



RESEARCH ARTICLE / ARASTIRMA MAKALESİ

The Experimental Investigation of The Recycling Effect on The Low Strain Rate Behavior of HDPE and PP Materials Under Tensile Loading

Geri Dönüştürmenin HDPE ve PP Malzemelerinin Düşük Gerinme Hızı Altındaki Mekanik Davranışlarına Olan Etkisinin Deneysel Olarak İncelenmesi

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Abstract

Thermoplastics are widely used as engineering materials due to their advantages such as lightweight, corrosion resistance, and low cost. However, thermoplastic waste stands out as one of the major contributors to environmental pollution. This situation not only presents an economic disadvantage but also reduces the quality of life. The recyclability of thermoplastic materials is a crucial feature to address these disadvantages. Recycling not only conserves raw materials but also reduces environmental pollution. However, changes in the molecular structure of thermoplastics during the recycling process can lead to degradation in their rheological and mechanical properties. In this project, The impact of recycling via extrusion on tensile strength and the elasticity modulus of High-Density Polyethylene (HDPE) and Polypropylene (PP) materials at different strain rates was investigated. The raw HDPE material was recycled once and thrice, while the raw PP material was recycled once. The results indicated that the mechanical properties of HDPE material remain largely unaffected even after three recycling processes, while the PP material shows a slight reduction in elasticity after one recycling process. Additionally, an increase in mechanical properties was observed for all material types at high strain rates. While this increase was nearly the same for both raw and recycled HDPE materials, recycled PP materials exhibited a higher increase in mechanical properties compared to raw PP material. The results suggest that HDPE and PP materials subjected to a limited number of recycling processes can still be used as engineering materials.

Keywords: Recycling, HDPE, PP, Strain Rate Behavior, Mechanical Characterization

Öz

Termoplastikler hafiflik, korozyona dayanıklılık ve düşük maliyetli olmaları gibi avantajları sayesinde yaygın bir şekilde mühendislik malzemesi olarak kullanılmaktadır. Ancak, termoplastik atıklar çevre kirliliğindeki en önemli sebeplerden bir tanesi olarak göze çarpmaktadır. Bu durum ekonomik olarak bir dezavantaj oluştururken hayat kalitesini de düşürmektedir. Termoplastik malzemelerin geri dönüştürülme kabiliyeti bu dezavantajları elimine etmek için çok önemli bir özelliktir. Geri dönüştürme yöntemi ile bir yandan hammadde tasarrufu sağlanırken bir yandan da çevre kirliliği azaltılmaktadır. Ancak, geri dönüştürme işlemi sırasında termoplastik malzemelerin moleküler yapısında meydana gelen değişiklikler reolojik ve mekanik özelliklerinde bozunmalara yol açabilmektedir. Bu projede ekstrüzyon ile geri dönüştürme işleminin Yüksek Yoğunluklu Polietilen (HDPE) ve Polietilen (PP) malzemelerinin farklı gerinim hızlarındaki çekme mukavemetine ve elastisite modülüne etkisi incelenmiştir. Ham HDPE malzemesi bir ve üç defa ekstrüzyona tabi tutularak, ham PP malzemesi ise bir defa ekstrüzyona tabi tutularak geri dönüştürme işlemi gerçekleştirilmiştir. Elde edilen sonuçlar HDPE malzemesinin üç defa geri dönüştürülse bile mekanik özelliklerini kaybetmediğini ancak PP malzemesinin bir defa geri dönüştürme sonucunda az da olsa elastikiyetini kaybettiği göstermiştir. Ayrıca, yüksek gerinim hızlarında tüm malzeme tiplerinin mekanik özelliklerinde bir artış olduğu görülmüştür. Bu artış oranı ham HDPE ve geri dönüştürülmüş HDPE malzemeleri için hemen hemen aynı seviyede iken geri dönüştürülmüş PP malzemelerinin yüksek gerinim hızlarındaki mekanik özelliklerindeki artış oranı ham PP malzemesine göre daha yüksek seviyede meydana gelmiştir. Sonuçlar, az sayıda geri dönüştürme işlemine maruz kalmış HDPE ve PP malzemelerinin mühendislik malzemesi olarak kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Geri Dönüşüm, HDPE; PP, Gerinim Hızı Davranış, Mekanik Karakterizasyon

1. Introduction

Thermoplastic materials are extensively utilized in sectors like the automotive, aviation, and packaging today due to their superior features, including being lightweight, corrosion-resistant, exhibiting high specific mechanical properties, ease of

production, and electrical and thermal insulating properties [1]. Due to these superior characteristics, the usage of thermoplastic materials is increasing day by day. Thermoplastic materials such as Polystyrene (PS), Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Polypropylene (PP) are the

most commonly used thermoplastic materials on a global scale [2-5]. Due to technological advancements, plastic consumption has surged by 500% over the past three decades and it is anticipated to continue to increase at a rate of 5-10% annually [1]. However, this demand for thermoplastic materials creates important ecological, social, health and economic problems [6]. The slow decomposition of plastic-based materials in nature has led to serious environmental consequences, such as soil and water pollution, as a result of the increased plastic consumption [7]. In addition, plastics are produced from petroleum-based chemical materials. Considering that 4% of petroleum-based chemicals are used annually for plastic production, it seems that the increase in plastic consumption also has an economic disadvantage.

At the 26th United Nations Climate Change Conference (COP26), it was decided to take rapid measures to mitigate global warming [8]. To achieve this decision, it is necessary to significantly reduce greenhouse gas emissions. It is estimated that petroleum-based plastics will contribute to approximately 15% of greenhouse gas emissions by 2050 [9,10]. Therefore, the recycling of plastic-based materials is of great importance in terms of creating a positive impact both economically and environmentally.

One of the most important characteristics of thermoplastic materials is their recyclability. Due to their low melting points, thermoplastic materials can be easily melted and reused through cost-effective production methods such as injection molding, extrusion, and casting, making them suitable for recycling in a serial and economic manner. Hence, through the recycling process, it is possible to achieve economic and environmental improvement by reducing carbon emissions and the amount of plastic waste. However, recycling process can degrade mechanical properties of virgin due to the fact that mechanical stress, oxidation, and thermal effects applied during recycling processes might lead to molecular degradation in the structure of thermoplastics [11-15]. Therefore, numerous researches have focused on investigating how recycling affects the mechanical characteristics of thermoplastics. [5], [16-21]. Oblak et al. carried out a research to examine the effect of the quantity of recycling cycles on the rheological and mechanical characteristics of high-density polyethylene (HDPE) material. A recycling process of up to 100 cycles was conducted using the extrusion method [21]. The results showed that the flowability of the melted polymer decreases with increasing cycle up to the 30th cycle because of increase in the viscosity. After 10 cycles, degradation in mechanical properties was observed. To prevent mechanical degradation during recycling, balancing additives such as peroxide are used within the extrusion process [22,23]. The purpose of these additives is to prevent the weakening of cross-links that occur during extrusion. [24]. Vidakis et al. [16] conducted research by using additive manufacturing to produce both virgin and recycled HDPE materials, investigating the suitability of recycled HDPE material for additive manufacturing with regard of mechanical characteristics. They conducted tensile, impact, and microhardness tests to compare the mechanical properties. As a result, they found that there was no deterioration in the mechanical properties of recycled HDPE, and it was deemed suitable for additive manufacturing. Handayani et al. [25] carried out research to investigate the mechanical properties of commercial recycled polypropylene (rPP) plastic. They reported a yield strength of approximately 16.36 MPa, an elastic modulus of about 295.93 MPa, and an ultimate tensile stress around 19.70 MPa. These values were found to be slightly lower than those of virgin polypropylene, indicating that the recycling process may affect the material's strength. Chiou and Lin [26] studied the effect of incorporating short glass fibers into

rPP on its mechanical properties, heat resistance, crystallization rate, and thermal stability. The results indicated that employing short glass fibers as a reinforcing phase improved these properties compared to pure polypropylene. Kartal and Selimoğlu [27] investigated the effect of pine wood sawdust and waste cotton as reinforcing phase on the mechanical properties of rPP. Results showed that the water uptake in polymer composites reinforced with pine wood sawdust and waste cotton was higher than that of pure rPP. Mihelcic et al. [28] investigated the effect of using stabilizer as additives on the rheological, optical, and mechanical properties of rPP. They found that incorporating a small amount of stabilizing additive significantly enhances the rheological, thermal, and mechanical properties of rPP, even after extensive recycling.

In the literature, the impact of recycling on the mechanical properties of thermoplastic materials has been widely examined. However, there is very limited research on the investigation of the mechanical behavior of recycled thermoplastic materials at different strain rates. This research focuses on investigating how the recycling process affects the mechanical characteristics of HDPE and PP materials under different strain rates in tensile testing. The significance of this study is to understand the effect of a limited number of recycling processes on the mechanical properties of widely used thermoplastic materials, specifically HDPE and PP, as engineering materials. Given the importance of conserving raw materials and reducing environmental pollution, this study offers valuable insights into the sustainable reuse of thermoplastics in industrial applications.

2. Materials and Methods

The materials used in this study are as follows:

- Raw HDPE (HDPE)
- One-time recycled HDPE (r1-HDPE)
- Three-times recycled HDPE (r3-HDPE)
- Raw PP (PP)
- One-time recycled PP (r1-PP)

The HDPE material was sourced from Tekkan Plastik company, while the PP and r1-PP materials were obtained from Mec Plastik company. All recycled HDPE materials (r1-HDPE and r3-HDPE) were obtained by melting through extrusion.

The properties of HDPE and PP materials are shown in Table 1.

Table 1. Some Mechanical and Physical Properties of HDPE and PP Materials.

Property	HDPE	PP
Density (g/cm ³)	0.94-0.97	0.895 - 0.92
Tensile strength (MPa)	20 - 37	30 - 40
Impact strength (kJ/m ²)	20 - 40	10 - 30
Working Temperature (°C)	-50 to +80	-10 to + 100

2.1. Recycling With Extrusion Process

In Figure 1, the extrusion device, feeding of granules, and obtaining the material as filament from the extrusion device are shown. The plastic material obtained in filament form was transformed into granules using a crushing machine and prepared for sample production for recycling. As a result of these processes, the HDPE material was subjected to cycles in the extrusion device once, twice, and three times, yielding r1-HDPE and r3-HDPE materials. Recycled r1-PP material was supplied by Mec Plastik. Table 2 lists the production parameters used in the plastic extrusion device for HDPE and PP materials.

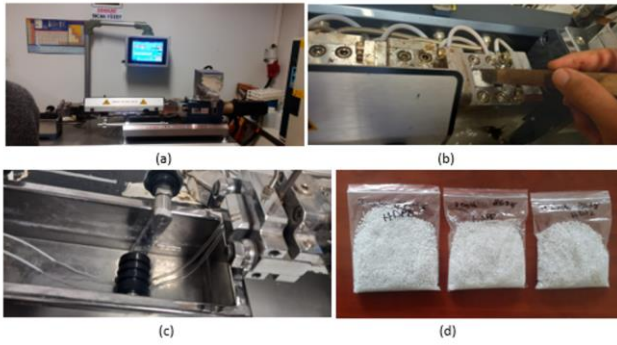


Figure 1. a) Plastic extrusion device, b) feeding of granules, c) filament output, and d) obtaining granules.

Table 2. The plastic extrusion parameters for HDPE and PP materials.

Parameter	Value
Motor (rpm)	50
Torque Ratio	21.30
Extruder (rpm)	5
Temperature (°C)	140
Input Temperature (°C)	75

The plastic extrusion process comprises several steps, including material preparation, feeding and heating, extrusion, shaping, and cooling to solidify. In material preparation, the thermoplastic material is cut into pellet form. Then, the pelletized material is transferred to the feeding section of the extrusion line through a screw mechanism and simultaneously heated for melting to obtain viscous form. The molten material in the extruder section is transferred into the shaping module via screw shaft mechanism. The shaping section is located at the end of the extruder, where the material is given the desired shape and size. In this section, a mold or die system is used. The mold or die system has a predetermined cavity for the material to pass through, allowing the material to take its shape. In the final step of cooling and cutting, after the shaping process, the plastic product is directed to an appropriate environment for cooling. Cooling ensures that the product reaches the desired hardness. Then, the product is cut or coiled, making it ready for use. Table 3 lists the parameters used in different sections within the extruder for both materials.

Table 3. Temperatures at different sections of extrusion device used for HDPE and PP recycling.

Temperature Zone	HDPE	PP
Feeding Zone (°C)	160 - 180	160-180
Melting Zone (°C)	180 - 220	180-230
Molding Zone (°C)	200 - 250	200-240
Cooling Zone (°C)	20 - 60	170-200

2.2. Tensile Test Specimen Manufacturing Via Plastic Injection Method

Sample production, compliant with ASTM D638 IV standard, was carried out using the plastic injection method for both raw and recycled materials. Plastic injection is a widely used manufacturing method in industry. This technique entails forcing molten plastic into a mold at high pressure to form the required shape.

The following steps are followed in the plastic injection molding process:

Material Preparation: The material to be used for the plastic injection process should be prepared in suitable granule form. It is important to remove moisture from the granules in a drying device before injection to prevent any adverse effects on mechanical properties and production parameters (see Figure 2(a)).

Mold Preparation: A mold that matches the geometry of the part to be produced must be prepared. The inner surfaces of the mold should be treated with necessary surface processes to prevent sticking.

Machine Setup: The injection machine, including the material feeding hopper, heating zones, injection unit, and pressure system, should be prepared. Machine settings should be adjusted based on the material type, mold design, and product requirements.

Injection: The material is melted in the heating zones and injected into the mold under high pressure by the injection unit. The material cools and solidifies inside the mold, taking its shape.

Ejection: After cooling, the molded product is properly removed from the mold and is ready for use.

In Figure 2, you can see the drying device, single-screw vertical extrusion device, and injection machine. The material, after exiting the extrusion in molten form, is collected within the feeding hopper in molten state and is inserted into the injection machine. In the injection molding machine, the heated material from the feed hopper is pushed into the mold at the required temperature and pressure.

The same injection parameters were used for HDPE and PP, and these parameters are listed in Table 4.

Table 4. The parameters used in the injection machine for HDPE and PP specimen manufacturing.

Parameters	Values
Extrusion temperature	180 (°C)
Mixing speed	100 rpm
Injection pressure	3 Bar
Injection temperature	220 (°C)

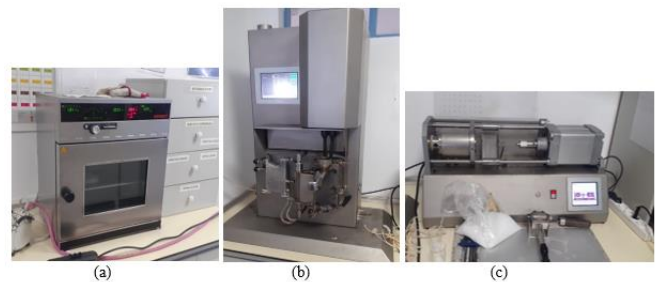


Figure 2. a) Drying oven, b) vertical extrusion machine, and c) plastic injection machine.

The geometric dimensions of the samples produced according to ASTM D638 IV standard are shown in Figure 3.

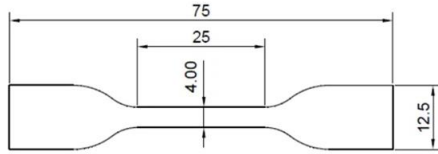


Figure 3. The geometric dimension of tensile test specimens.

2.3. Tensile Test

Tensile tests were conducted using five specimens for each type samples at three distinct rates of strain (5 mm/min, 50 mm/min, and 100 mm/min). From the tensile test, force (F) and elongation (ΔL) are obtained as raw data. Afterward, stress (Equation 1) is determined by dividing the applied force by the cross-sectional area of the sample. Strain (Equation 2) is then calculated by dividing the change in length by the original length ($L_0=25$ mm).

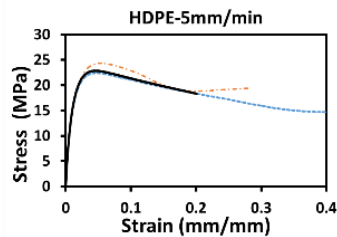
$$\sigma = \frac{F}{A} \quad (1)$$

$$\varepsilon = \frac{\Delta L}{L_0} \quad (2)$$

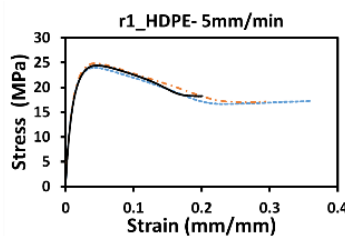
Stress-strain curves are obtained using stress and strain values. In stress-strain curves, the maximum stress represents the tensile strength of the material (σ), and the slope of the linear portion of the curve represents the elastic modulus (E). In the study, the calculated tensile strength and elasticity values for each material type were used to investigate the impact of recycling on mechanical characteristics at different strain rates.

3. Results and Discussion

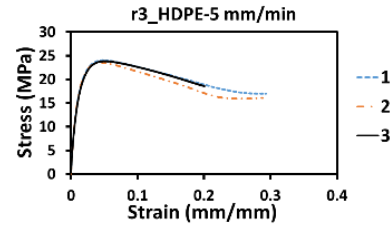
Figure 4 displays the stress-strain curves obtained from tensile tests conducted at a 5 mm/min for HDPE, r1-HDPE, and r3-HDPE materials. In Table 5, the maximum stress and the values for the elastic modulus have been determined from the stress-strain curves for HDPE, r1-HDPE, and r3-HDPE materials are listed, respectively. Figure 5 compares the average maximum stress, elastic modulus, and strain values for HDPE, r1-HDPE, and r3-HDPE materials. The results indicate that one- and three-times recycling do not have any adverse effects on the mechanical characteristics of HDPE. The mechanical characteristics of all three materials are nearly at the same level.



(a)



(b)

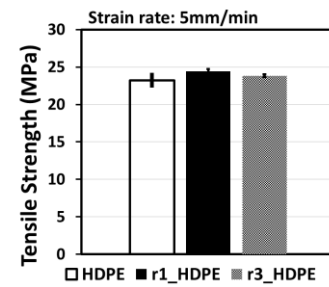


(c)

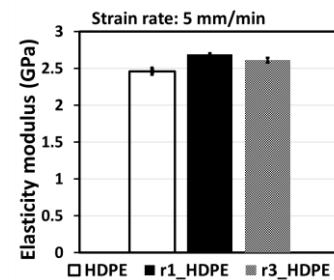
Figure 4. Stress-strain curves of a) HDPE, b) r1_HDPE, and c) r3_HDPE at 5 mm/min strain rate.

Table 5. The mechanical properties of HDPE material at 5 mm/min strain rate.

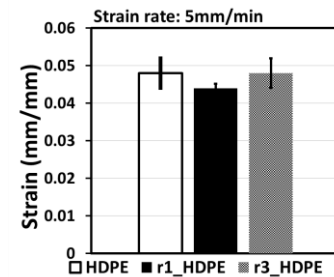
	HDPE_5		r1_HDPE_5		r3_HDPE_5	
No	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	25.61	2313	22.43	2561.98	24.07	2648.37
2	24.64	2569.64	24.38	2451.14	23.58	2556.16
3	23.01	2619.08	22.87	2497.52	23.86	2628.70
Mean	24.4	2500.7	23.2	2503.55	23.84	2611.08
S.D.	0.93	116.02	0.72	39.36	0.17	34.34



(a)



(b)



(c)

Figure 5. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for HDPE, r1_HDPE and r3_HDPE at 5 mm/min strain rate.

Figure 6 displays the stress-strain curves obtained from tensile tests conducted at 50 mm/min for HDPE, r1-HDPE, and r3-HDPE materials. Table 6 list the maximum stress and elastic modulus for HDPE, r1-HDPE, and r3-HDPE materials, respectively. Figure 7 compares the average maximum stress, elastic modulus, and strain values for HDPE, r1-HDPE, and r3-HDPE materials. The results indicate that one and three times of recycling do not have any adverse effects on the mechanical characteristics of HDPE at the 50 mm/min.

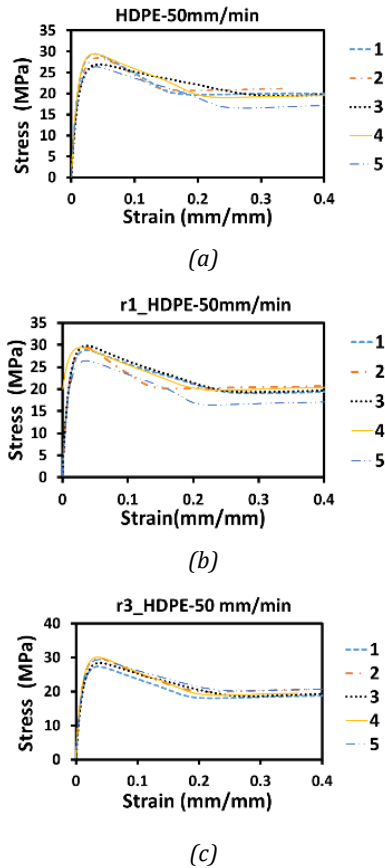


Figure 6. Stress-strain curves of a) HDPE, b) r1_HDPE, and c) r3_HDPE at 50 mm/min strain rate.

Table 6. The mechanical properties of HDPE material at 50 mm/min strain rate.

No	HDPE_50		r1_HDPE_50		r3_HDPE_50	
	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	29.41	3081.86	28.85	2972.30	27.31	2956.10
2	28.48	2770.42	29.47	3054.45	29.91	3127.51
3	26.95	2702.35	29.81	2974.02	28.35	2860.78
4	29.49	3096.22	29.43	3016.35	30.15	3165.78
5	26.36	2993.34	26.41	2916.25	29.37	2984.73
Mean	28.1	2928.8	28.80	2986.67	29.02	3018.98
S.D.	1.16	148.32	1.13	42.43	0.96	102.86

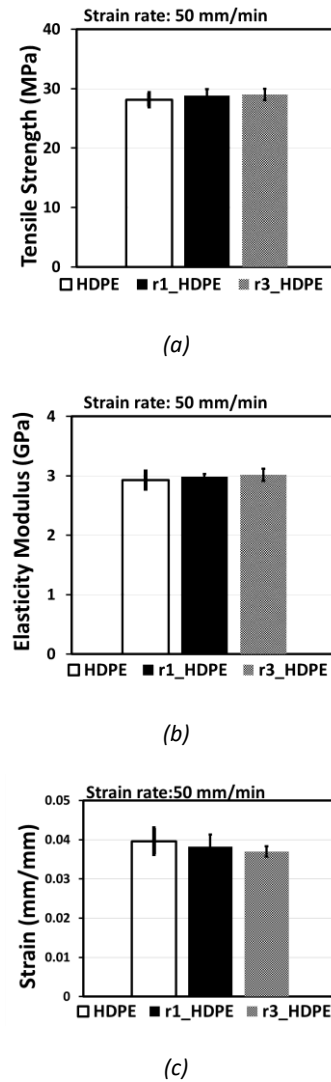
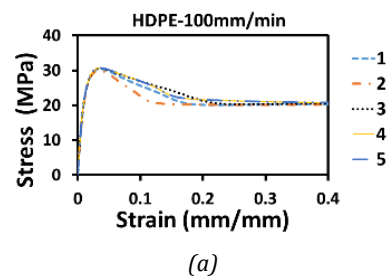
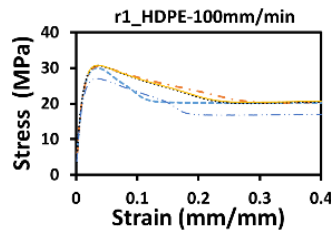


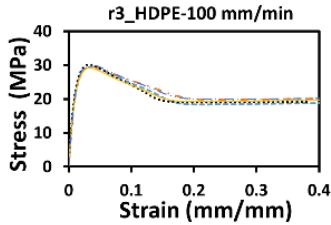
Figure 7. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for HDPE, r1_HDPE and r3_HDPE at 50 mm/min strain rate.

Figure 8 displays the stress-strain curves obtained from tensile tests conducted at 100 mm/min for HDPE, r1-HDPE, and r3-HDPE materials. In Table 7 the maximum stress and the values for the elastic modulus have been determined from the stress-strain curves for HDPE, r1-HDPE, and r3-HDPE materials are listed, respectively. Figure 9 compares the average maximum stress, elastic modulus, and strain values for HDPE, r1-HDPE, and r3-HDPE materials at 100 mm/min strain rate. The results indicate that one and three times of recycling do not have any adverse effects on the mechanical properties of HDPE even at 100 mm/min.





(b)

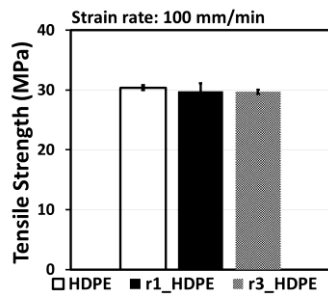


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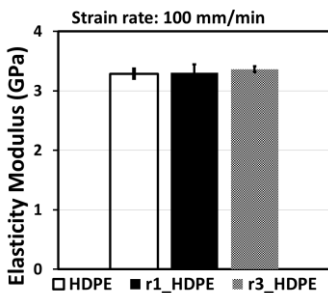
Figure 8. Stress-strain curves of a) HDPE, b) r1_HDPE, and c) r3_HDPE at 100 mm/min strain rate.

Table 7. The mechanical properties of materials at 100 mm/min strain rate.

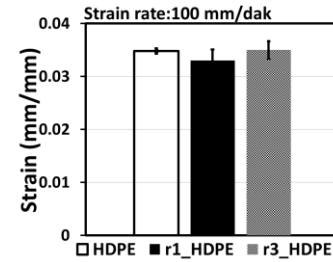
Specimen no	HDPE_100		r1_HDPE_100		r3_HDPE_100	
	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	30.54	3251.04	30.01	3151.91	29.49	3392.08
2	30.01	3151.91	30.51	3163.19	29.58	3344.87
3	30.64	3394.01	30.68	3438.20	30.10	3451.48
4	30.71	3317.53	30.74	3252.74	29.14	3282.26
5	30.00	3317.53	27.00	3523.40	30.19	3346.75
Mean	30.38	3286.40	29.79	3305.89	29.70	3363.49
S.D.	0.28	74.00	1.29	136.45	0.36	51.29



(a)



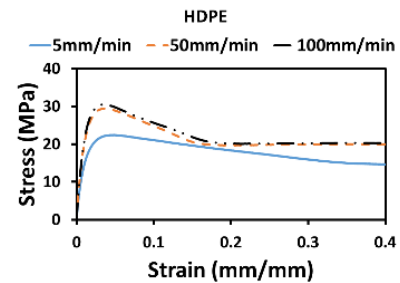
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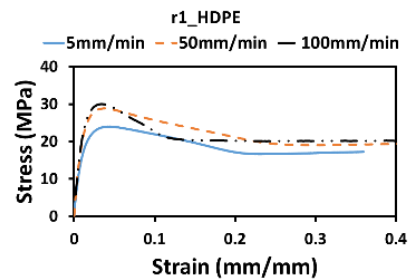
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Figure 9. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for HDPE, r1_HDPE and r3_HDPE at 100 mm/min strain rate.

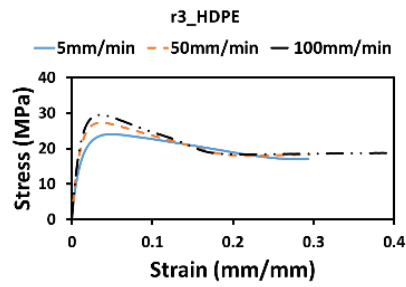
Figure 10 presents the stress-strain curves that allow for a comparative examination of the impact of strain rate on the mechanical characteristics of HDPE, r1-HDPE, and r3-HDPE materials. As observed, the maximum stress is lowest for all material types at a strain rate of 5 mm/min. However, stress-strain curves at 50 mm/min and 100 mm/min exhibit nearly the same characteristics. In Figures 11, 12, and 13, bar charts display the average tensile strength, elastic modulus, and strain values for HDPE, r1-HDPE, and r3-HDPE materials, respectively. The increase in maximum strength at 50 mm/min is approximately 17%, 24%, and 21% for HDPE, r1-HDPE, and r3-HDPE materials, respectively. At 100 mm/min, the increase in maximum strength is approximately 25%, 28%, and 25% for the same materials, respectively. The increase in elastic modulus at 50 mm/min is approximately 17%, 19%, and 16% for HDPE, r1-HDPE, and r3-HDPE materials, respectively, while at 100 mm/min, it is approximately 31%, 32%, and 29%, respectively. The reduction in strain at higher strain rates is due to the stronger strain-hardening effect, which leads to more brittle behavior in polymer materials.



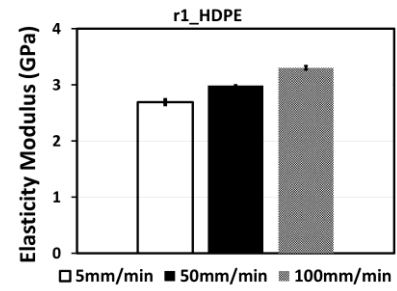
(a)



(b)

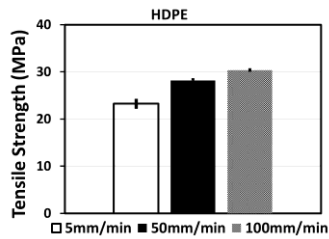


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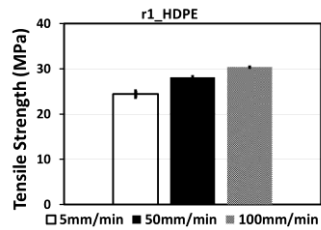


(b)

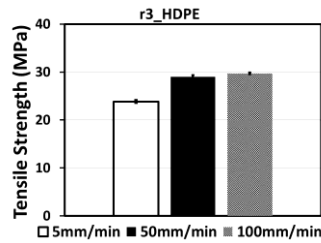
Figure 10. Stress-strain curves of a) HDPE, b) r1_HDPE, and c) r3_HDPE materials at different strain rates.



(a)

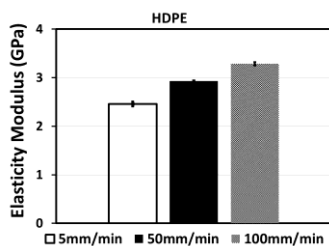


(b)

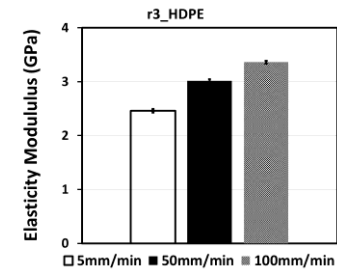


(c)

Figure 11. Average tensile strength of a) HDPE, b) r1_HDPE and c) r3_HDPE materials at different strain rates.

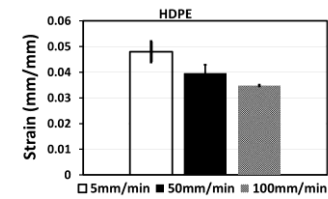


(a)

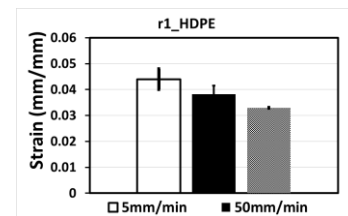


(c)

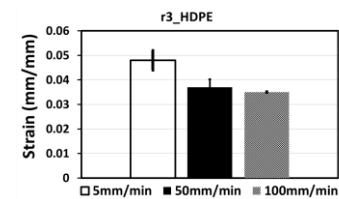
Figure 12. The average elasticity modulus of a) HDPE, b) r1_HDPE and c) r3_HDPE materials at different strain rates.



(a)



(b)



(c)

Figure 13. The average strain values at tensile strength of a) HDPE, b) r1_HDPE and c) r3_HDPE materials at different strain rates.

Figure 14 displays the stress-strain curves obtained from tensile tests performed at 5 mm/min for PP and r1-PP materials. In Table 8, the maximum stress and the values for the elastic modulus have been determined from the stress-strain curves for PP and r1-PP materials at 5 mm/min are listed, respectively. Figure 15 compares the average maximum stress, elastic modulus, and strain values for PP and r1-PP materials. The results indicate that one time of recycling has a minor weakening impact on the mechanical characteristics of PP at 5 mm/min. This decrease in mechanical properties is approximately 5% for maximum stress and approximately 9% for elastic modulus.

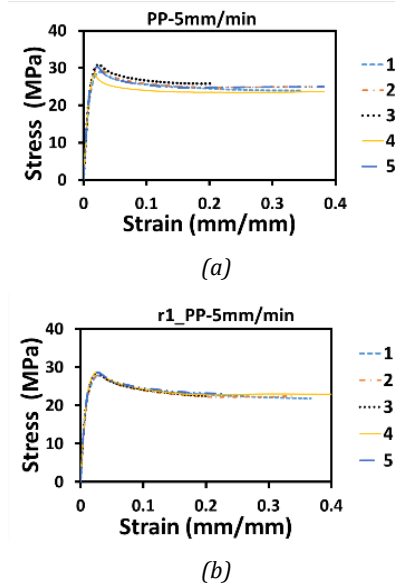


Figure 14. Stress-strain curves of a) PP and b) r1_PP materials at 5 mm/min strain rate.

Table 8. The mechanical properties of PP material at 5 mm/min strain rate.

Specimen no	PP_5		r1_PP_5	
	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	28.98	3173.53	27.85	2979.24
2	30.20	3217.49	28.01	2960.11
3	30.97	3389.01	28.58	3082.09
4	28.34	3352.39	28.78	3089.34
5	30.32	3513.69	28.67	3117.17
Mean	29.76	3329.22	28.38	3045.59
S.D.	0.88	111.70	0.34	57.85

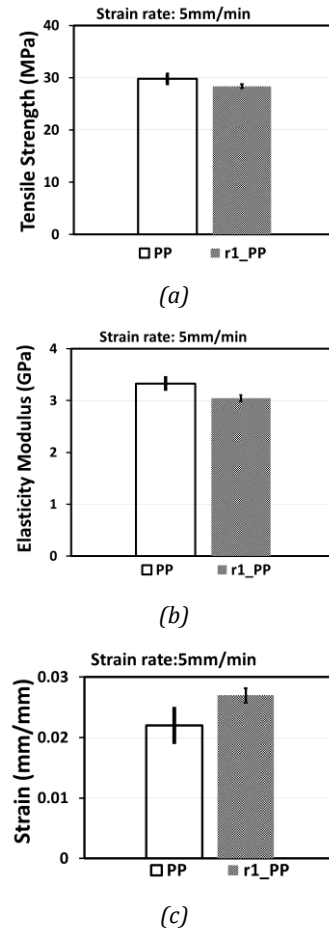


Figure 15. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for PP and r1_PP at 5 mm/min strain rate.

Figure 16 displays the stress-strain curves obtained from tensile tests performed at 50 mm/min for PP and r1-PP materials. In Table 9, the maximum stress and the values for the elastic modulus have been determined from the stress-strain curves for PP and r1-PP materials at 50 mm/min are listed, respectively.

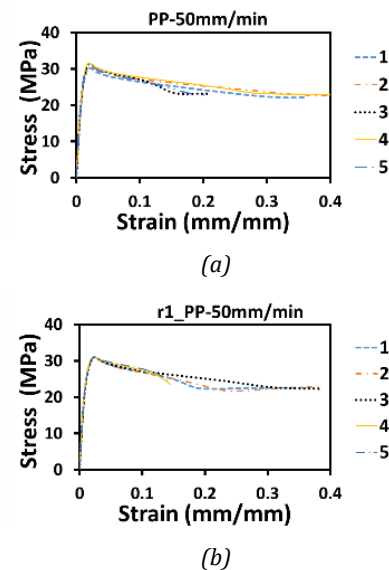
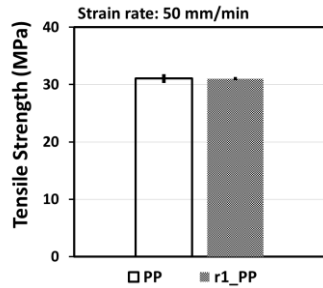


Figure 16. Stress-strain curves of a) PP and b) r1_PP materials at 50 mm/min strain rate.

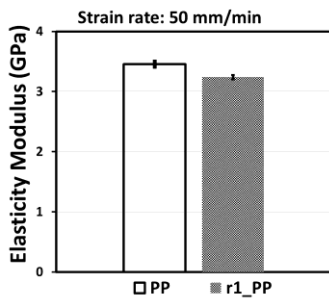
Table 9. The mechanical properties of PP material at 50 mm/min strain rate.

	PP_50		r1_PP_50	
Specimen no	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	30.25	3503.30	30.95	3208.27
2	30.67	3378.45	30.89	3215.91
3	31.35	3445.69	31.01	3243.56
4	31.62	3509.33	31.17	3314.71
5	31.32	3446.02	31.10	3210.78
Mean	31.04	3456.56	31.02	3238.64
S.D.	0.45	43.39	0.09	36.57

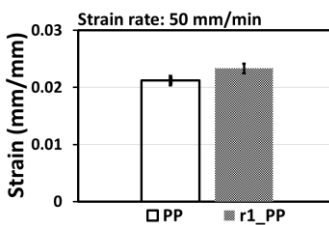
Figure 17 compares the average maximum stress, elastic modulus, and strain values for PP and r1-PP materials. The results indicate that one time of recycling has a minor weakening impact on the mechanical characteristics of PP at 50 mm/min. This decrease in mechanical properties is almost negligible for maximum stress and approximately 7% for elastic modulus.



(a)



(b)

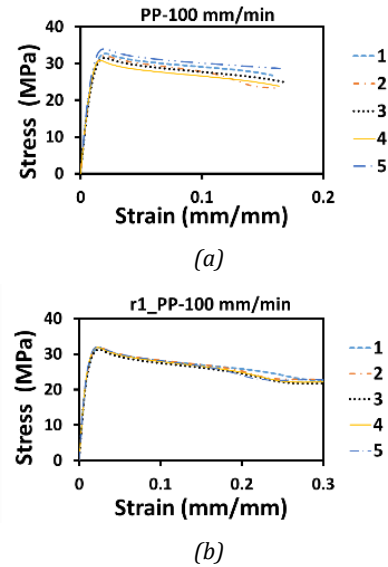


(c)

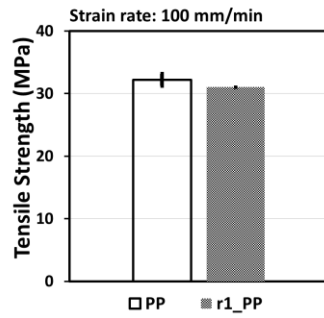
Figure 17. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for PP and r1_PP at 50 mm/min strain rate.

Figure 18 presents the stress-strain curves obtained from tensile tests performed at 100 mm/min for PP and r1-PP materials. In Table 10, the maximum stress and the values for the elastic

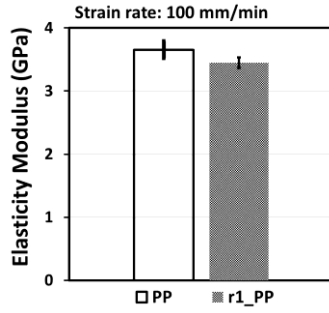
modulus have been determined from the stress-strain curves for PP and r1-PP materials at 100 mm/min are listed, respectively. Figure 19 compares the average maximum stress, elastic modulus, and strain values for PP and r1-PP materials. The results indicate that one cycle of recycling has a minor weakening impact on the mechanical characteristics of PP at 100 mm/min. This decrease in mechanical properties is approximately 1% for maximum stress and around 6% for elastic modulus.

**Figure 18.** Stress-strain curves of a) PP and b) r1_PP materials at 100 mm/min strain rate.**Table 10.** The mechanical properties of PP material at 100 mm/min strain rate.

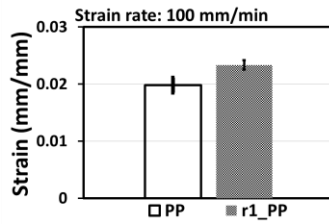
	PP_100		r1_PP_100	
Specimen no	Strength (MPa)	Elasticity modulus (MPa)	Strength (MPa)	Elasticity modulus (MPa)
1	32.67	3525.63	31.77	3282.91
2	32.11	3489.50	31.95	3418.07
3	31.49	3624.32	31.24	3488.77
4	30.76	3745.25	31.87	3498.07
5	33.95	3890.46	32.15	3554.87
Mean	32.20	3655.03	31.80	3448.54
S.D.	0.99	134.57	0.28	85.38



(a)



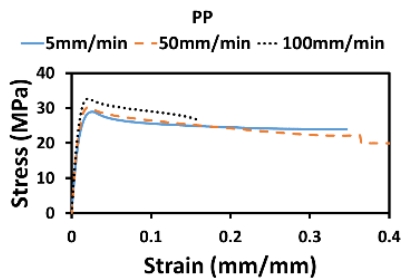
(b)



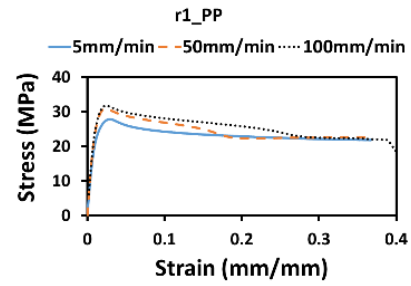
(c)

Figure 19. Average a) tensile strength, b) elasticity modulus, and c) strain at tensile strength for PP and r1_PP and r3_HDPE at 100 mm/min strain rate.

Figure 20 displays the stress-strain curves that allow for a comparative analysis of the impact of strain rate on the mechanical characteristics of PP and r1-PP materials. As observed, an surged in the strain rate results in an overall enhancement in the mechanical properties for all material types.



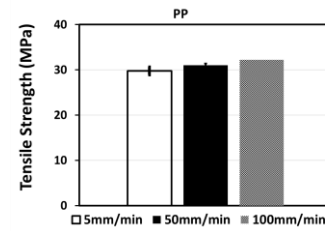
(a)



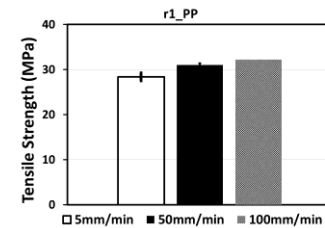
(b)

Figure 20. Stress-strain curves of a) PP and b) r1_PP materials at different strain rates.

Figures 21, 22, and 23 present bar graphs depicting the average tensile strength, the elastic modulus, and strain values for PP and r1-PP materials, respectively. At a tensile rate of 50 mm/min, the maximum tensile strength increase is approximately 4% for PP and around 11% for r1-PP materials, while at 100 mm/min, the strength increase is approximately 8% for PP and about 14% for r1-PP materials. The increase in the elastic modulus at a strain rate of 50 mm/min is approximately 4% for PP and 6% for r1-PP materials, while at 100 mm/min, the surged in the elastic modulus is approximately 9% for PP and 13% for r1-PP materials.



(a)



(b)

Figure 21. Average tensile strength of a) PP and b) r1_PP materials at different strain rates.

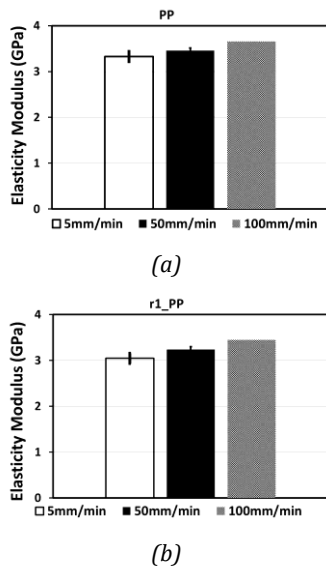


Figure 22. Average elasticity modulus of a) PP and b) r1_PP materials at different strain rates.

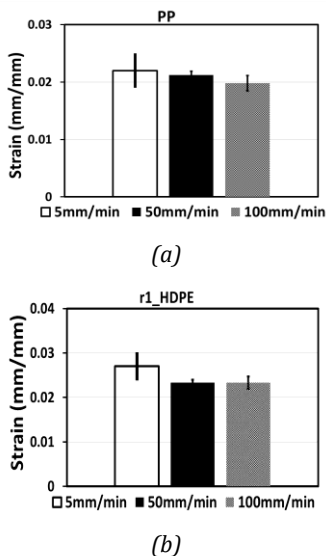


Figure 23. Average strain values at tensile strength for a) PP and b) r1_PP materials at different strain rates.

4. Conclusions

It was observed that one- and three-times mechanical recycling did not result in notable alterations to the mechanical characteristics of HDPE at all strain rates. This outcome suggests that a small number of recycling processes do not lead to substantial changes in the molecular structure of HDPE. Additionally, recycled HDPE materials show comparable improvements in tensile strength and elastic modulus to those of virgin HDPE across different strain rates.

The effect of recycling on mechanical properties is more pronounced in the case of PP material. It is observed that a single cycle of mechanical recycling does not have a notable effect on the tensile strength of PP, but it slightly weakens the elastic modulus. According to current research, recycling has minimal effect on the mechanical characteristics of polypropylene (PP) when it is tested under tensile loading at low strain rates. In this study, however, at high strain rates, recycled PP material exhibits higher increase rate in tensile strength and elastic modulus compared to virgin PP material.

The findings obtained in this study illustrate that recycled HDPE and PP materials, after undergoing a restricted number of recycling cycles, can be considered dependable engineering materials. This highlights the importance of recycling in terms of sustainability. The following remarks can be concluded based on the findings:

Since HDPE and PP can retain their mechanical properties even after multiple recycling cycles, recycling these thermoplastics for reuse in engineering applications is both sustainable and economical. This process minimizes environmental waste and reduces material costs.

rPP can be used in high-performance applications, such as automotive or construction materials, where mechanical strength and durability are crucial, as it exhibits enhanced mechanical properties even at high strain rates.

Ethics committee approval and conflict of interest statement

The authors of this article declare that the materials and methods used in their studies do not require ethical committee approval and/or legal-specific permission.

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Author Contribution Statement

Mehmet Sait Karanfil: Project administration, Methodology, Investigation, Writing Original Draft; Arif Ergin: Methodology, Investigation, Writing Original Draft; Mehmet Güçlü: Methodology, Investigation, Writing Original Draft, Writing Review & Editing; Beyza Sarıcaoğlu: Methodology, Investigation; Fatih Turan: Supervision, Methodology, Investigation, Writing Original Draft, Writing Review & Editing; Hande Çelebi: Supervision, Methodology, Investigation.

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