Polymer Bulletin
https://doi.org/10.1007/s00289-024-05367-x

ORIGINAL PAPER

Revitalizing high-density polyethylene (HDPE) waste: from environmental collection to high-strength hybrid yarns

Fatih Suvari[1] · **Hakan Gurvardar**[2]

Received: 4 January 2024 / Revised: 18 May 2024 / Accepted: 14 June 2024
© The Author(s) 2024

Abstract

Plastic products are used in large quantities. However, the fact that plastics do not degrade in nature for many years causes environmental pollution. Addressing this issue, the study focuses on recycling the widespread high-density polyethylene (HDPE) plastic waste. In this study, HDPE waste was collected randomly from the environment, mirroring real-world scenarios. Then, the waste was transformed into granules. Afterward, washing and drying processes were carried out. HDPE filaments of different linear densities were successfully produced from the waste plastic granules. Tensile tests revealed that the breaking strength of the filaments from waste plastic was lower than that of virgin HDPE filaments, highlighting the challenges of recycling. Hybrid yarns were formed by twisting the filaments with cotton yarn to improve the mechanical properties of the filaments from waste plastic. Remarkably, statistical analysis demonstrated that the breaking load values of the hybrid yarns from waste plastic were statistically equivalent to those made from virgin polymer. This outcome indicated that the hybrid yarns made from waste HDPE plastic were as strong as those made from virgin HDPE polymer. In addition, both hybrid yarns exhibited a breaking load 36% higher than the reference extra-twisted cotton yarn. The hybrid yarn formation made filaments produced from waste plastic a valuable component of the high-strength hybrid yarn. Overall, this study shows that recycling HDPE plastics can lead to the production of high-strength hybrid yarns, which can contribute to reducing plastic waste pollution.

Keywords Polyethylene · Waste plastic · HDPE filament · Hybrid yarn

✉ Fatih Suvari
suvari@uludag.edu.tr

[1] Textile Engineering Department, Faculty of Engineering, Bursa Uludag University, Bursa, Turkey

[2] Textile Engineering Department, Graduate School of Natural and Applied Sciences, Bursa Uludag University, Bursa, Turkey

Published online: 24 June 2024

Introduction

Plastics are extensively utilized in various industries, including transportation, construction, healthcare, food products, and packaging, due to their lightweight nature, durability, affordability, and disposable convenience. In developed countries, the average plastic consumption per person reaches up to 100 kg annually [1]. However, the surge in plastic production and usage has resulted in significant environmental issues. As most plastic waste takes a long time to decompose in nature, it accumulates primarily in oceans and seas, posing a severe threat to marine life. Some projections suggest that if this trend persists, certain seas may contain more plastic waste than fish by 2050 [2].

Implementing suitable recycling methods, such as mechanical recycling, can effectively reduce plastic waste and enable its reusability. The process involves segregating and retrieving plastic materials from garbage and designated recycling areas, followed by sorting and breaking them down into smaller pieces for easier handling. The materials are then washed to remove any labels or impurities and can be utilized in their shredded and cleaned form or melted and cooled to form chips, which can serve as raw plastic materials [3].

HDPE polymers are spun by melt spinning, which involves multiple steps. Initially, the HDPE granules are melted down from a solid to a liquid state in the extruder. The molten polymer is then guided through a spinneret having minuscule holes. The size of the holes has an effect on the diameter of the resulting continuous filament. The extruded HDPE is rapidly cooled by air or water system to solidify and maintain its shape. The filament is then stretched and strengthened through a series of rollers. As the filament undergoes this stretching process, it becomes thinner, resulting in the desired filament diameter. Finally, filaments are wound onto spools or bobbins for storage and transportation [4, 5]. The utilization of HDPE filaments is primarily observed in outdoor settings, where their ability to resist mildew provides a notable advantage. Examples of such applications include sun breakers, shade nets, safety nets, wind walls, agricultural nets, swimming pool covers, fishing nets, fishing lines, and strings [4, 6–8]. Additionally, the unique chemical resistance of HDPE filaments renders them a suitable choice for filter fabrics and geotextiles [6, 7].

According to the 2022 report of OECD, 44.71 million tons of HDPE plastic waste were generated worldwide in 2019 [9]. It is probable that this amount has risen since then. Regrettably, many HDPE materials are discarded and contribute to environmental pollution. Despite HDPE plastic being one of the most prevalent waste plastic globally [3, 9, 10], recycled HDPE is predominantly employed in the production of various items such as storage containers, boxes, pipes and toys [3] through plastic injection or extrusion methods, rather than being used for yarn or filament production. On the other hand, environmental legislation's growing demands are driving polyolefin filament producers to increase the use of recycled polyolefin in their products [5]. Rising environmental consciousness is also motivating manufacturers to find ways to use more recycled polyolefin in their merchandise.

Significant research has been conducted on the repurposing of HDPE plastics across various fields. Some studies have explored the application of recycled HDPE fibers as reinforcement in concrete [11, 12]. These studies have shown that incorporating specific quantities of recycled HDPE fibers can enhance certain mechanical characteristics of concrete, such as tensile strength [11, 12]. It has been noted, though, that recycled HDPE fibers generally exhibit lower mechanical performance compared to virgin fibers [11]. However, the utilization of fibers produced from waste HDPE has been shown to positively impact the mechanical properties of concrete, indicating their potential as a viable reinforcement material for construction purposes [11]. In another research focused on building materials, the aim was to fabricate composite materials using natural fibers as reinforcement and waste HPDE as the matrix [13]. The study explored the possibility of producing eco-friendly fiber-reinforced polymer composites from discarded HDPE plastic and natural fibers. The researchers suggested that the resulting material could serve as a sustainable alternative to traditional building materials like floor tiles, pavement, and blocks [13]. Some studies have been conducted on the use of recycled HDPE filaments in 3-D printers for additive manufacturing [14, 15]. The mechanical characteristics of HDPE filaments were found to stay stable through the initial five recycling cycles. However, both studies observed a subsequent decrease in these properties beyond the fifth recycling step. The results indicated that recycled HDPE filaments could be effectively employed in 3-D printing [14, 15].

As summarized above, in the literature, there are various studies on utilizing recycled HDPE fibers in different applications. Although HDPE is one of the most commonly found types of plastic waste, there is limited research on converting waste HDPE into filament for fabric use. One possible reason is that filaments made from waste HDPE may not be strong enough for fabric production, possibly due to factors like previous heat treatment of the waste plastic, exposure to environmental conditions, and the unsuitable internal structure of randomly gathered waste plastic. Accordingly, in a research examining the life cycle assessment of a company that produces filaments from HDPE polymer and subsequently manufactures woven nets for agriculture, it is observed that the use of recycled HDPE reduces environmental impact [16]. However, due to a decrease in product quality associated with the use of waste HDPE polymer, only a small quantity (8%) of recycled granules can be incorporated into the production of filaments and woven nets [16]. This result is supported by the study that examined polyethylene net structures used in agriculture [8]. It is stated that the mixture of waste and virgin homopolymer will not be suitable due to the presence of "alien" chemical groups in the waste resulting from its photooxidative degradation history [8].

In this study, a hybrid yarn formation technique is employed to overcome the constraints associated with using filaments made from waste HDPE plastic and to improve the overall strength. This method combines the beneficial characteristics of different components [17]. By combining a commercially available cotton yarn with a recycle HDPE filament, it is aimed to form a hybrid yarn that exhibits significantly improved strength. The successful development of this hybrid yarn holds promising potential for its application in technical textiles and composite materials.

Materials and methods

Materials

Petkim Petrochemical Company's S0464 high-density polyethylene chips were used in the study as a virgin HDPE polymer. According to the company catalog, the polymer is suitable for the production of various products such as monofilaments, food containers, medium-sized water and oil cans, medium-sized containers, and kitchenware.

Bottle caps are generally manufactured using HDPE polymer. The coding number "2" printed on the bottle caps identifies that the material is HDPE. Discarded caps were collected from the environment randomly to reflect real-world situations. Specifically, only caps with the "2" code were chosen to ensure the resulting filaments were made from HDPE polymer.

Collected waste HDPE plastics were first cut with strong scissors into small granules of 2–4 mm in size. Cutting plastic waste into small granules made them easier to process in later stages. Afterward, the washing process was carried out using a magnetic stirrer set to 120 revolutions per minute (rpm), during which 100 g of HDPE granules were washed in 500 ml of water within a beaker at 60 °C for a duration of 20 min. Dirt, dust or other foreign matter accumulated on the waste material was cleaned in this way. The plastic granules were then dried in a hot oven at a temperature of 60 °C for 25 min to evaporate any residual water content. At this point, the material was ready for the production of filaments.

Filament production method

The filament production process was carried out using a laboratory-type synthetic filament production machine, as seen in Fig. 1. The synthetic filament production machine comprises five heating zones that extend from the extruder to the nozzle. The extruder is equipped with three heating zones, while the nozzle has two. Electric resistances heat these zones, and independent airflow fans cool them if



Fig. 1 Laboratory-type synthetic filament production machine



Fig. 2 Granular waste HDPE plastic in the extruder hopper



Fig. 3 Filament made from virgin HDPE

the temperature exceeds the set value. The PLC (programmable logic controller) system of the synthetic filament machine controls all heating and cooling operations. Once the polymer melts due to applied heat, the extruder's rotating screw pushes the molten polymer forward to the nozzle. The quench-air system, located just after the nozzle, provides faster solidification of the molten polymer and promotes filament formation.

The granular waste plastic material was placed in the extruder hopper, as shown in Fig. 2, to initiate the filament production process. Extruder temperature, an important production parameter, was chosen as 210 °C for each heating zone in this study. According to the information in the literature, this temperature value could be used for the production of HDPE filament [4].

In filament manufacturing using virgin HDPE polymer chips, production was carried out at different extruder motor speeds, specifically varying between 1 and 3 rpm. In filament production using waste HDPE plastic, extruder speeds of 2 rpm, 2.5 rpm, and 3 rpm were used.

The quench-air temperature was the same as the ambient temperature, which was 24 ± 2 °C. Subsequently, the produced filament was wound onto the bobbin. Images of the filaments produced from virgin and waste HDPE polymer during the winding process are shown in Figs. 3 and 4, respectively. It is noteworthy to mention that the filament made from waste HDPE exhibits a blue hue owing to the predominant collection of blue-colored HDPE bottle caps.

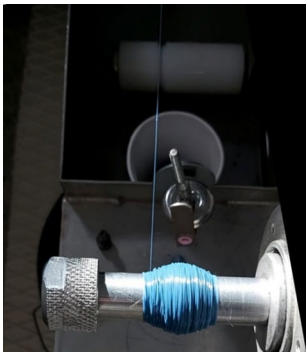


Fig. 4 Filament made from waste HDPE

Test methods

Linear density measurements

The linear density of filaments, which is correlated directly with their thickness, was determined according to ASTM D1907-12, where specimens of 100 m were prepared by means of a reel, and weights were measured with an analytical balance. Linear densities were calculated in the unit of "tex" according to Eq. 1.

$$\text{Linear density[tex]} = 10^3 \times \frac{\text{mass of specimen}[g]}{\text{length of specimen}[m]} \tag{1}$$

Breaking strength and breaking extension tests

Breaking strength and extension tests of filaments were conducted using Shimadzu AG–X plus tensile testing machine by ISO 2062:2009 standard test method except for the gauge length. The gauge length was set to 100 mm due to the high elongation of the filaments. The test speed was set at 250 mm/min in accordance with the relevant standard.

Filaments were conditioned at $65 \pm 2\%$ relative humidity and 20 ± 2 ℃ for at least 24 h before the tests mentioned above.

Polymer characterization

Differential scanning calorimetry (DSC) tests were carried out according to ISO 11357–3:2018 standard by heating up to 200 ℃ with a heating rate of 10 ℃/min. Nitrogen gas was used in the test. The weight of the virgin HDPE filament tested was 3.96 mg, and the weight of the recycle HDPE filament was 3.27 mg.

The molecular structure and chemical bonds of virgin and recycle HDPE filaments were analyzed through fourier transform infrared spectroscopy (FTIR). The attenuated total reflectance (ATR) method was utilized for the measurements,

which is a convenient spectroscopy method that does not require any special sample preparation. The measurements were conducted within the wavenumber range of 450–4000 cm^{-1}.

The melt flow rate (MFR) test was performed according to the ASTM D1238-20 standard. The test was conducted under specific conditions, including a preheat time of 300 s, a test temperature of 190 ℃, and a test mass of 2.16 kg. MFR testing was conducted on virgin HDPE polymer chips and waste HDPE granules.

Results and discussion

Effect of extruder speed on filament linear density

Filament production was carried out using different extruder speeds and two types of HDPE polymer: virgin and recycled. In the case of virgin HDPE, six specific extruder speeds were used, whereas three different speeds were employed for recycled HDPE. Following production, the linear densities of all filaments were measured.

The relationship between the extruder speed and the linear density of filaments is illustrated in Fig. 5. Upon examination of Fig. 5, it is evident that the filament linear density increases in a nearly straight line as the extruder speed increases for both virgin and recycled HDPE. The regression analysis resulted in high regression coefficient (R^2) values of 0.9724 and 0.9912 for virgin and recycled HDPE, respectively, indicating a strong and direct relationship between extruder speed and filament linear density. The linear equations that best represent this relationship are $y = 21.314x$ for virgin HDPE and $y = 21.839x$ for recycled HDPE, where x represents extruder speed, and y represents filament linear density. These equations can be utilized to determine the appropriate extruder speed for achieving a desired filament linear density.

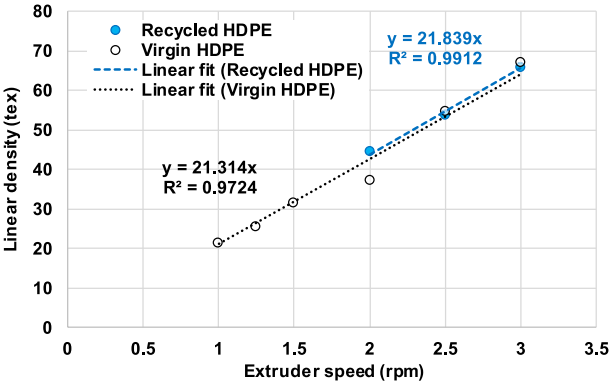


Fig. 5 Filament linear density change with increasing extruder speed

Breaking strength of HDPE filaments

Filaments with varying linear densities were produced by altering the extruder speeds and subsequently subjected to a breaking strength test. Figure 6 displays the breaking load values of filaments with different linear densities produced from both virgin and waste HDPE. The results indicate that an increase in filament linear density leads to a corresponding increase in breaking load. Due to the proximity of certain average breaking load values and the presence of standard deviations in the results, it became necessary to conduct a statistical analysis. For this purpose, an analysis of variance (ANOVA) F test for independent groups was performed with a significance level (α) of 0.05 to analyze the breaking load data. LSD (least significant difference) test, which makes direct comparisons between individual groups, was run afterward ($\alpha = 0.05$). The statistical test results indicate that each average breaking load value differs significantly from the others, and the observed increase in breaking load is statistically significant as well. Upon comparing the breaking load values of virgin and recycle HDPE filaments, it is evident that the breaking load values of virgin HDPE filaments are greater than those of recycle HDPE filaments. The lower breaking strength compared to virgin HDPE filaments highlights the challenges and limitations of recycling.

Even though both virgin and recycle filaments are of the same polymer origin (HDPE) and produced using identical machine parameters, examining their internal structures is necessary to understand the cause of the disparity in breaking load values. To carry out this examination, filaments manufactured from virgin and waste HDPE were subjected to a DSC test. The DSC test results for the virgin HDPE filaments and the recycle HDPE filaments are presented in Figs. 7 and 8, respectively.

According to the DSC test results, the virgin HDPE filament exhibits a melting temperature of 125 ℃, whereas the recycle HDPE filament has a slightly lower melting temperature of 124 ℃. These values align with the melting temperature data in the literature for HDPE polymer [5]. The crystallization temperature values for both filaments are very similar, at approximately 120 ℃. Notably, the DSC test results

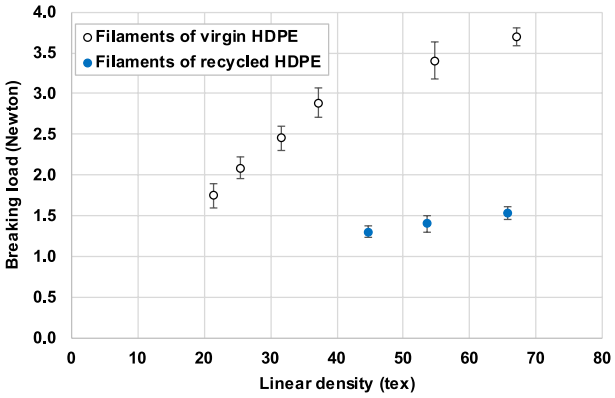


Fig. 6 Breaking load values of the filaments made of virgin and recycled HDPE

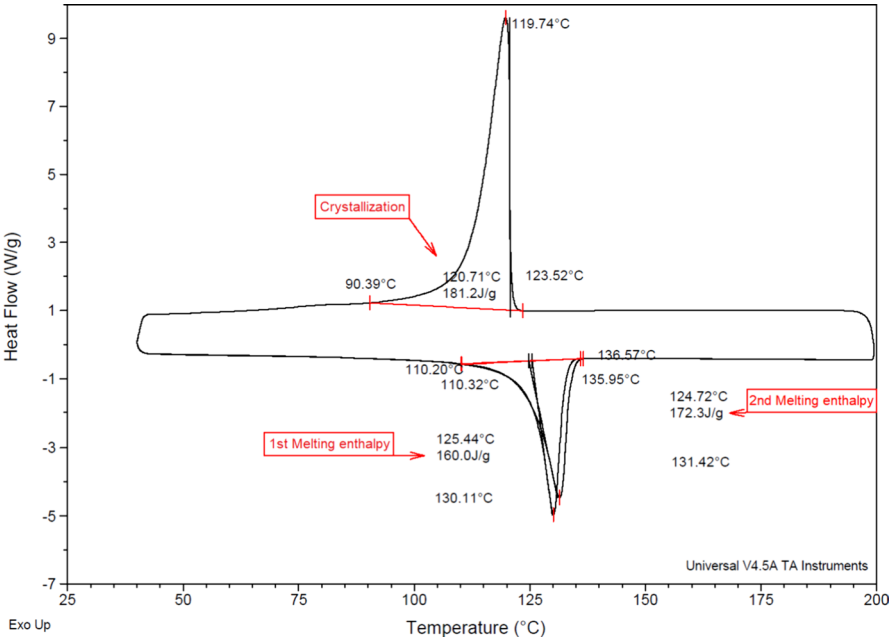


Fig. 7 Temperature-heat flow graph of the virgin HDPE filament

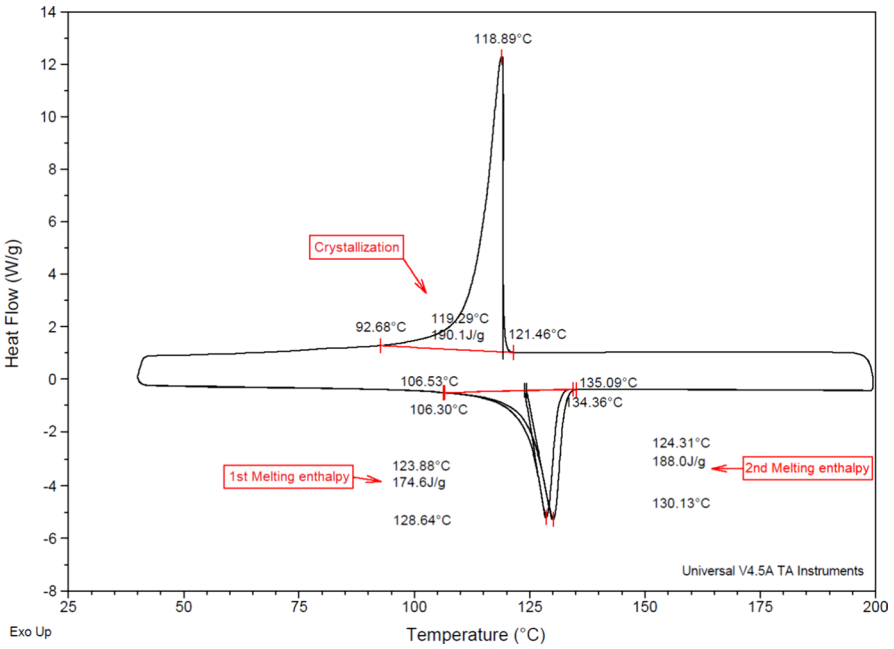


Fig. 8 Temperature-heat flow graph of the recycle HDPE filament

reveal a significant difference in the first heating energy (melting enthalpy) during melting between the virgin and recycle HDPE filaments. Specifically, the recycle HDPE filament requires more heating energy per unit mass, with a measured heating energy of 174.6 J/g compared to 160 J/g for the virgin HDPE filament. Crystallization of both virgin and recycle filaments can be determined by comparing the heating energy values required to melt the filaments with the energy value needed to melt 100% crystalline PE polymer. Equation 2 can be used to perform this calculation.

$$C = \frac{\Delta H_{\mathrm{m}}}{\Delta H_{lit}} \tag{2}$$

In Eq. 2, C represents the degree of crystallization, ΔH_{m} is the measured melting enthalpy, and ΔH_{lit} is the reference melting enthalpy of the fully crystalline PE. The melting enthalpy value of 100% crystalline PE polymer is 293 J/g in the literature [18]. Applying Eq. 2, the calculated crystallization of the virgin HDPE filament is 54.6%, while the recycle HDPE filament exhibits a crystallization of 59.6%. The recycle HDPE filament has a surprisingly higher level of crystallization, despite its low breaking load values. This is unexpected because plastics with higher crystallization levels are typically stiffer and stronger [19]. However, the material's properties are not solely determined by its crystallization but also by the size of its structural units and molecular orientation [19].

FTIR test was performed on virgin and recycle HDPE filaments to obtain more information about the material's internal structure. ATR-FTIR spectra of virgin HDPE and recycle HDPE filaments are given in Figs. 9 and 10, respectively. The measured wavenumber range is 450–4000 cm^{-1}. The absorption bands at 2847 cm^{-1} and 2916 cm^{-1} correspond to symmetrical and asymmetrical stretches in CH_2 units in PE, respectively [20–22]. HDPE polymer is expected to exhibit two peaks around 720 ± 10 cm^{-1} wavenumber [21]. These characteristic peaks, specifically at 718 cm^{-1} and 729 cm^{-1}, are visible in the FTIR test outcomes for both virgin and recycle filaments. At 718 cm^{-1}, the rocking vibrations of CH_2 groups in the amorphous phases are observed, whereas at 729 cm^{-1}, the rocking vibrations of CH_2 groups in the crystalline phases are detected [20]. The presence of these two peaks at 718 cm^{-1} and 729 cm^{-1} in both virgin and recycled HDPE filaments confirms that the polymers used in the study are HDPE. Furthermore, the absorbance ratio of peaks (absorbance at 729 cm^{-1} / absorbance at 718 cm^{-1}) is higher in the case of recycled HDPE filament, indicating a higher crystallinity, which is consistent with the results of the DSC test.

The fact that virgin HDPE filaments with lower crystallization have much higher breaking load values is thought to be related to the molecular chain length. Because generally, longer molecular chains positively impact the mechanical properties of the polymers [19, 23]. MFR tests conducted on virgin HDPE chips and waste HDPE granules show that (see Table 1) the MFR of virgin HDPE is lower, indicating higher viscosity of the molten virgin polymer. This notable difference in melt viscosities supports the notion that the virgin HDPE polymer has longer molecular

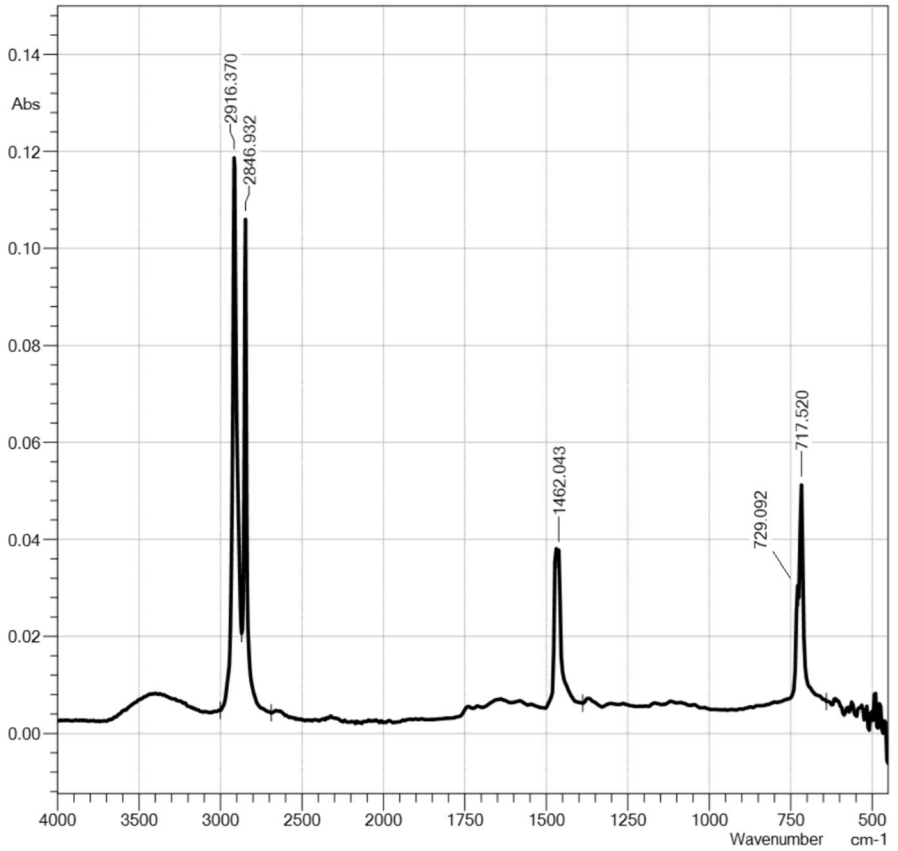


Fig. 9 The infrared spectrum of a virgin HDPE filament

chains, which also contributes to the higher breaking load values observed in virgin HDPE filaments.

Formation of the hybrid yarns

In this part of the study, hybrid yarns were formed by twisting the filaments with another yarn. The intention is to enhance the strength of the filaments produced from waste HDPE and form a hybrid material suitable for fabric production. For hybrid yarn formation, Ne 16/1 cotton yarn with *Z* twist of 551 turns per meter (tpm), produced through ring spinning, was chosen. Since the Ne 16/1 yarn count is equivalent to 36.9 tex in the tex numbering system, the filaments closest to this yarn count were selected from the filaments made from virgin HDPE and waste HDPE polymer. Accordingly, filament counts of 37.1 tex from the virgin HDPE polymer and 44.7 tex from the waste HDPE polymer, both produced at an extruder speed of 2 rpm, were used for hybrid yarn formation.

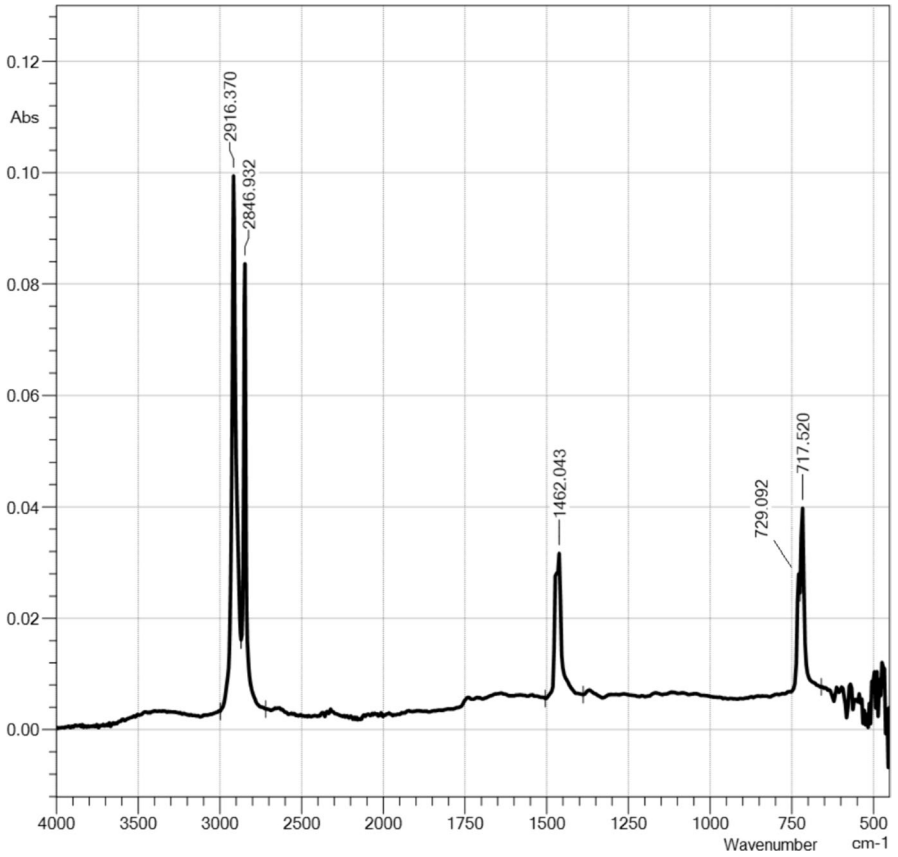


Fig. 10 The infrared spectrum of a recycle HDPE filament

Table 1 MFR values of virgin HDPE chips and waste HDPE granules

Sample name	Waste HDPE granules	Virgin HDPE chips
Preheat time (s)	300	300
Test temperature (℃)	190	190
Test weight (kg)	2.16	2.16
Melt flow rate (g/10 min)	6.33	0.333

The cotton yarn, which had a twist value of 551 tpm, was placed alongside the untwisted HDPE filament made from waste plastic as shown in Fig. 11. A twist of 200 tpm was applied in the *Z* twist direction using the Officine Brustio brand (origin: Italy) twisting device (see Fig. 12). The image of the resulting hybrid yarn is given in Fig. 13. In order to make a comparison, similarly, the same cotton yarn was positioned side by side with HDPE filament produced from virgin polymer and 200 tpm

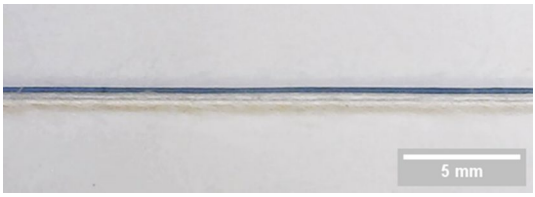


Fig. 11 Cotton yarn and recycle HDPE filament positioned side by side on the twisting device

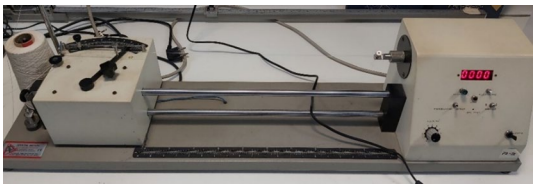


Fig. 12 Twisting device

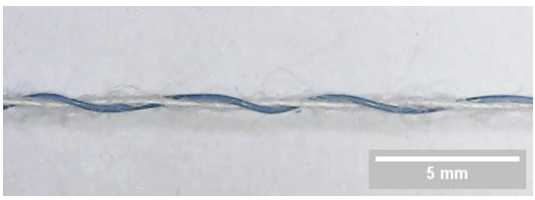


Fig. 13 Hybrid yarn made from recycled HDPE

twist was given in the *Z* direction in the twisting device. To accurately assess the potential improvements achieved through hybrid yarn formation, the cotton yarn used in the study was separately placed in the twisting device and given a twist of 200 tpm in the same *Z* direction, resulting in a twist value of 751 tpm. Because of the extra stress given during twisting, yarns were not stable just after the twisting and tended to return their previous untwisted form. This behavior is called yarn liveliness in yarn technology [24, 25]. Heat setting can be used to overcome this problem [24]. In heat setting, by subjecting yarn to heat, the structure becomes soft and start to relax, reducing any residual stresses or tensions within the yarn [24]. This relaxation allows the components to reorganize themselves within the yarn structure, enabling them to settle into their twisted positions more securely. In this study, both the hybrid yarns and the extra-twisted cotton yarn were exposed to hot air for 2 min to prevent the unwinding of the twist and ensure the fixation.

Breaking strength and breaking extension results of hybrid yarns

In accordance with the ISO 2062:2009 standard, both reference yarns and produced hybrid yarns were subjected to breaking load tests. Table 2 provides a summary of the details regarding the reference yarns and components of the hybrid yarns.

Figure 14 displays the breaking load results of reference and hybrid yarns described in Table 2. An ANOVA *F* test was conducted on the breaking load data in Fig. 14, using a significance level (α) of 0.05. Following this, a LSD test was performed ($\alpha = 0.05$) to determine the presence of any significant differences in

Table 2 Reference yarns and components of the hybrid yarns

Hybrid and reference yarns	Hybrid yarn component	
	1st component	2nd component
Hybrid yarn made from waste HDPE	Cotton yarn (linear density: Ne 16/1)	Recycle HDPE filament (linear density: 44.7 tex)
Hybrid yarn made from virgin HDPE	Cotton yarn (linear density: Ne 16/1)	Virgin HDPE filament (linear density: 37.1 tex)
Reference cotton yarn (twist: 551 tpm, linear density: Ne 16/1)	N/A	
Reference cotton yarn with an extra twist (twist: 751 tpm, linear density: Ne 16/1)	N/A	

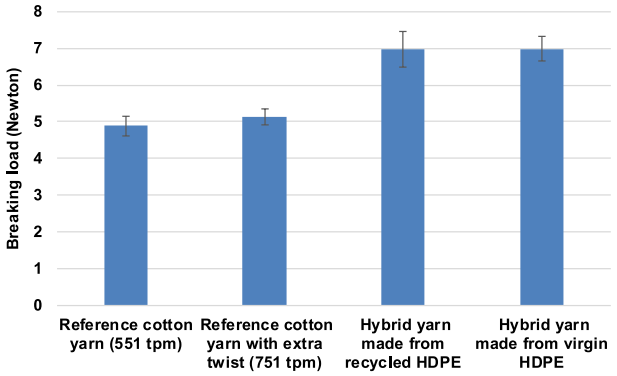


Fig. 14 Breaking load values of reference yarns and hybrid yarns

the experimental results. The application of the additional twist to the reference cotton yarn resulted in a statistically significant increase in the breaking load value, from 4.89 to 5.12 Newtons. This is an anticipated result as the twisting process creates a helical structure that promotes interlocking and increased friction between fibers, resulting in stronger yarns [25].

Upon further examination of Fig. 14, it was observed that the breaking load values of hybrid yarn of virgin HDPE and hybrid yarn of recycle HDPE exhibited an increase of approximately 42% compared to the breaking load of the reference cotton yarn. Additionally, these hybrid yarns demonstrated a breaking load that was 36% higher than that of the extra-twisted cotton yarn. This suggests that combining cotton and HDPE filaments in the production of hybrid yarns leads to an overall improvement in strength compared to using cotton and HDPE filaments individually. Notably, even weaker recycle HDPE filaments have now become a valuable component of a strong hybrid yarn.

When the breaking load values of the hybrid yarn produced from recycled polymer and the hybrid yarn produced from virgin polymer were compared, the average breaking load values were extremely close. They did not exhibit any

statistically significant difference. This outcome indicates that the hybrid yarn made from recycled HDPE is just as strong as the hybrid yarn made from virgin HDPE polymer.

Despite the notable strength advantage of virgin filaments over recycle filaments, it may be surprising that the hybrid yarns produced from virgin HDPE and the hybrid yarns made from recycled HDPE exhibit similar breaking load values. To understand this unexpected outcome, it is necessary to analyze the breaking extension results of both reference cotton yarns and hybrid yarns. Figure 15 displays the breaking extension results of the reference and hybrid yarns. Upon examination of the results, it is evident that the breaking extension values are closely aligned, ranging from 6.38 to 6.99%. It should be noted that, in contrast, the breaking extension values of both virgin and recycle HDPE filaments alone (over 100%) are significantly higher than these values (refer to Fig. 16). The results presented in Fig. 15 clearly show that the breaking extension values of the hybrid yarns closely resemble those of the cotton yarns. This is because the cotton component, with its limited stretchability, leads the hybrid yarn to break at low elongation levels when subjected to tension by the tensile strength test device, as observed during the tests illustrated in Fig. 17.

As given in Fig. 15, breaking extension values of virgin and recycle hybrid yarns are close to 7%. At this particular extension point, reference cotton yarn tend to reach its breaking point when tested alone. Consequently, when the reference cotton yarn is a component of the hybrid yarn, it gives potentially its full strength just before the failure of the hybrid yarn. On the other hand, when tested individually, both virgin and recycle HDPE filaments exhibit relatively smaller strength values at 7% extension (refer to Fig. 16). As depicted in Fig. 16, the force-extension curve illustrates that as extension values increase, the virgin HDPE filament demonstrates greater strength compared to the recycled counterpart. This difference can be attributed to the improved orientation [26] of longer molecule chains within the amorphous regions of virgin HDPE. However, the strength gap between virgin and recycle filaments diminishes notably at 7% extension. As a result, due to the low breaking extension behavior of the hybrid yarns, the strength contributions of virgin and recycle HDPE components to their respective

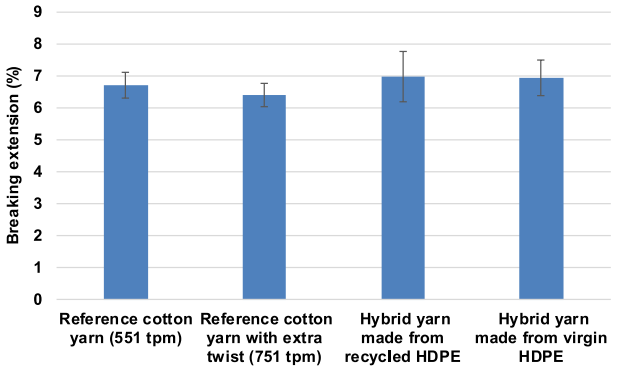


Fig. 15 Breaking extension values of reference yarns and hybrid yarns

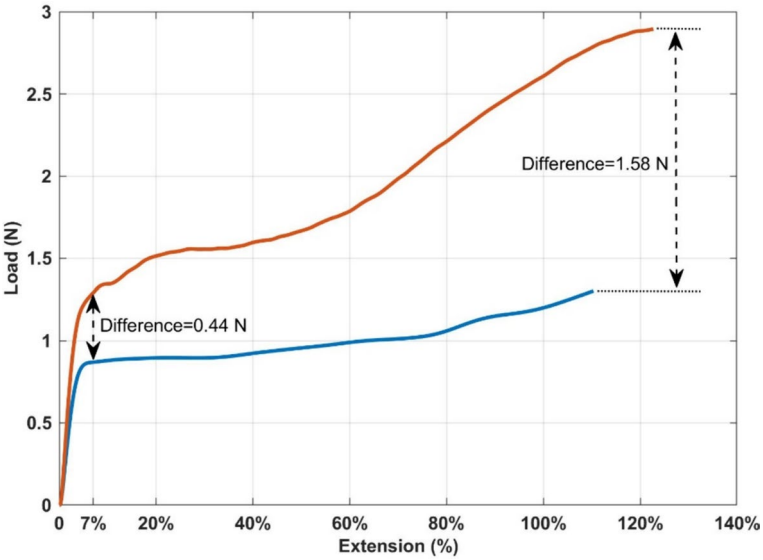


Fig. 16 Load-extension curves of the virgin and recycle HDPE filaments

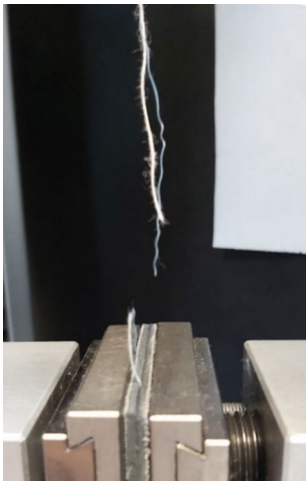


Fig. 17 Image of hybrid yarn after a break in the tensile strength testing device

hybrid yarns become more similar. This clarifies why the breaking load values of hybrid yarn produced from virgin HDPE and hybrid yarn made from recycle HDPE are very closely aligned.

Conclusion

By utilizing the melt spinning method, it was possible to produce filaments with various linear densities using the waste HDPE plastic. Through regression analysis, it was determined that the extruder speed and the linear density of the filaments exhibited a linear relationship. This finding enables the calculation of the required extruder speed for achieving a specific linear density using the derived linear equations.

As expected, the breaking strength of the filaments increased with their linear density. However, filaments produced from waste HDPE displayed significantly lower breaking strength compared to those made from virgin HDPE polymer. This result highlighted the challenges and limitations of recycling HDPE waste, providing valuable insights into the material's performance. To enhance the mechanical properties of the filaments, hybrid yarns were formed by twisting the HDPE filaments together with the cotton yarn. Remarkably, the hybrid yarns of recycled HDPE demonstrated a 36% higher breaking strength in comparison with the breaking strength of the extra-twisted reference cotton yarn. Moreover, there was no statistically significant difference in the breaking load values between the hybrid yarns made from waste plastic and those made from virgin polymer. The hybrid yarn formation effectively transformed the filaments made from waste HDPE into valuable and alternative components of high-strength hybrid yarns. Consequently, this study highlighted the potential of reusing HDPE plastics in the production of hybrid yarns, thereby contributing to the reduction in plastic waste pollution.

Fabrics produced from hybrid yarns can serve as reinforcing elements in natural fiber-reinforced polymeric composites. The presence of HDPE in the yarn can enhance fabric and polymer matrix interaction. These fabrics show potential for being shaped directly through 3-D compression molding, allowing for the creation of 3D composites with natural materials. Additionally, the fabrics can find outdoor applications, such as sun protection, shade nets, safety nets, and wind barriers.

Author contributions F.S. contributed to conceptualization, methodology, supervision, writing—review and editing. H.G. contributed to conceptualization, methodology, supervision, review.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability All necessary data appear in the submitted article.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long

as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Gourmelon G (2015) Global plastic production rises, recycling lags. Vital Signs 22:91–95
2. Johnston I (2017) How plastic is damaging planet Earth. In: Independent. https://www.independent.co.uk/environment/plastic-how-planet-earth-environment-oceans-wildlife-recycling-landfill-artificial-a7972226.html
3. Francis R (2017) Recycling of polymers. Wiley, Weinheim, Germany
4. Kolanjikombil M (2018) The substrates-fibres Yarn and Fabrics. Woodhead Publishing Limited, New Delhi, India
5. McIntyre JE (2005) Synthetic fibres: nylon, polyester, acrylic, polyolefin. Woodhead Publishing Limited, Cambridge, England
6. Swicofil A (2023) Polyethylene monofilament yarns and fibers from Swicofil. https://old.swicofil.com/pe.html
7. Ugbolue SCO (2009) Polyolefin fibres: industrial and medical applications. Woodhead Publishing Limited, Cambridge, England
8. Scarascia-Mugnozza G, Sica C, Russo G (2012) Plastic materials in european agriculture: actual use and perspectives. J Agric Eng 42:15. https://doi.org/10.4081/jae.2011.28
9. OECD (2022) Global plastics outlook-plastics waste in 2019 by region, polymer and application. In: OECD. https://stats.oecd.org//Index.aspx?DataSetCode=PLASTIC_WASTE_7#. Accessed 16 May 2024
10. Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:25–29. https://doi.org/10.1126/sciadv.1700782
11. Pešić N, Živanović S, Garcia R, Papastergiou P (2016) Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. Constr Build Mater 115:362–370. https://doi.org/10.1016/j.conbuildmat.2016.04.050
12. Bhavi BIK, Reddy VV, Ullagaddi PB (2012) Effect of different percentages of waste high density polyethylene (HDPE) fibres on the properties of fibre reinforced concrete. Nat Environ Pollut Technol 11:461–468
13. Soni A, Kumar S, Majumder B et al (2023) Synergy of waste plastics and natural fibers as sustainable composites for structural applications concerning circular economy. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-26365-y
14. Vidakis N, Petousis M, Maniadi A (2021) Sustainable additive manufacturing: Mechanical response of high-density polyethylene over multiple recycling processes. Recycling 6:1–14. https://doi.org/10.3390/recycling6010004
15. Tipu JAK (2023) Mechanical properties evaluation of recycled high density polyethylene via additive manufacturing. https://doi.org/10.5281/zenodo.10012303
16. Dassisti M, Intini F, Chimienti M, Starace G (2016) The case study of an HDPE (high density polyethylene) net company in Italy. Energy 108:7–18. https://doi.org/10.1016/j.energy.2016.01.043
17. Mankodi HR (2011) Developments in hybrid yarns. In: Gong RH (ed) Specialist yarn and fabric structures. Woodhead Publishing Limited, Cambridge, UK, pp 21–55
18. Blaine RL (2002) Thermal applications note. Polym Heats Fusion 1–2
19. Netszch GmbH (2023) Crystallinity / Degree of Crystallinity. In: Netzsch. https://analyzing-testing.netzsch.com/en/training-know-how/glossary/crystallinity-degree-of-crystallinity

20. da Silva DJ, Wiebeck H (2018) CARS-PLS regression and ATR-FTIR spectroscopy for eco-friendly and fast composition analyses of LDPE/HDPE blends. J Polym Res 25:112. https://doi.org/10.1007/s10965-018-1507-5
21. Smith BC (2021) The infrared spectra of polymers, part I: introduction. Spectroscopy 36:17–22
22. Smith BC (2021) The ınfrared spectra of polymers II: polyethylene. Spectroscopy 36:24–29. https://doi.org/10.56530/spectroscopy.xp7081p7
23. Nunes RW, Martin JR, Johnson JF (1982) Influence of molecular weight and molecular weight distribution on mechanical properties of polymers. Polym Eng Sci 22:205–228. https://doi.org/10.1002/pen.760220402
24. Yildirim K, Köstem AM, Aydin N et al (2014) Twist setting temperature and time effects on morphology of polyethylene terephthalate yarn. Tekst ve Konfeksiyon 24:186–194
25. Lord PR (2003) Handbook of yarn production. Woodhead Publishing Limited, Cambridge, England
26. Saville BP (1999) Physical testing of textiles. Woodhead Publishing Limited, Cambridge

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.