MECHANICAL AND THERMAL PROPERTIES OF RECYCLED HIGH-DENSITY POLYETHYLENE: EXPERIMENTAL INVESTIGATION

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Abstract. Plastic waste is an ongoing problem of environmental sustainability, and there is a need to develop a realistic solution to materials recovery and recycling. This article explains the mechanical and thermal characteristics of the recycling of high density polyethylene (HDPE) Grade 300 in the form of pellets and films from post-consumer and post-industrial plastic waste. Five recycled HDPE film were also tested in tensile testing according to ASTM D882-18, with the highest stress values of stress of between 9 and 11 MPa at the longest elongation of 167%, and the average Youngs modulus of approximately 465.7 MPa. Differential scanning calorimetry (DSC) was used to perform a thermal characterisation according to ASTM E1356, which showed that recycled HDPE pellets have a melting onset of 128.3 °C and a maximal melting temperature of 165.6 °C with an enthalpy of fusion of 66.64 $J \cdot g^{-1}$, while film specimens have a lower melting onset of 111.4 °C with an ultimate melting temperature of 124.4 °C and an enthalpy of 101.7 $J \cdot g^{-1}$. The general findings indicate that recycled HDPE has mechanical and thermal properties that are similar to the published values of virgin HDPE, thus indicating that recycled HDPE can be used as a practical engineering material in various structural and thermal uses. The findings are added to the evidence base on the need to incorporate recreational polymers in sustainable material engineering.

Keywords: recycled HDPE, mechanical properties, thermal properties, sustainable materials, polymer recycling.

Introduction

Plastics are one of the most common synthetic materials in contemporary engineering and industry [1] and are cherished by their durability [2], chemical resistance [3], low density and their wide array uses in multiple fields such as in the protecting clothing [4], construction [5] and health care industry [6]. Nevertheless, it is these very properties that make plastics functionally superior, especially the fact that they are resistant to various forms of biological and chemical degradation, which makes plastics persist in the environment even after their useful service life is over. Poor waste management and improper disposal of plastic materials have resulted in the accumulation of plastic materials in both terrestrial and marine ecosystems and the documented implications on the biodiversity, integrity of food chains, and health of human beings [7]. The resultant pressure has led to increased worldwide attention regarding the development of closed-loop material systems, where waste streams are repurchased and reused back into productive operation instead of being disposed.

Unlike the other grades of polyethylene, HDPE is distinguished by a highly linear molecular structure with minimal side-chain branching, giving it a high level of crystallinity and hence a high level of density, tensile strength, and stiffness [8]. In commercial applications, HDPE is widely used in containers, pipes, films, and structural profiles [9]. It is especially suitable for demanding service applications as a result of its moisture, ultraviolet radiation, and a wide variety of chemical reagent resistance. Importantly, HDPE is assigned with resin identification code 2, making it one of the most widespread reused and recycled polymers in municipal and industrial recycling programmes around the world.

Previous studies have covered the characteristics of both virgin and recycle HDPE in a variety of applications and processing backgrounds. The tensile strength of recycled HDPE has been reported to be between 8-10 MPa with elastic moduli approximately between 0.48 and 1.45 GPa [10-12] and standardised tensile testing procedures have also been used to determine the performance of thermoplastic polymer specimens manufactured under various processing parameters [13]. Differential scanning calorimetry (DSC) thermal characterisation has also determined melting temperature ranges consistent across thermoplastic systems with virgin material, although comparisons of virgin and processed polymer forms have shown that the technique is sensitive to crystallinity changes during processing; DSC studies have shown that changing virgin material to processed can result in variation in peak temperature and enthalpy of fusion [14]. Research on the inclusion of recycled polymers in hierarchical and composite material structures has also shown that the history of processing has a significant impact on the ultimate mechanical and thermal behaviour of the resulting structures [15-17].

Research on recycled HDPE, in particular, has shown similar functionality to regular virgin-grade materials in terms of stiffness, impact strength, and life cycle [18]. Nevertheless, one of the weaknesses of the available literature is a that there is scarcity of systematically acquired experimental evidence of recycled HDPE based specifically on post-consumer streams of waste that have been processed and tested as a collective, especially data that collectively define the mechanical and thermal performance domains. Current research will fill this gap by offering an experimental characterisation of the mechanical and thermal properties of the grade 300 HDPE recycled product, based on post-consumer waste and post-industrial waste, both in pellet and film form.

Materials and methods

The plastic material tested in this paper was the recycled high-density polyethylene Grade 300, which is derived from post-consumer and post-industrial plastic waste. J&J Plastics in the Industrial Development Area, Edayar, Binanipuram, Kerala, India processed the recycled material. Two specimen forms have been tested, HDPE pellets and the thin films made of the said pellets. HDPE Grade 300 is a recycled polyethylene, which is in compliance with ISO 15270 standards on plastic waste recovery and recycling, and with ASTM D4976 standards of polyethylene material characterisation.

The recycled HDPE pellets produced on post-consumer waste was an industrial process consisting of a series of steps that was undertaken at the J&J Plastics facility. The first step was to collect plastic waste at home, industrial, and agricultural locations where it was washed at an automated sorting system, the TOMRA AUTOSORT 4 belt conveyor system, separating by resin, size, and weight. The removal of contaminants was carried out with a STEINERT UniSort PR sensor-based separation system to remove metallic, glass and non-HDPE products. A Vecoplan VEW 404 system was used to clean and wash the sorted material, and the material in a Sorema T1600 machine to eliminate remaining moisture and other surface contaminants.

The material was cleaned and shredded on a Weima WLK 10 machine to flakes that were ground to a fine granule, which is a suitable melt processing flake. Pelletisation and extrusion was done with an NGR A65 extruder, where the filtered molten HDPE was pressured through a die and pellets were cut. The resulting new pellets were then cooled and dried in a Conair CD60 system. The last quality control measure was an inspection by X-ray inspection by S + S Inspection Raycon, which identified any residual contaminant in the product stream of the pellets. The completed pellets were packaged to proceed with further processing.

The pellets were melted in a series of melting processes to produce recycled HDPE film. Melting of the pellets was performed on a KUHNE MDO machine and film extrusion on a Davis-Standard DS S3 film extrusion unit, which provides a choice in film thickness and film width. The extruded film was allowed to cool off in the air to stabilize its size, after which it was wound into rolls using a Kampf Converting Machinery Conslit winder. The roll material was then cut to the required specimen sizes using an Atlas Converting equipment Titan SR8 cutting machine. The quality check of the film was done with a Thermo Fisher Scientific Nicolet iS50.

Tensile properties were determined on a Mecmesin Multi-Test 2.5-i testing machine with 250 N load cell. The use of the specimen dimensions was guided by ASTM D882-18 in which each sample had a length of 200 mm and width of 25 mm with a grip distance of 100 mm. Thickness, which was then used to obtain cross-sectional area, was measured in each of the individual specimens. Raw force displacement data were transformed to engineering values of stress and strain using the Hooke law relationship in which the Young's modulus E is determined as the ratio of stress σ to strain ε.

Differential scanning calorimetry (DSC) was carried out by use of a NETZSCH DSC 214 Polyma differential scanning calorimeter in the presence of a flowing nitrogen atmosphere with a purge rate of 30 ml/min according to ASTM E1356 as mentioned in [19; 20].

Results and discussion

Fig. 1 presents a response to tensile stress(σ)-strain(ε) response of five specimens of recycled HDPE film. All showed a typical thermoplastic behaviour and an initial linear elastic regime, succeeded by a plateau of nearly constant stress at large strains, typical of the cold-drawing mechanism found in semicrystalline polyethylene.

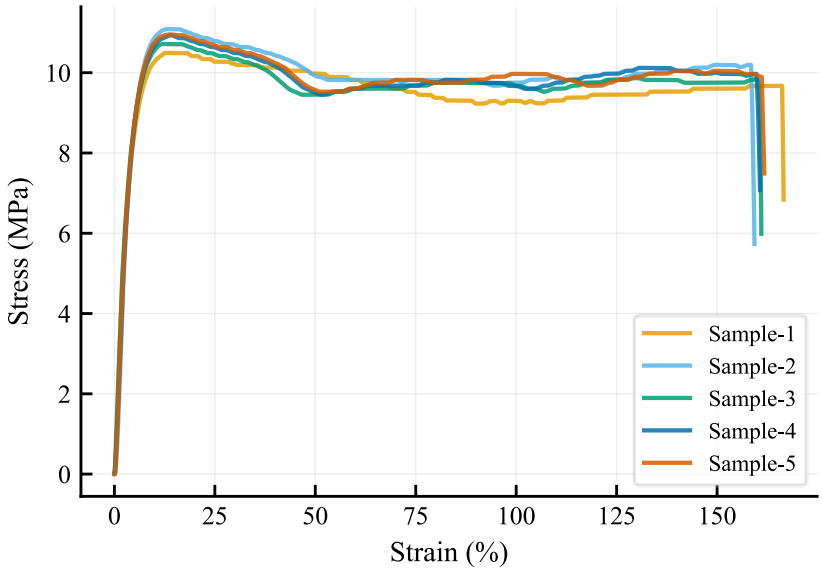

Fig. 1. **Stress(σ)-strain(ε) curves for five recycled HDPE film specimens**

The detailed mechanical property values for each specimen are summarised in Table 1.

Table 1

Summary of the mechanical properties of the recycled HDPE film specimens

Sample	Thickness *t*, µm	Ultimate Tensile stress σ max, MPa	Elongation at break,%	Young's Modulus, MPa
1	209	10.09	166.6	458.64
2	208	10.66	159.4	469.61
3	208	10.37	161.0	500.97
4	210	10.52	160.8	431.14
5	207	10.58	162.1	468.19

Table 1 presents that the thickness of the specimens was close to 207-210 µm, which suggests the same level of film production. The maximum tensile stress of the different specimens was between 10.09 and 10.66 MPa, the mean of which is about 10.44 MPa. The elongation at break was between 159.4% and 166.6% and the Young modulus between 431.14 and 500.97 MPa with an average value of approximately 465.7 MPa. The reproducibility between specimens, as evidenced by the overlapping stress(σ)-strain(ε) curves in Fig. 1 is a sign of a uniform and reproducibly processed material, which is a requirement for sound engineering use.

In comparison to these data with the published data on virgin HDPE, which commonly has a tensile strength range of 20-37 MPa and an elastic modulus of 800-1500 MPa [21], it is clear that recycled HDPE Grade 300 has a lower stiffness and strength. This decrease is looked at and can be attributed to chain scission, residual contamination, and lower molecular weight due to thermal and mechanical processes during the recycling process. However, the tensile strength values of 9-11 MPa are in line with the already published data on recycled HDPE of similar feedstocks, proving that the material acts within the anticipated limits. The degree of feedstock purity, ensured through multi-stage sorting and contaminant removal in the present study, plays a critical role in these outcomes; higher residual contamination typically reduces tensile strength and broadens the DSC melting transition, whereas cleaner feedstocks yield more consistent mechanical response and sharper thermal peaks, as evidenced by the minimal variation observed across specimens. The elongation ability - strain values go as high as 167% and thereafter the loads start decreasing, which is beneficial in a case where there is a need to absorb energy or even resistant to brittle fractures.

The fact that both the stress and the modulus values scatter across the specimens is relatively thin allows concluding that the multistage cleaning, sorting, and extrusion of the recycled feedstock was successful in producing a homogeneous pellet feedstock. The coefficient of the variation of ultimate

tensile stress of the five samples is minimal, which shows that quality control processes during the manufacture of fabrics were effective in restricting the variability that is often mentioned as a problem with recycled polymer feedstocks.

Fig. 2 represents the DSC thermograms of recycled HDPE pellets and film. The endothermic melting transitions of both specimens are also well defined, which proves the semicrystalline characteristics of the recycled material.

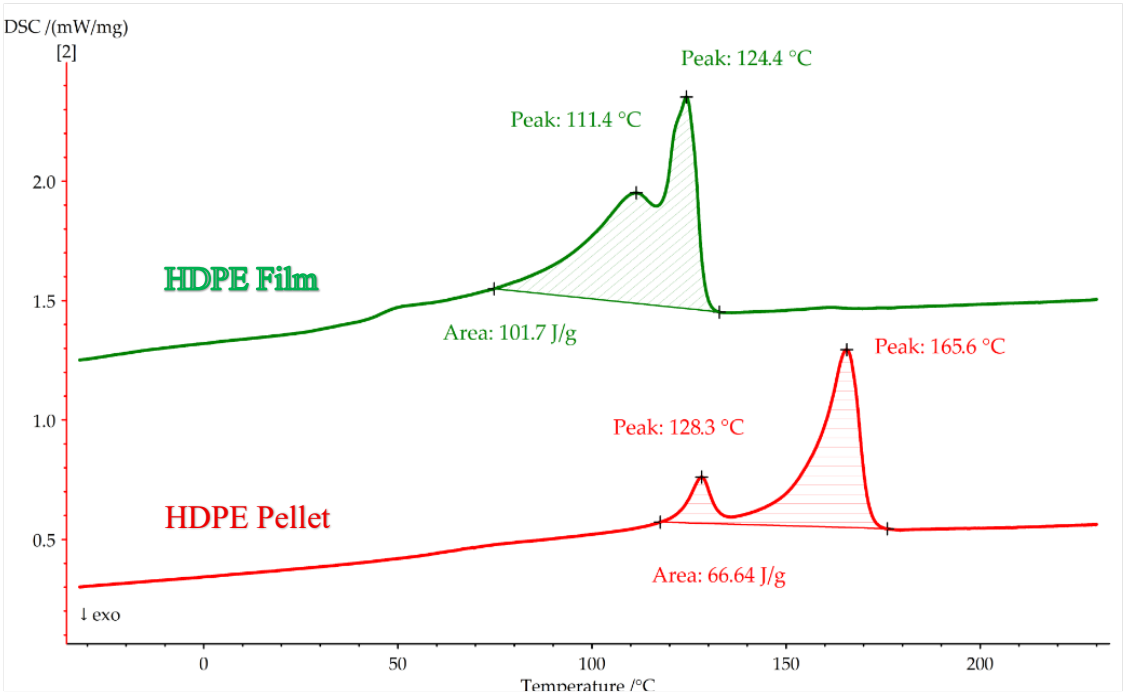

Fig. 2. **DSC of recycled HDPE pellets (red curve) and recycled HDPE film (green curve)**

In the case of recycled HDPE pellets, the melting temperature began at 128.3 °C, the maximum melting temperature was 165.6 °C, and the enthalpy of fusion was 66.64 $J \cdot g^{-1}$. In the recycled HDPE film, the melting point was also lower at 111.4 °C with a maximum point of 124.4 °C and a much higher enthalpy level of 101.7 $J \cdot g^{-1}$.

The thermal behaviour of the pellet and film forms is different; this deserves to be discussed. The lower onset and maximum melting temperature in the film (124.4 °C) compared to the pellets (165.6 °C) is in line with there is a fact that the less thermally perfect crystalline population in the film in which the mechanical and thermal working of extrusion and drawing causes the average lamellar thickness and crystal perfection of the semicrystalline microstructure to decrease. Less perfect lamellae are thinner and melt at lower temperatures, in line with the Gibbs-Thomson relation, which is in line with the observed change. Simultaneously, the increased enthalpy of film fusion (101.7 $J \cdot g^{-1}$ vs. 66.64 $J \cdot g^{-1}$ in the case of pellets) represents an increased level of overall crystallinity which is probably caused by crystallisation under strain during the drawing and rapid-cooling of the air process of film production. These two findings, lower melting and increased crystallinity do not contradict but rather result in the film having more crystalline material but crystalline material organised into thinner, less perfect lamellae that melt at a lower temperature than the larger, more perfect crystals in the pellet form. The thermomechanical processing of semicrystalline polymers can be well-established in terms of orientation and rapid cooling.

The highest recorded melting temperature of the pellet form (165.6 °C) is within the generally accepted range of HDPE, which is generally quoted at 120 to 140 °C with extensive impalate crystal formations and 175 °C with well-developed lamellae, which again confirms the quality of the recycled material. The enthalpy values of the fusion of both forms are lower than the values reported in high-crystallinity virgin HDPE (approximately 120-290 $J \cdot g^{-1}$ of 100% crystalline polyethylene as theoretical reference), which represents the low crystallinity anticipated in a reprocessed product. However, the clear and crisp melting boundaries as seen in the thermograms suggest that the recycled HDPE still has

a microstructure that is well-ordered enough to give predictable thermal characteristics in its process and service.

In terms of application, the thermal data show recycled HDPE pellets to be thermally stable at the temperature experienced by a wide variety of engineering service conditions. The beginning of the melting of the pellet form of 128.3 °C at a load-bearing temperature gives a definable upper limit to the service temperature when the material is under load, and the other time, the onset of the melting of the film form is 111.4 °C, which implies that thermal management must be considered with regard to the processing history of the particular product form. Its thermal conductivity of about 0.41-0.52 $W \cdot mK^{-1}$ plus a low thermal expansion coefficient (about 100-200 $\times 10^{-6}$ $°C^{-1}$) also contributes to its usefulness in processes with moderate thermal cycling.

Combined, mechanical and thermal characterisation information indicates that recycled HDPE Grade 300 has sufficient material behaviour in both property spaces that it should be considered as an engineering material in a situation where it is necessary to have moderate tensile loads in addition to thermal stability up to about 110-128 °C. The tensile strength of 9-11 MPa coupled with high ductility makes the material suitable for use in semi-structural and non-primary load bearing applications. The clear and repeatable thermal shifts ensure predictable processing behaviour and sufficient stability at service temperatures at room temperature and moderately high service temperatures.

One of the results of this research is the internal consistency of the results in each form of material. Mechanical testing was performed on film samples, and the average values were: Young's modulus was 465.7 MPa and a tensile strength of about 10.44 MPa, values lower compared to virgin HDPE. Analysis of the film form using DSC gave an enthalpy of fusion of 101.7 $J \cdot g^{-1}$, which is indicative of a high level of crystallinity induced during the drawing of the film. The pellet form, in turn, exhibited a reduced enthalpy of 66.64 $J \cdot g^{-1}$ and a higher and sharper melting peak, which are signs of reduced yet more thermally perfect crystals. In both types, the decrease in mechanical stiffness and strength compared to virgin HDPE is related to the structural modifications the recycling process has brought to the material, such as scission of the chains and the change in crystalline structure.

Conclusions

1. Tensile tests conducted on recycled HDPE film specimens indicated an ultimate stress of between 9 and 11 MPa with the average Youngs modulus of approximately 465.7 MPa and a large elongation capacity of up to 167% strain. The recycling and fabrication process was proven to be consistent, as reproducibility of the results occurred between specimens.
2. The DSC analysis revealed that the melting start temperature of 128.3 °C and 111.4 °C of the pellet and film, respectively, and the highest melting temperatures of 165.6 ° C and fusion 124.4 °C, and enthalpies of 66.64 $J \cdot g^{-1}$ and 101.7 $J \cdot g^{-1}$. Their morphological variation, which is based on strain-based crystallisation and reduction of the crystal size, was ascribed to morphological alterations which were introduced during the extrusion of the film.

Author contributions

Conceptualization, H.K.M. and J.V.S; methodology, A.K.P., H.K.M., and V.V.; software, J.V.S.; validation, J.V.S.; formal analysis, A.K.P.; investigation, A.K.P., H.K.M., and V.V.; data curation, A.K.P., H.K.M., and V.V.; writing – original draft preparation, H.K.M.; writing – review and editing, J.V.S.; visualization, J.V.S.; project administration, J.V.S.; funding acquisition, H.K.M. All authors have read and agreed to the published version of the manuscript.

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