performance. Increasing PPr improved fluidity and inert-condition stability but reduced oxidation resistance and ductility. Extrusion homogenization enhanced oxidative stability of recycled PP by 22%, supporting its use in circular economy applications. [2]. Plastic encompasses a broad spectrum of materials with unmatched properties and extraordinary diversity, finding applications across various sectors. Among these, engineering thermoplastics and advanced engineering thermoplastics, also known as ultra-polymers, are particularly noteworthy for their unique characteristics and exceptional performance [3]. Recent advancements in dynamic covalent chemistry have spurred interest in polymer networks that mimic traditional cross-linked materials while retaining thermoplastic qualities [4].

Blending polybutylene terephthalate (PBT) with polycarbonate (PC) to enhance thermo-chemical and mechanical resistance remains challenging due to phase blockages leading to material segregation [5]. A significant hurdle for polyethylene (PE) pipe-grade resin manufacturers is identifying viable applications for recycled high-density polyethylene (HDPE), especially in pressure pipes [6]. This study explores data-driven modeling to predict tensile strength and modulus of extruded film containing recyclates. Die pressure proved a key quality indicator, correlating with viscosity and degradation. Including melt flow rate, shear viscosity, and feedstock type greatly improved prediction accuracy, with Generalized Additive Models reaching to 85.7% for tensile strength. Results highlight the need for better recyclate classification and larger datasets to enhance industrial predictive modeling.7]. The properties of recycled polypropylene blends, including shape, thermal characteristics, and fracture behavior, have been studied using calorimetry and microscopic examination [8].

Microplastics, often linked to environmental pollutants, can attract materials such as metals, drugs, and polycyclic aromatic hydrocarbons in aquatic environments [9]. The difficulty in combining PBT and PC for enhanced thermo-chemical and mechanical resistance is compounded by phase boundary coalescence during melting, leading to unwanted material segregation [10]. Developing applications for recycled plastics that are as functional as those made from virgin polymers remains a significant challenge, particularly when integrating recycled HDPE into PE pipe-grade resins used for pressure pipes [11]. Virgin polypropylene (Mosten TB 003) was mechanically reprocessed up to 18 times to simulate recycling cycles, with mechanical, thermal, and molecular properties evaluated. Reprocessing caused chain shortening, ~30% molecular weight loss, reduced thermal stability, and yellowing. HS-SPME/GC–MS detected fewer volatiles in highly reprocessed PP, with key compounds identified at 120 °C. [12].

This innovative method enables the incorporation of various reinforcements and polymeric materials into thermoset and thermoplastic matrices [13]. Recycling, especially through tertiary strategies like chemical recycling, is the optimal approach for minimizing waste and recovering valuable materials, with a focus on the fundamental chemistry of each recycling pathway [14]. Additionally, this study examines the composition, thermal properties, and fracture surface characteristics of recycled polypropylene through calorimetry and microscopic analysis, providing valuable insights into blended recycled polypropylene [15]. It also compares the mechanical and processing qualities of virgin pipe-grade PVC with recycled PVC from bottles and pipes, emphasizing the importance of particle size and re-stabilization in achieving consistent and reliable mechanical properties in virgin/recycled PVC blends [16,17].

Within the realm of polyurethane, thermoplastic polyurethane (TPU), a segmented block copolymer classified as a thermoplastic elastomer (TPE), is widely used across numerous industrial domains [18,19]. The pervasive use of plastic polyolefins, polyesters, and polystyrene, which constitute 80% of the global plastic market, has turned waste disposal into a significant environmental issue. Consequently, environmental protection organizations and plastics manufacturers are continually researching innovative methods to recycle and upcycle waste plastics into sustainable new products [20]. The advent of thermoplastic composites has leveraged the remelting and remolding capabilities of thermoplastic matrices while preserving the thermomechanical properties of embedded fibers [21].

Notably, thermoplastic polymers, with their low density, high strength, and corrosion resistance, are increasingly favored over conventional materials like metals or aluminum [22-24]. In composite materials, plastics often serve as matrices reinforced with fibers for enhanced strength in specific directions [25,26]. These materials, which exhibit greater strength compared to simple plastics, are commonly used in constructing industrial pressure tanks, offering high stress-bearing capability while reducing weight [27,28].

Mechanical properties between virgin high impact polypropylene, injected, and recycled one was compared by Fernandes and Shazad [29,30]. Two mixtures, one composed of 30% recycled PP and 70% virgin PP, and other one of 50% recycled PP and 50% virgin PP were assessed to investigate the impact of recycling on mechanical properties. They observed that the tensile properties (ultimate tensile strength, yield strength and strain) did not vary, however, the impact resistance only for samples with up to 30% recycled PP was acceptable for automotive use. Samples above this percentage (50% and 100% recycled PP) showed a significant reduction in impact strength. For comparative purposes, the virgin PP had an impact resistance of 78.7 kJ / m² and the PP 100% recycled 19.7 kJ/m².

The literature review indicates that a wide variety of plastics are used across numerous applications, from household items to industrial products. After their initial use, many of these plastics become waste; however, thermoplastics offer the advantage of being reusable. In local industries, such plastics are often recycled to manufacture various products, though their strength is rarely evaluated against that of virgin materials. Consequently, it is important to investigate how recycling affects the mechanical properties of these materials. A simulation-based approach can help analyze their behavior under loading conditions and provide a basis for comparison with experimental findings. This study examines the tensile and impact properties of widely used plastics such as polyethylene, polypropylene, polyamide, and polyvinyl chloride. In particular, polypropylene recycling was simulated through multiple injection molding cycles to reshape the material. The primary objective is to determine whether recycled polymers—especially recycled PP—maintain mechanical properties comparable to virgin polymers, thereby assessing their suitability for similar applications.

2. Methodology. - The major focus of this study was mechanical properties evaluation of recycled plastics commonly used at domestic and industrial level. Four polymers were selected for recycling purpose due to their extensive use. These selected polymers are listed below:

a. Recycled polypropylene (PPr)
b. Recycled poly vinyl chloride (PVCr)
c. Recycled polyamide (PAr)
d. Recycled polybutylene terephthalate (PBTr)

Recycling process was performed by using a Central co-rotating twin-screw extruder as shown in Figure I with 800 mm long screws (25 mm diameter). The temperature of the barrels changed between 180°C and 215°C while the output rate remained constant at 100 g/min. Calcium Carbonate ($CaCO_3$) was added to enhance mechanical properties, Calcite type crystals in 2-3 micrometer range were added while recycling. The use of these recycled plastics includes an extensive examination of their viability for eco-friendly and sustainable applications, providing insightful information on the industrial utilization of these recycled materials.

Figure I. Recycling of Plastics.

Using ASTM D638 for tensile testing and ASTM D256 for impact testing of recycled materials, mechanical properties were assessed, providing an understanding of the way extrusion parameters affect material qualities for industrial applications. Tensile tests were performed at room temperature, 20°C, and 60°C in accordance with ISO 527 standards. When the stress reached 5 MPa, the testing speed was increased to 50 mm/min from 1 mm/min. The data was sampled at a rate of 50 hertz. According to ISO 179 specifications, notched impact tests were conducted at 20°C using a Rosand Instrumented Falling Weight Tester (type 4). Before testing, specimens were pre-conditioned for 30 minutes within the temperature chamber. Recycling of PP was performed by using different recycling percentages with virgin PP as mentioned in Table I.

Sample	Virgin (%)	Recycled (%)
PPv100	100	-
PPr10	90	10
PPr20	80	20
PPr30	70	30
PPr100	-	100

Table I. Composition of recycled and virgin polypropylene.

To guarantee equal dispersion, a primary batch of polypropylene and stabilizers was created. The additives were added as stabilizers to PPv for evaluating impact of additives to mechanical properties. Two types of stabilizers named Hindered Amine Light Stabilizers (HALS) and Antioxidant (Irganox B215) were added in a constant proportion to PPv and PPr. Eight samples with different blending of additives were produced as shown in Table II, Recycled polypropylene was double blended for blends with EOR and $CaCO_3$. A Batten Feld BSKM 45/20 HY or DSM micro extruder/injection mold was used to create test specimens that were 2 mm thick at 23°C. Following that, 48 hours of conditioning at 23 °C and 50% humidity took place on all samples before testing. Elastomers such as ethylene-propylene rubber (EPR) were mixed in different proportions to enhance toughness and impact resistance but have the side effect of also reducing the yield strength and young's modulus as illustrated by Fernandes [25]. This drawback was countered by addition of inorganic fillers such as Calcium carbonate, $CaCO_3$ which provides increased impact energy, improved hardness, and higher modulus and tensile strength, while lowering the cost. Higher molecular weight PVC having K value approx. 75 was utilized as Virgin pipe-grade PVC (VPPVC) with standard pipe composition, contains 2.4% $CaCO_3$ powder and 2% stabilizer/lubricant. Normal bottles after consumed (RBPVC) was granulated into 9mm, 5mm, and 3mm pieces. Rigid PVC pipes (RPPVC) after extensive utilization were selected as a recycled material and pelletized through a 3mm screen. Qualitative analyses revealed a higher $CaCO_3$ level (about 5%) and trace amounts of rubber. Table III comprised of different mixing compositions, Virgin with recycled bottle material (VRB) and Virgin with recycled pipe material (VRP).

Sample	Stabilizers (S) (%)	ELASTOMER (E) (%)	$CaCO_3$ (C) (%)
PP+S	0.3	-	-
PP+S+E	0.3	5	-
PP+S+E+C	0.3	5	10
PPr+S+ E+ C	0.3	5	20
PP+S+E+C	0.3	10	10
PPr+S+E+C	0.3	10	20
PP+S+C	0.3	-	10
PPr+S+C	0.3	-	20

Table II. Polypropylene composition with different additives.

Sample Code	Composition (%)
VRB20	VPPVC 83, RBPVC 17
VRB40	VPPVC 71, RBPVC 29
VRB60	VPPVC 62, RBPVC 38
VRB80	VPPVC 56, RBPVC 44
VRB100	VPPVC 50, RBPVC 50
VRP20	VPPVC 83, RPPVC 17
VRP40	VPPVC 71, RPPVC 29
VRP60	VPPVC 62, RPPVC 38
VRP80	VPPVC 56, RPPVC 44
VRP100	VPPVC 50, RPPVC 50

Table III. Formulation of PVC for beverage bottles.

Samples	Composition (%)	
	PBT	HDPE

H0	100	0
H5	95	5
H10	90	10
H15	85	15
H100	0	100

Table IV. Composition of testing samples.

Initiating with the PA-12 sample preparation derived from waste produced during Selective Laser Sintering (SLS) operations, this research promotes environmentally friendly Additive Manufacturing (AM) procedures. The main objective is to turn excess polymer powder, which is often discarded, into a useful raw material. The idea is to promote a cradle-to-cradle approach in which waste from one stage forms a foundation for another. This work focuses on developing novel polymeric blends, with a focus on PA-12 usage, to improve the sustainability of 3D printing for the construction of prosthetic limbs utilizing Fused Deposition Modelling (FDM) technology.

The following groups of specimens were prepared:

a. pure PA-12,

b. pure reused PA-12 and mechanically milled TPU pellets,

c. pure reused PA-12 and aramid short fibers,

d. pure reused PA-12 and graphite powder.

Sample details are given in Table IV and for testing recycled thermoplastics such as PPr, PVCr, PAr, and PBTr, specimens should be prepared according to ISO 294-1 injection-molding guidelines. Mechanical characterization typically includes tensile testing in accordance with ASTM D638, impact resistance measured using ASTM D256. Melt flow rate or volume is determined following ASTM D1238, with ISO 1133-2 recommended for moisture-sensitive materials like PA and PBT. All specimens should be conditioned following ASTM D618, typically at 23 ± 2 °C and 50 ± 5 % RH for at least 96 hours, with additional pre-drying or desiccation for hygroscopic resins to prevent moisture-induced degradation. The automotive and construction sectors frequently utilize PBT, a thermoplastic with a reputation for chemical resistance, insulation, and easy processing. Its poor tensile strength and impact resistance are caused by its rapid crystallization. PBT is frequently combined with other polymers to improve its characteristics.

3. Results and Discussions. -

3.1 Testing of Recycled Plastics. -

a. Density variation: The effects of calcium carbonate and elastomers on density and melt flow index show how recycled PP's qualities might potentially be changed for specific applications. Table V shows the density and melt flow index for different recycled polypropylene blends, based on eight tests for each material. Adding calcium carbonate greatly increases density, from 908 kg/m³ for stabilized recycled polypropylene to 1029 kg/m³ for a 20% calcium carbonate blend.

Sample Compositions	**Density (kg/m³)**	**Melt Flow Rate (g/10min)**
PP + S	908	14.6
PP + S + 5%E	906	19.7
PP + S + 5%E + 10%C	968	14.4
PP + S + 5%E + 20%C	1033	14.6

PP + S + 10%E + 10%C	973	16.1
PP + S + 10%E + 20%C	1029	15.8
PP + S +10%C	974	14.3
PP + S +20%C	1038	14.5

Table V. Effect on Density and Melting behavior of Polypropylene.

The melt flow index also rises with elastomer content, from 14.6 g/10 min for a 5% EOR blend to 19.6 g/10 min. Melt flow rate measures how easily a polymer flows when melted, which affects its processability during manufacturing. Density measures mass per unit volume and influences a polymer's mechanical properties. Both values are important for optimizing polymer performance in different applications.

The density values of various PVCr composites which are represented in Table III. 5x samples were tested for evaluation of density fluctuations and mentioned in Table VI. S0 illustrate the minimum amount of recycling and S5 indicate the maximum amount as shown in Table III.

Samples	S0	S1	S2	S3	S4	S5
Density	145	147	151	154	158	161

Table VI. Density variations.

3.2 Melt Viscosity. - The renograms of PVCr composites are characterized in Figure II indicate that recycled polymer matrix results in the reduction of melt viscosity.

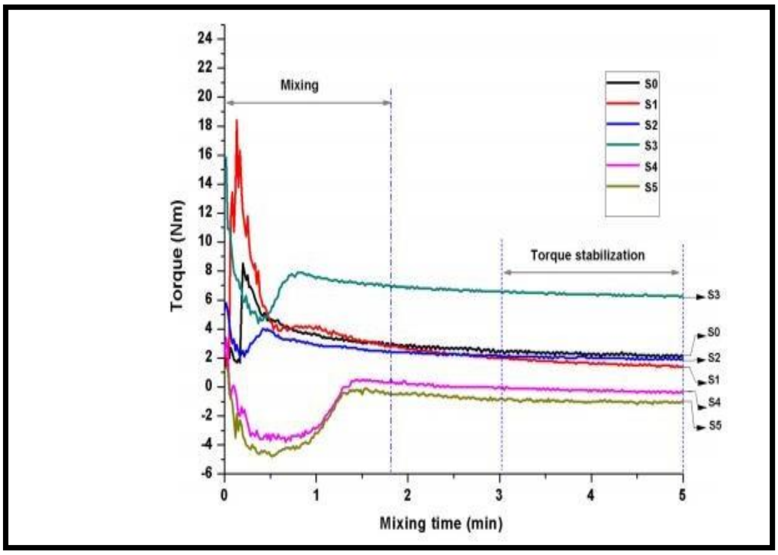

Figure II. Viscosity Variations

b. Tensile strength variations: The study demonstrated that the inclusion of PPr to a blend with PPv had no discernible impact on the yield stress and Young's modulus at room temperature. However, the recycling procedure reduced the impact strength of PP which is the result of additional hardness. The tensile properties of polypropylene were tested at -20°C, 23°C, and 60°C with various calcium carbonate and elastomer compositions are presented in Table VII.

Sample Compositions	**Youngs Modulus (MPa)**	**Yield Stress (MPa)**	**Yield Strain (%)**	**Maximum Elongation (%)**
Temperature during testing= -20ºC				
PP + S	3400 ± 200	43.8 ± 0.7	3.4 + 0.1	110 + 50
PP + S +5%E	2800 ± 300	43.5 ± 0.6	4.1 + 0.6	95 + 30
PP + S + 5%E + 10%C	3300 ± 600	41.4 ± 0.3	3.6 + 0.3	120 + 30
PP + S + 5%E + 20%C	3100 ± 500	39.0 ± 0.3	3.4 + 0.3	120 + 40
PP + S + 10%E + 10%C	2800 ± 300	39.8 ± 0.6	4.3 + 0.4	160 + 80
PP + S + 10%E + 20%C	3000 ± 700	37.9 ± 0.5	3.9 + 0.4	200 + 100
PP + S +10%C	3300 ± 300	42.4 ± 0.3	2.8 + 0.2	160 + 70
PP + S +20%C	3700 ± 700	40.4 ± 0.6	2.4 + 0.1	120 + 50
Temperature during testing= 23ºC				
PP + S	1010 ± 60	24.6 ± 0.1	6.7 + 0.1	16 to 580
PP + S +5%E	910 ± 30	23.6 ± 0.4	8.9 + 0.7	>150
PP + S + 5%E + 10%C	970 ± 40	22.2 ± 0.9	8.5 + 0.1	>150
PP + S + 5%E + 20%C	1080 ± 120	20.4 ± 0.1	8.3 + 0.1	>150
PP + S + 10%E + 10%C	890 ± 50	20.4 ± 0.2	12.5 + 0.1	>150
PP + S + 10%E + 20%C	960 ± 80	19.5 ± 0.1	9.5 1 1.1	>150
PP + S +10%C	1140 ± 40	22.9 ± 0.1	6.2 # 0.2	>150
PP + S +20%C	1250 ± 60	21.6 ± 0.1	5.6 + 0.2	>150
Temperature during testing= 60ºC				
PP + S	590 ± 140	14.5 + 0.1	10 + 2	>150
PP + S +5%E	390 ± 40	13.1 + 0.1	13.5 + 0.5	>150
PP + S + 5%E + 10%C	410 ± 80	12.7 + 0.2	11 + 2	>150
PP + S + 5%E + 20%C	380 ± 40	12.1 # 0.1	12 # I	>150

PP + S + 10%E + 10%C	320 ± 30	12.2 1 0.2	12 + 4	>150
PP + S + 10%E + 20%C	340 ± 20	11.3 + 0.1	13 + 2	>150
PP + S +10%C	420 ± 70	13.9 # 0.1	11.1 + 0.6	>150
PP + S +20%C	450 ± 60	13.6 + 0.1	9.9 1 0.2	>150

Table VII. Tensile testing results.

At −20 °C and 23 °C, Young's modulus stayed between 1-3 MPa. Increasing calcium carbonate slightly reduced yield stress, while the elastomer had minimal impact. All samples showed necking. Maximum elongation was stable but showed high variation. The stress–strain curves indicate that adding recycled PP to virgin PP has little effect on yield stress. The difference between PPv100 and PPr100 was only 3.87%.

The study examined blends of recycled PVC with virgin pipe-grade PVC to see how they affected mechanical properties and processing. Stress-strain curves in Figure II illustrates that recycled PVC was more ductile and had greater elongation at break than virgin PVC. These results offer guidance for enhancing PVC blend performance.

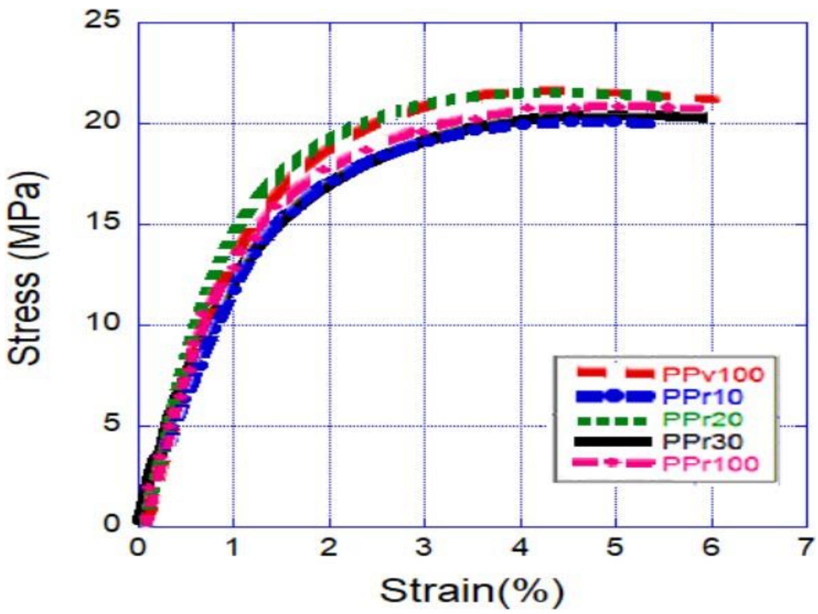

Figure III. Stress-strain curve for PPr.

As a result, the study shows that using 100% recycled PP or blending it with virgin PP has minimal impact on the tensile parameters as shown in Figure III, including yield strength and elastic modulus. However, it is crucial to recognize that the impact strength decreases, demonstrating that the recycling process makes PP extremely stiff and resistant to plastic deformations.

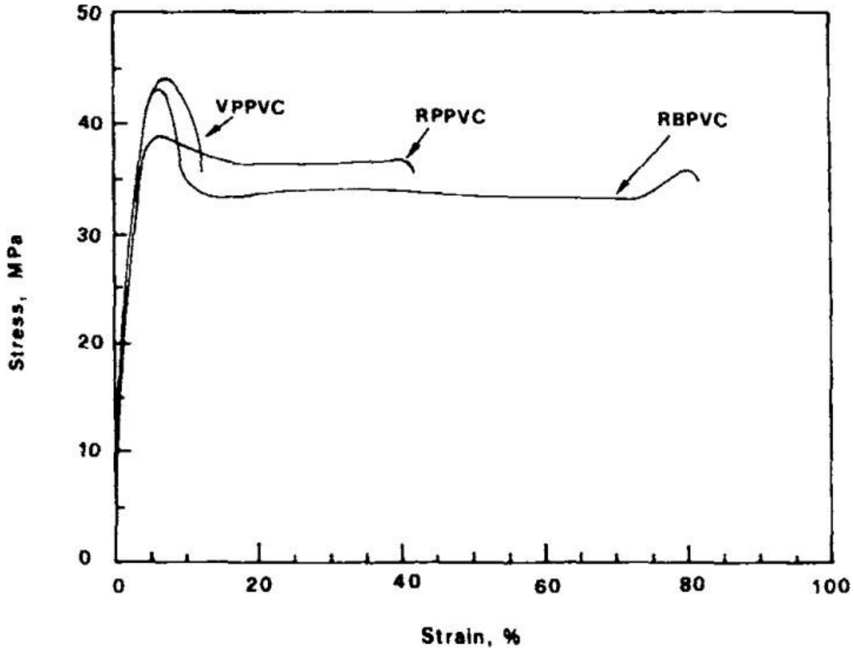

Figure IV. Stress strain curve PVCr.

Stress-strain curves for virgin and recycled PVC are shown in Figure IV. A polymer modifier gives the RBPVC curve its ductility. The VPPVC and RPPVC curves differ. Recycled material shows ductility and high elongation at break, which indicates a modifier is present in the recycled pipes. Recycled PVC from bottles and pipes needs stabilizers because stabilizer loss during manufacturing and use lowers heat resistance. The impact modifier in RBPVC reduces modulus and tensile strength compared to virgin pipe-grade PVC. However, it increases elongation and impact strength. PVC from pipes used for 4-5 years can stretch more before breaking.

Despite having the same modulus, virgin PA-12 performs better than recycled PA-12 powder in terms of elongation at break as depicted in Figure V. The expansion of 10% TPU marginally brings down the modulus however essentially increments ductile strain and energy at break. At 20%, the modulus diminishes to 0.4 GPa, with a further ascent in tensile strain. Aramid filaments upgrade the modulus, with 5% making an unobtrusive difference and 10% prompting a huge ascent to 0.9 GPa, however malleable endure break drops to 36.3%.

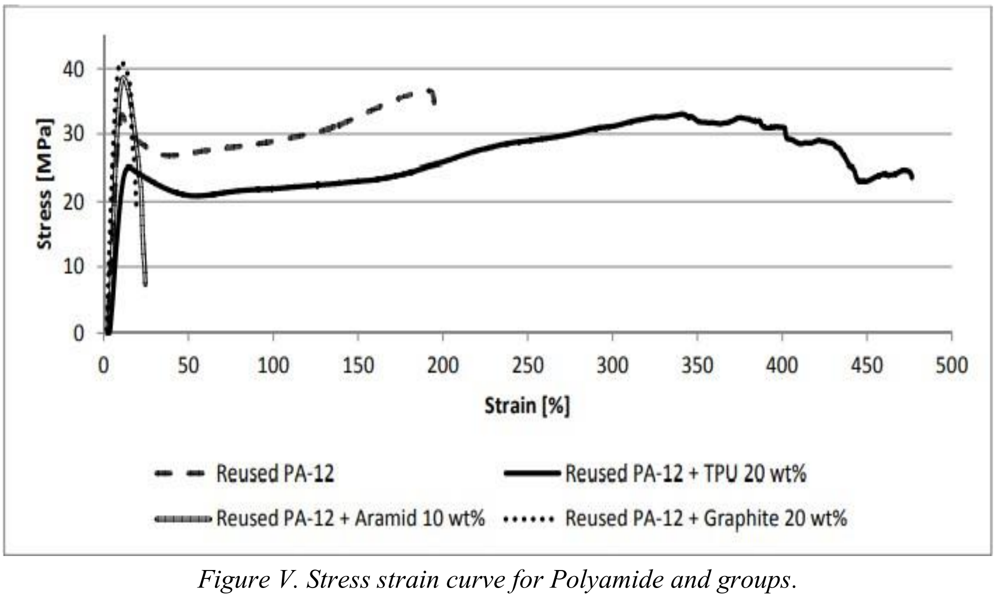

Figure V. Stress strain curve for Polyamide and groups.

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Our research on recycled PA-12 looked at the effects of additions such thermoplastic polyurethane (TPU) and aramid short fibers. While aramid fibers enhanced the modulus, TPU lowered the modulus while increasing the tensile strain and energy at break. These results provided useful insights for modifying recycled PA-12's properties for specific engineering applications.

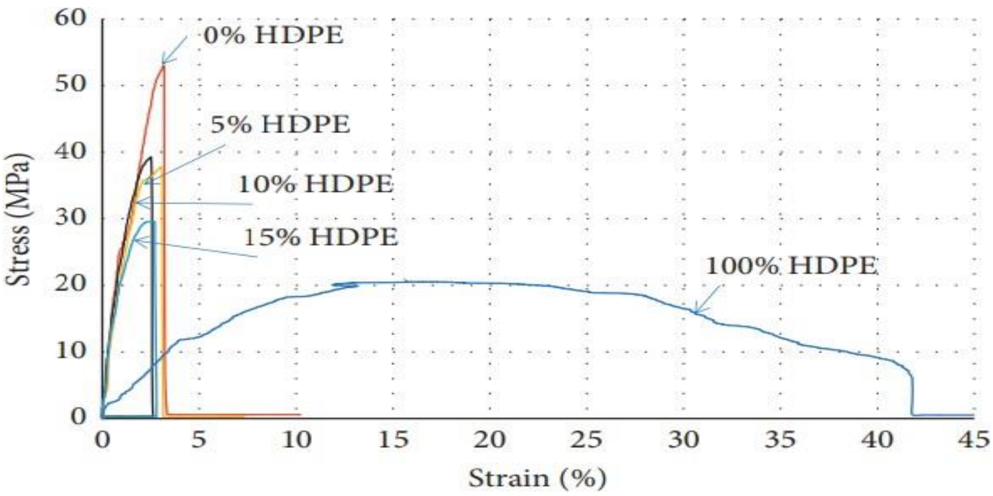

Figure VI. Stress strain curve for PBT mixed with HDPE.

The stress-strain curves of the samples depicted the pure PBT is very brittle with an exceptionally low value of elongation of about 2.5%. Adding HDPE to PBT will lead to a decrease in tensile strength. The tensile strength values of the composite samples are in the middle of pure PBT and HDPE as represented in Figure VI.

c. Impact Testing: According to the Charpy test results at -20°C with six specimens per composition, the inclusion of elastomer and calcium carbonate had no effect on impact energy and maximum force. The fracture mechanism of these samples is also brittle fracture as shown in Table VIII. In general, adding HDPE will reduce tensile strength compared to pure PBT. Because, for incompatible blends such as PBT/HDPE, incompatibility between the two components can result in weaker bonding between the components, poorer mechanical properties, and other problems such as welding line failure in the injection molding process.

Sample Compositions	Energy (KJ/m^2)	Max Force (N)
PP + S	2.0 ± 0.3	270 ± 34
PP + S +5%E	1.7 ± 0.2	275 ± 21
PP + S + 5%E + 10%E	2.2 ± 0.2	270 ± 35
PP + S + 5%E + 20%E	1.8 ± 0.1	280 ± 11
PP + S + 10%E + 10%E	2.5 ± 0.9	280 ± 26
PP + S + 10%E + 20%E	2.0 ± 0.3	330 ± 32
PP + S +10%E	2.1 ± 0.3	270 ± 69
PP + S +20%E	2.0 ± 0.3	3700 ± 33

Table VIII. Impact test Results.

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Insights into the tensile and impact behavior of recycled PP, PVC, PA, and PE can serve as a foundation for shaping effective manufacturing and sustainability strategies. In manufacturing, the introduction of performance-based grading systems, standardized processing guidelines, and design-for-recycling principles can enhance material consistency and recyclability. Establishing rigorous quality control measures, including mechanical testing and supplier certification, will strengthen trust in recycled polymers. On the sustainability front, policy measures such as fiscal incentives, eco-label programs, and mandated recycled content thresholds can accelerate adoption. Implementing closed-loop production systems and take-back initiatives can further minimize reliance on virgin plastics. A centralized, publicly accessible database linking mechanical properties with environmental metrics can guide informed material choices. Embedding life cycle assessment requirements into regulations will ensure that both durability and ecological impact are addressed in product development.

d. ANSYS Simulation: ANSYS software was utilized to verify the characteristics of recycled engineering thermoplastic, we ran multiple simulations. Dark blue denotes extremely low stress, light blue denotes low stress, yellow denotes moderate stress, and red denotes high stress. Fracture is caused by an increase in tension during elongation and deformation. In this tensile test simulation of a polymer specimen, one end of the dog-bone sample is fully constrained to prevent displacement or rotation, while a uniaxial displacement or tensile load is applied to the opposite end along the X-axis. The fine mesh consists of a structured hexahedral arrangement in the gauge section to ensure uniform stress distribution, with finer mesh density in the transition regions to capture stress gradients accurately. The element quality appears high, with minimal distortion, ensuring reliable deformation and strain predictions for the polymer material under tensile loading.

Polypropylene (PPr 20): Figure VII depicts the total deformation which is measured in millimeters and is depicted using a color gradient, where blue represents the minimum deformation and red indicates the maximum deformation (2.1305 mm). The specimen exhibits the highest deformation at both ends, with deformation gradually decreasing towards the center, illustrating the stress concentration and distribution along the length of the specimen. The deformation pattern aligns with expectations for the given loading and boundary conditions.

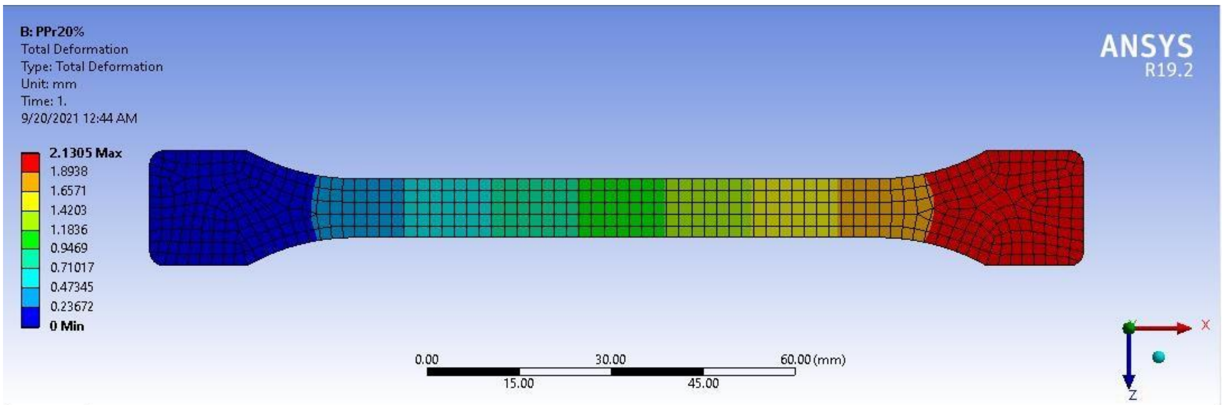

Figure VII. Total Deformation of PPr 20.

Polypropylene (PPr 100): Figure VIII illustrates the total deformation distribution of a 100% recycled polypropylene specimen under a specified loading condition. The deformation is measured in millimeters representing the maximum deformation (1.8824 mm). The highest deformation is observed at one end where tensile force applied to the specimen, with a gradual decrease towards the center, indicating stress concentration and distribution. The total deformation reduced due to increment in recycling percentage.

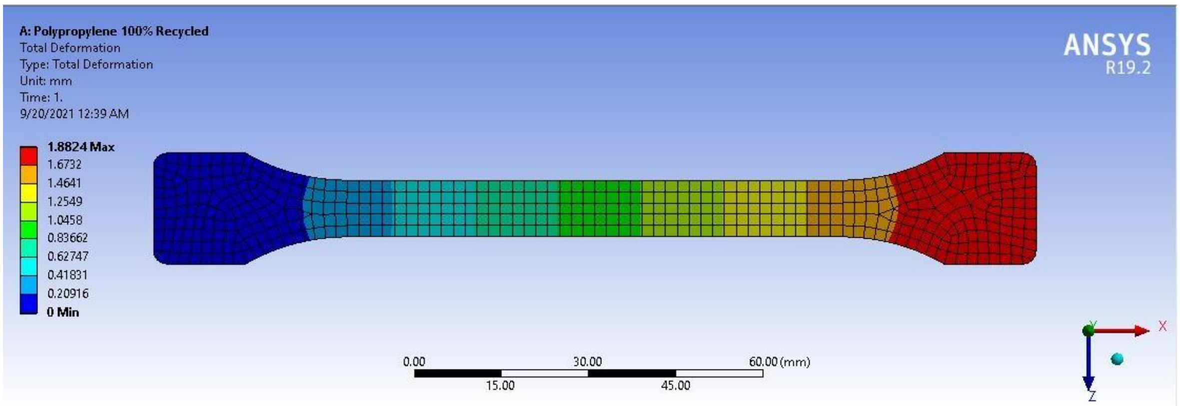

Figure VIII. Total Deformation of PPr 100.

An understanding of how a structure deforms under applied loads or heat impacts may be obtained from these complete deformation simulations. It assists in evaluating structural integrity, load distribution, and design validation by presenting the amount and direction of displacement.

3.3 Recycled PVC. -

3.3.1 Density Test. -

ANSYS Simulation of Recycled Polyvinyl Chloride: The fluctuation in stresses and deformations is investigated to figure out the structural behavior of recycled polyvinyl chloride (PVC) as shown in Figure IX and Figure X. Through critical insights into stress distribution and material reaction, these simulations improved our understanding of the mechanical characteristics of recycled PVC for use in sustainable engineering.

RBPVC:

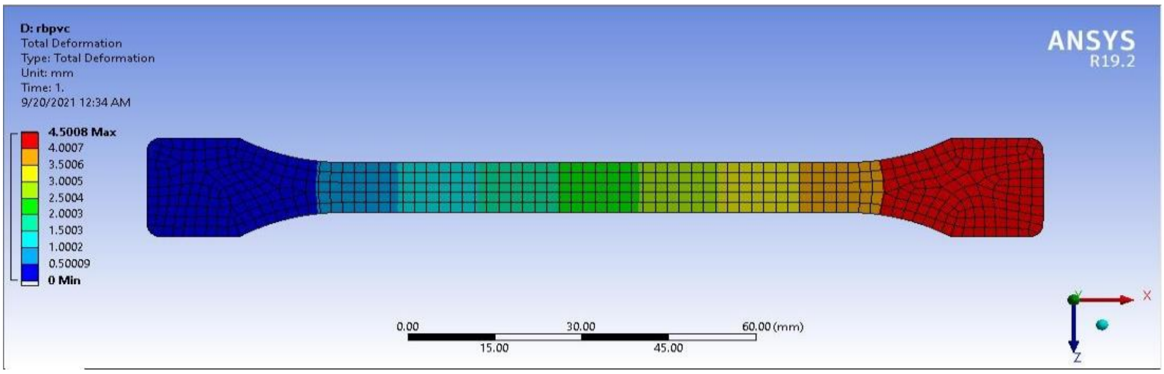

Figure IX. Total deformation for RBPVC.

RPPVC:

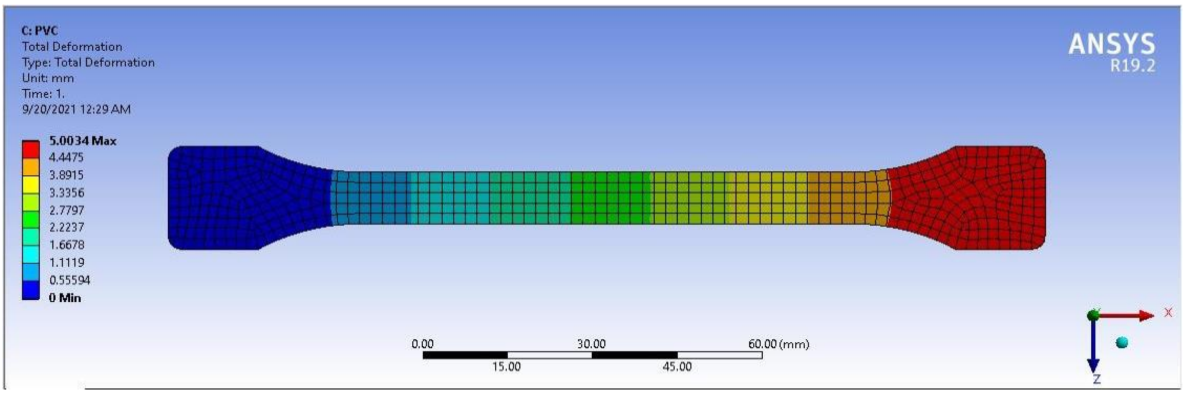

Figure X. Total deformation for RPPVC.

Figure IX depicts the total deformation distribution of a recycled polyvinyl chloride (RBPVC) specimen under a specified loading condition. Maximum deformation (4.5mm) was achieved by applying load at one end. Figure X exhibits a higher maximum deformation value (5.01mm). Both figures demonstrate a similar pattern of maximum deformation at the ends and a gradual decrease towards the centre, indicating consistent stress concentration and distribution along the specimen's length. The higher deformation in the RPPVC specimen suggests a difference in mechanical properties between the virgin RPPVC and recycled RBPVC materials under identical loading conditions. The composites' overall performance was further improved by their increased thermal stability. The material's applicability for many uses in the building industry is reinforced by its notably low water absorption propensity. This composite's added value makes it especially well-suited to produce several goods, such as flooring sheets and tiles, offering a promising path for market use and growth.

ANSYS Simulation of Recycled Polyamide: Recycled polyamide's structural dynamics were studied by conducting simulation of strength analysis and the findings revealed subtleties related to stress, which helped shape a more complex comprehension of its mechanical behavior for applications in sustainable engineering. Figure XI shows the total deformation distribution of a recycled polyamide 12 (PA-12). The major deformation (10.1mm) was observed at one end because force applied at this end. The specimen exhibits the fracture location at the central narrow section due to necking phenomena, indicating a significant stress concentration. The other end of the specimen displays lower deformation value, with the deformation increasing towards the center, demonstrating a pronounced localized deformation pattern typical under such loading conditions.

PAr:

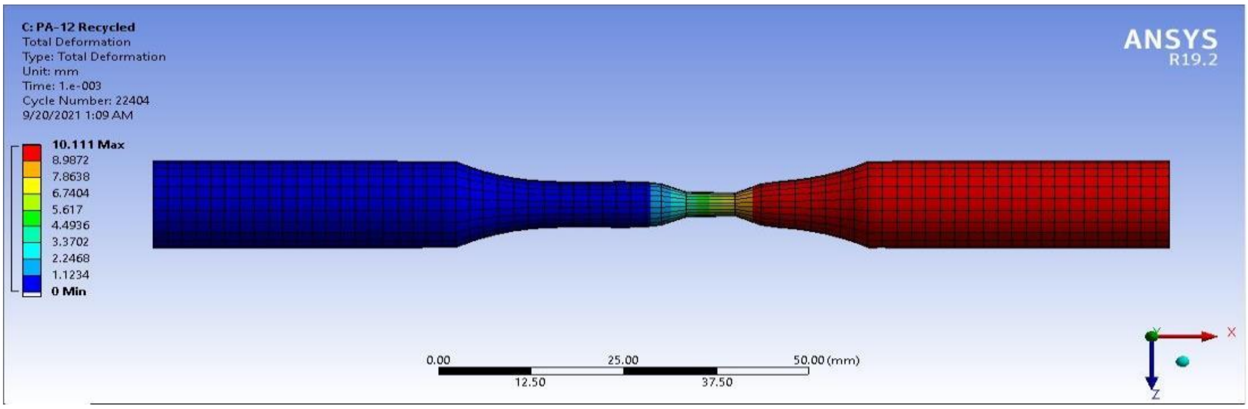

Figure XI. Total deformation for PAr-12.

PAr with TPU:

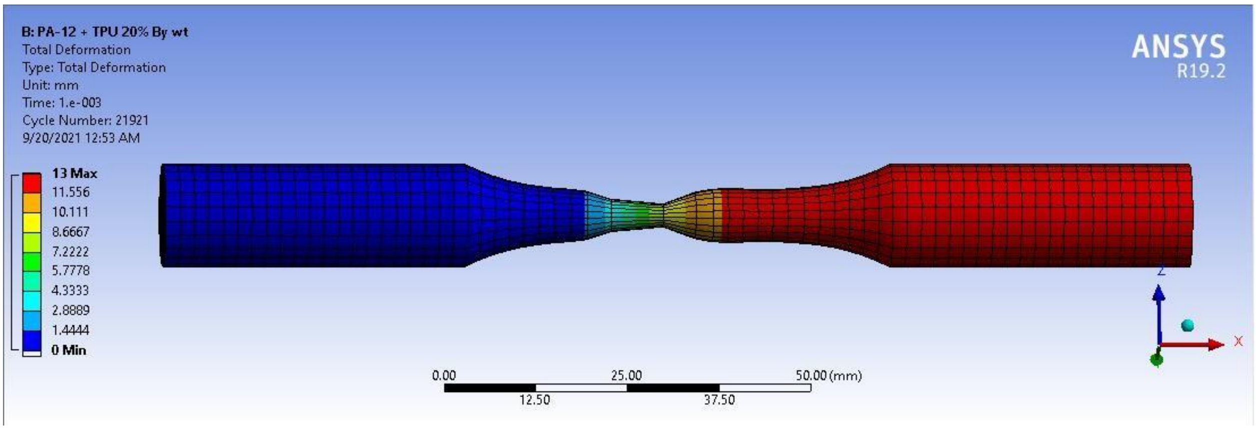

Figure XII. Total deformation for PAr with TPU.

Figure XII depicts the total deformation distribution of a polyamide 12 (PA-12) specimen with 20% TPU by weight. Maximum deformation (13 mm) was observed from loading end towards center. Significant stress concentration was noted towards center which indicate the failure point due to potential necking. The deformation decreases towards the other end of the specimen. The maximum deformation value of 13 mm is higher than that of the recycled PA-12 specimen, suggesting that the addition of TPU affects the mechanical properties and deformation behavior of the material under the applied load.

ANSYS Simulation of PBTr: Structural dynamics of PBT after adding high-density polyethylene (HDPE) were performed and the results provided information on the distribution of stress during deformation as shown in Figure XIV and Figure XV. The behavior of PBT without HDPE is illustrated in Figure XIII in which 3.48mm maximum deformation achieved. This might direct future optimizations for its use in a variety of engineering settings. This method advances our knowledge of the mechanical behavior of HDPE and advances the field of sustainable materials engineering.

PBT + 0% HDPE: Figure XIII displays the total deformation distribution of a PBT specimen with 0% high-density polyethylene (HDPE) under a specified loading condition. The highest deformation occurs at loading end of the specimen, with deformation values decreasing towards the center. Potential failure may occur near center due to less stress bearing area.

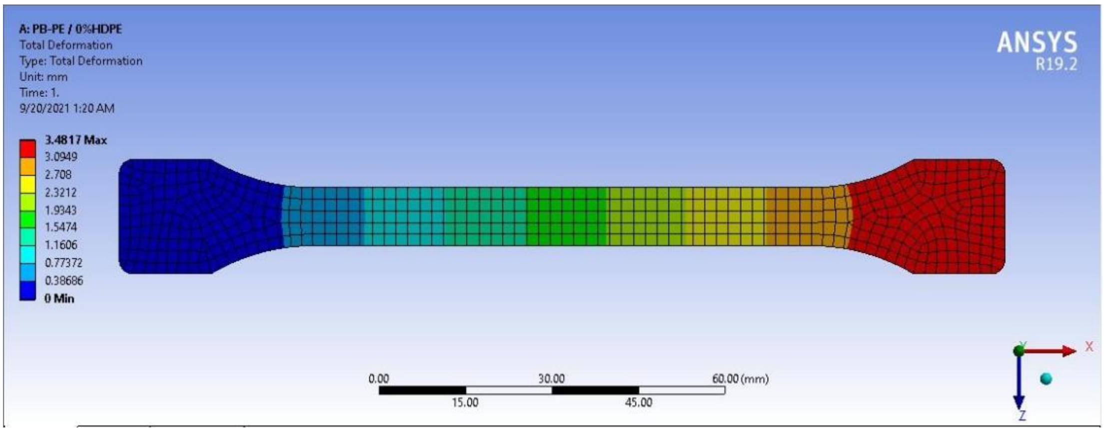

Figure XIII. Total deformation for PBTr.

PBTr + 5% HDPE: Figure XIV illustrates the total deformation distribution of a static structural analysis of a specimen and revealed that maximum deformation (3.2902 mm) was observed at loading end. The highest deformation occurs at one end of the specimen, with a gradual decrease towards the center. This pattern of deformation indicates stress concentration at the extremities and a more uniform deformation in the middle section, reflecting the material's response.

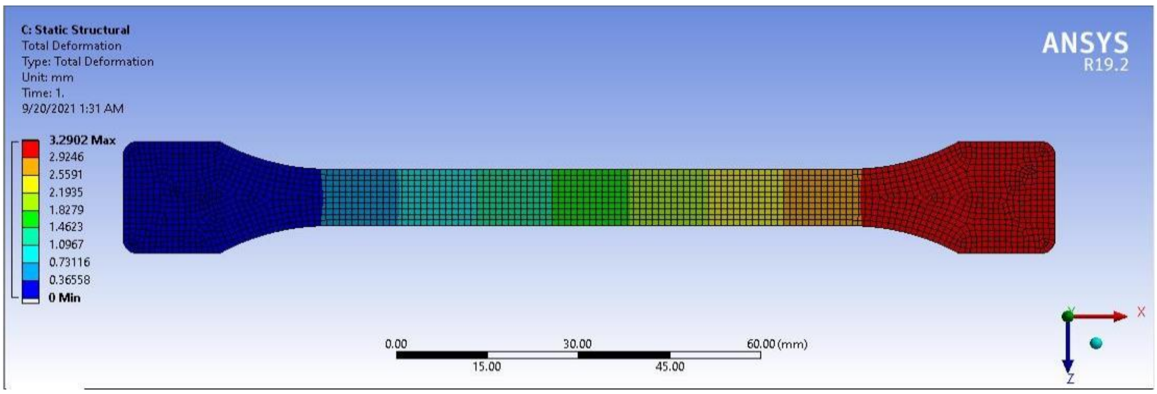

Figure XIV. Total deformation of PBTr after 5% HDPE.

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PBTr + 10% HDPE: Figure XV illustrates the equivalent elastic strain distribution of a specimen containing 10% high-density polyethylene under a specified loading condition. The strain is measured in mm/mm and displayed with a color gradient, where blue represents the minimum strain (0.000036008 mm/mm) and red signifies the maximum strain (0.024592 mm/mm). The highest strain is concentrated in the central region of the specimen, while the strain values decrease towards the ends. This pattern indicates that the central section experiences the greatest elastic deformation, reflecting the material's response to the applied load and highlighting areas of potential stress concentration and failure.

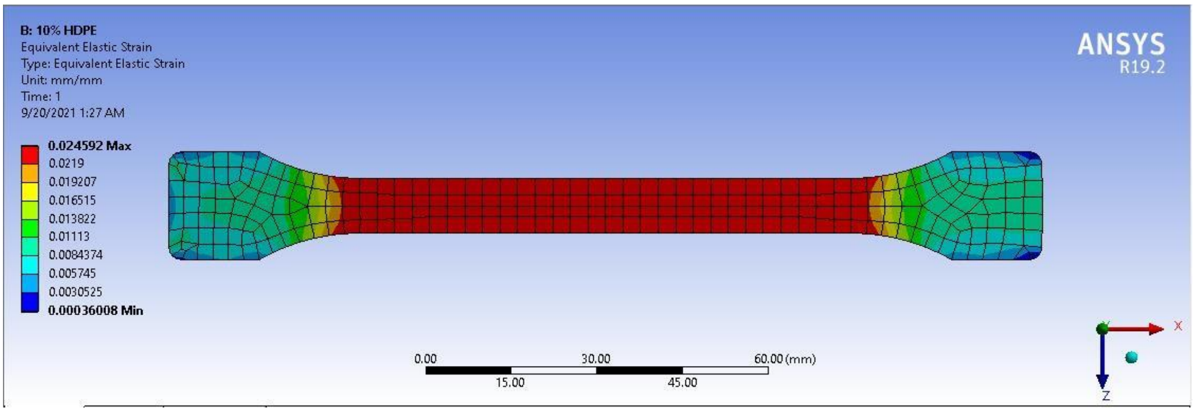

Figure XV. Equivalent elastic strain.

There isn't a single universal standard that dictates a fixed number of permissible recycling cycles for polymers like different materials responded in a change manner to heat such as for PVC, single cycle was opted due to its inclination towards temperature sensitivity. The minimum sample size suggested by the standard was adopted, with five specimens tested for each polymer to ensure a complete analysis because any uncertainty can be easily managed by using these values.

4. Conclusion. - In this engineering approach, a comprehensive study on the characteristics of various recycled plastics was conducted and findings indicate;

i. Addition of polypropylene (PP) with virgin PP does not affect significantly the yield stress and Young's modulus at room temperature.

ii. However, the recycling process makes PPr harder and stiffer, reducing its impact strength. The incorporation of elastomers and calcium carbonate impacts the density and melt flow index, suggesting potential modifications to recycled polypropylene properties for practical applications.

iii. Stress-strain curves demonstrated that recycled PVC outperforms virgin PVC in terms of ductility and elongation at break, providing crucial insights for enhancing PVC mixture performance. The total deformation analysis of recycled PVC and virgin PVC further supports these findings, showing higher deformation in recycled PVC, indicative of its superior ductility.

iv. Additionally, this study investigated the effects of aramid short fibres and thermoplastic polyurethane (TPU) additives on recycled polyamide-12 (PA-12). TPU decreased the modulus while increasing tensile strain and energy at break, whereas aramid fibres enhanced the modulus.

v. Deformation analysis showed significant strain concentrations in the central sections of these specimens, emphasizing the impact of additives on mechanical behaviour. For instance, the PA-12 with 20% TPU exhibited higher maximum deformation, reflecting its improved tensile properties.

vi. The results after blending PB and PE with HDPE showed that the central region experiences significant elastic deformation, which is crucial for understanding stress distribution in these materials.

5. Future recommendation. - Combine mechanical performance data with life cycle assessment and cost analysis to provide a comprehensive framework for industry adoption and policy formulation and more detailed study regarding mechanical properties like creep and fatigue can be performed.

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Author contribution:

1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

EAJ has contributed to: 1, 2, 3, 4, 5 and 6.

AS has contributed to: 1, 2, 3, 4, 5 and 6.

IA has contributed to: 1, 2, 3, 4, 5 and 6.

AAH has contributed to: 1, 2, 3, 4, 5 and 6.

UNA has contributed to: 1, 2, 3, 4, 5 and 6.

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