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Mechanical Testing of Recycled HDPE Extruded Hollow Section

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Abstract. High density polyethylene (HDPE) is a thermoplastic polymer which is classified as one of the highly consumed types of plastics. One major advantage of thermoplastic materials is their ability of recycling and reprocessing which will bring considerable economic and environmental benefits. The present paper, therefore, endeavors to explore the practical possibility of using recycled HDPE hollow section as a replacement of virgin HDPE made by the extrusion process. The main focus of the study was to evaluate the mechanical performance of the recycled HDPE and compare the results with virgin or non-recycled HDPE. The modulus of elasticity, tensile yield and ultimate strength, compressive yield and ultimate strength, flexural yield and ultimate strength and the coefficient of thermal expansion were the main parameters to be checked against the respective mechanical properties. Thus, pursuant to the results, it was found out that the modulus of elasticity and the tensile yield strength are lower in recycled HDPE compared to the non-recycled HDPE. However, there is no significant difference between the recycled and non-recycled HDPE for the tensile ultimate strength, compressive yield strength and compressive ultimate strength. The flexural yield strength and flexural ultimate strength properties of the recycled HDPE proved to be superior to those of the non-recycled HDPE. The coefficient of linear thermal expansion of the recycled HDPE sample was 130 μm/(m.°C) and that for the non-recycled HDPE was 142 μm/(m.°C).

Keywords: High density polyethylene, Thermoplastic, Extrusion, Recycled, Mechanical properties

1 Introduction

Polyethylene (PE) is one of the highly consumed polymers in the world available with different density grades. The density grades can be categorized mainly into four categories as; low density polyethylene (LDPE), high density polyethylene (HDPE), linear low density polyethylene (LLDPE), ultrahigh- molecular weight polyethylene (UHMWPE) (Harper, 2002). Polyethylene density range from 0.91- 0.97 g/cm^3 and the density of the particular category is governed by the morphology of the backbone, length of polymer chains and side branching of the polymer (Hearn, 2008).

High density polyethylene (HDPE) is a thermoplastic polymer used to manufacture variety of products including bottles, pipes etc. HDPE structure is described as semicrystalline with a combination of amorphous and thin lamellae crystals (Harper, 2000). The greater the degree of crystallinity, the higher the tendency of the materials brittleness due to the weak interfaces between each crystal structure. In contrast, the higher the amorphous characteristics of the region, the more rubber-like becomes the HDPE behaviour depending on its glass transition temperature (Barraclough, 2011). The combination of crystalline and amorphous regions secures the HDPE extreme toughness and brittleness at lower temperatures, causing it to become rubbery and more flexible at higher temperatures which, in turn, builds up to the HDPE improved recycling and reprocessing ability (Rudolph, Kiesel, & Chuanchom, 2017).

The most common method of processing HDPE is the extrusion process, which creates objects of a fixed cross sectional profile. HDPE pellets are fed into the extruder barrel and compressed and heated by conduction, and then, the melted plastic is forced under pressure through a die that forms the ultimate product with the desired shape (Hsueh et al., 2020).

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Being a thermoplastic polymer, HDPE can be melted and reprocessed to another product, even with the extent of thermo mechanical properties and degradation of the recycled materials being strongly dependent on the structure of HDPE and processing conditions (Qian, Mansfield, & Baird, 2017). The degradation occurs during both the first processing and successive recycling and reprocessing operations, and generally, under suitable reprocessing conditions, the properties of the recycled material are similar to those of the virgin HDPE (Goodship, 2007). The study focuses exclusively on evaluating the mechanical performance of recycled HDPE hollow section made through the extrusion process.

2 Methodology

2.1 Measurement of the specific gravity

Specific gravity (SG) is the ratio of the mass in air of a unit volume of the impermeable portion of the material at 23°C to the mass in air of equal density of an equal volume of gas-free distilled water at the same temperature. Specific gravity of both recycled and non-recycled HDPE extruded hollow section was measured according to ASTM D 792, a standard test method for density and specific gravity (relative density) of plastics by displacement.

Well cleaned recycled and non-recycled HDPE single piece test specimens were conditioned at 23±2°C and 50±5% relative humidity for not less than 40 hours prior to testing. Then the weight of the test specimen was measured in air using an analytical balance with a precision within 0.1mg, accuracy within 0.05% and equipped with a stationary support for the immersion vessel above the balance pan. Subsequently, the immersion vessel was mounted on the support and the specimen was completely immersed in water at a temperature of 23±2°C. Bubbles adhered to the specimen and sample holders were removed by rubbing them with a wire. The mass of the suspended specimen was measured and recorded as "b" (the mass of the specimen and sinker). Then the weight of the sample holder in the water with immersion to the same depth, as used in the previous step, was measured and recorded as "w" (mass of the sample holder in liquid) and the specific gravity was calculated as,

$$SG = \alpha / (\alpha + w - b) \quad (1)$$

Where, α = mass of the specimen, without wire or sinker in air

b = mass of the specimen (and sinker, if used) completely immersed in water
w = mass of totally immersed sinker (if used)

2.2 Modulus of elasticity test

The test was done using the tensile test machine with a test speed of 500 mm/min and an extensometer. Five test specimens from each Recycled and non- recycled HDPE without defects like scratches, pits, sink marks and flash were conditioned at 23±2°C and 50±5% relative humidity for 16 hours. The dimensions of the test specimens are as in Table 1,

Table 1. Dimensions of the test specimens

Specimen type	Dimension (mm)
Overall length	170
Length of narrow parallel- sided portion	80 ± 2
Radius	24 ± 1
Distance between broad parallel- sided portions	109.3 ± 3.2
Width at ends	20.0 ± 0.2
Thickness	10.0 ±0.2
Gauge length	4.0 ± 0.2
Initial distance between grips	115 ± 1

The conditioned test specimens were next placed on the grips of the tensile machine to align the longitudinal axis of the test specimen with the axis of the test machine. The grips were tightened to

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avoid slippage and movement of the test specimens during the test. After setting the pre stress, a calibrated extensometer was positioned symmetrically about the middle of the parallel portion and on the center line of the test specimen. Then the specimen was tested for modulus at two strains, 0.05% and 0.25 % at a rate of 500mm/ min as in Figure 1, and the results were calculated using equation 2 below,

Fig. 1. Modulus of elasticity test

$$Et = (\sigma_2-\sigma_1) / (\varepsilon_2-\varepsilon_1) \quad (2)$$

Et = tensile modulus, expressed in megapascals (MPa)

σ_1 = stress, expresses in MPa, measured at the strain value ε_1= 0.0005 (0.05%)
σ_2 = stress, expresses in MPa, measured at the strain value ε_2= 0.0025 (0.25%)

2.3 Tensile Yield strength (σ_y)

The yield point of the material is the first point on the stress-strain curve at which an increase in strain occurs without an increase in stress. Applying the same test procedure and test data with respect to the elasticity of the modulus test, the following calculations were done.

$$F = (Et \times A \times v)/60L \quad (3)$$

F= rise rate of the force, expressed in newtons per second (N/s)

Et = tensile modulus (MPa)
A = cross sectional area of the test specimen (mm^2)
V= test speed (mm/min)
L = gripping distance (mm)
Thus, based on the above force (F), the tensile yield strength (σ_y) was calculated using the equation 4 below, where the factor which changes to "F" in formulation 3 is the gripping distance

$$\sigma_y = F/A \quad (4)$$

2.4 Tensile ultimate strength (σ_b)

This is the stress at which the maximum strength is reached at its point of break. This is also known as the strength at break. The factor which changes to "F" in formulation 3 is the gripping distance. The test procedure itself is illustrated in Figure 2

$$\sigma_b = F/A \quad (5)$$

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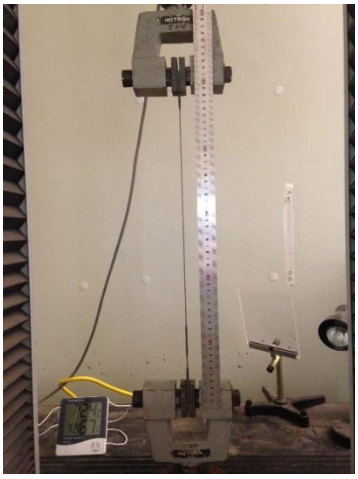

Fig. 2. Tensile ultimate strength test

2.5 Compressive yield and ultimate strength test

This was tested using ASTM D6641 standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture. The compressive strength and stiffness properties of a polymer matrix composite material were thus determined by means of the combined loading compression test fixture. A test fixture as in Figure 3 was used for the test in which a straight side composite specimen of rectangular cross section is placed at the middle of the test fixture. A typical test specimen is 114 mm in length, 13 mm in width, having an unsupported (gage) length of 13 mm when installed in the fixture. The fixture which subjects the specimen to combine end and shear loading is itself loaded in compression between flat platens of a universal testing machine and load strain data were collected at the yield point and ultimate strength point. The compressive yield and ultimate strength test were calculated using the following equation,

$$F_{cu} = P_f/wh \quad (6)$$

F_{cu} = Compressive strength (MPa)
P_f = Maximum load to failure (N)
w = Specimen gage width (mm)
h = Specimen gage thickness (mm)

Fig. 3. Compressive yield and ultimate strength test

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2.6 2.6 Flexural yield and ultimate strength test

Five from each recycled and non-recycled test specimens with a length of 80 ± 2 mm, width 10.0 ± 0.2 mm and thickness 4.0 ± 0.2 mm were conditioned at 23±2°C and 50±5% relative humidity for 16 hours prior testing. Then the test speed was set to 500 mm/min and the test specimen was placed symmetrically on the two supports and the force was applied at the mid span. The force and the corresponding deflection of the specimen during the test were recorded. The flexural yield stress and ultimate strengths were calculated using equation 7 below and the relevant applied force values. The testing procedure is illustrated in Figure 4,

$$\sigma_f = 3\,FL / 2bh^2 \qquad (7)$$

σf = Flexural stress parameter
F= Applied force (N)
L = Span (mm)
b = Width of specimen (mm)
h = Thickness of specimen (mm)

Fig. 4. Flexural yield and ultimate strength test

2.7 Coefficient of thermal expansion

The testing was performed according to the ASTM D 831 standard test method for linear thermal expansion of solid materials by thermo mechanical analysis. The test specimens were between 2 and 10 mm in length and have flat and parallel ends to within ± 25 µm. The initial specimen length was measured in the direction of the expansion test to ± 25 µm at 20 ^{0}C to 25 ^{0}C and was placed on the specimen holder of the thermo mechanical analyser. The furnace and specimen temperature sensor were placed near the specimen and load force was applied to the sensing probe. The appropriate ordinate and abscissa sensitivity was selected on the graphical representation. The specimen was then heated at a constant rate of 5^{0}C/min over the temperature range of 20 ^{0}C to 100 ^{0}C and the changes in length were recorded. The linear thermal expansion was calculated according to equations 8 and 9

$$\alpha_m = (\triangle L_{sp} \times k) / (L \times \triangle T) \qquad (8)$$

$$k = (\alpha_{ref} \times L_{ref} \times \triangle T_{ref}) / (\triangle L_{ref}) \qquad (9)$$

α m= mean coefficient of linear thermal expansion, µm/(m/°C),
α ref = mean coefficient of linear thermal expansion, for reference material, µm/(m·°C)

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k = calibration coefficient, from test method E2113
L = specimen length at room temperature,
△L ref = change of reference material length due to heating (μm)
L ref = reference material length at room temperature (μm)
△L sp = change of specimen length (μm)
△T ref = temperature difference over which the change in reference material length is measured° C, typically 100 °C,
△T = temperature difference over which the change in specimen length is measured, °C,
T = midpoint temperature of the temperature range △T

3 Results and Discussion

3.1 Specific gravity

The recycled HDPE resulted a specific gravity of 0.953 g/cm^3 ± 0.001 while the non-recycled HDPE was 0.990 g/cm^3 ± 0.001. The results obtained for the specific gravity show a significant difference between recycled and non-recycled HDPE. The changes in crystalinity structure, porosity and loss of plasticizers during the remelting process while recycling are possible reasons for the change in specific gravity (Mustafayeva, 2020). Generally, the greater the proportion of crystalline regions, the higher the density of the material. Crystalline regions are those which are highly ordered and densely packed molecular chains, and it is these crystalline regions that might have been affected during the recycling process which ultimately results in a decreased density of the recycled HDPE (Andersson, 2004).

3.2 Modulus of elasticity test

The results obtained for the modulus of elasticity test are recorded in Table2

Table 2. Modulus of elasticity results of the recycled HDPE

Specimen	modulus of elasticity (MPa)	
	Initial linear section	0.05-0.25%
1	509	128
2	655	157
3	679	181
4	690	356
5	753	690
Average	657	302

The average of the tests within the first linear section is 657 MPa which ranges from 509 to 753 MPa with a standard deviation of 90 MPa. The average of the tests from 0.05-0.25% is 302 MPa with a standard deviation of 234 MPa. The average modulus of non-recycled HDPE ranges around 900-1550 MPa (Bamberger Polymers, 2019). Subject to the modulus results, the recycled HDPE has a lower modulus value against the non-recycled HDPE which prompts a reduction in the material properties after recycling. It is particularly the reduction in modulus that strongly correlates with the fact that the recycled material imposes lower strength and stiffness when compared with the non-recycled material and hence can easily become brittle unlike the non-recycled HDPE (Pawlak, 2007).

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3.3 Tensile Yield strength

Table 3 below indicates the yield tensile strength of each recycled HDPE sample

Table 3. Tensile yield strength results of the recycled HDPE

Test specimen	Tensile yield strength (MPa)
1	18.79
2	18.63
3	18.91
4	18.92
5	19.18
Average	18.89

The average of the yield tensile strength of recycled HDPE is 18.9 MPa with a standard deviation of 0.20 MPa. The non-recycled HDPE registered yield strength of 21-35MPa (Bamberger Polymers, 2019), which is greater than the recycled sample. This results emphasis the maximum strength of the non-recycled HDPE is greater than the recycled HDPE and hence the recycled HDPE can easily become brittle during practical applications relative to the recycled HDPE.

3.4 Tensile ultimate strength

Results obtained for the tensile ultimate strength are displayed in Table 4 below,

Table 4. Tensile ultimate strength results of the recycled HDPE

Test specimen	Tensile ultimate strength (MPa)
1	12.26
2	12.39
3	12.42
4	12.88
5	13.24
Average	12.40

The average of the tensile ultimate strength of recycled HDPE samples were 12.4 MPa with a standard deviation of 0.4 MPa. Conversely, the ultimate tensile strength or the strength at the point where the material is broken at around 5- 6 MPa in the non-recycled HDPE (Bamberger Polymers, 2019). Moreover, none of the test samples were broken before full extension and all the specimens were stretched for the full extension of the equipment as revealed in Figure 5,

Fig. 5. Recycled HDPE test specimens after stretched to full extension

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3.5 Compressive yield and ultimate strength

The compressive yield strength and ultimate strength results of the recycled HDPE samples are presented in Table 5 below,

Table 5. Compressive yield strength and ultimate strength of recycled HDPE

Test specimen	Compressive yield strength (MPa)	Compressive ultimate strength (MPa)
1	21.63	15.59
2	22.16	16.73
3	23.52	19.35
4	24.68	20.43
5	25.12	20.64
Average	23.4	18.6

The average of the compressive yield strength tests is 23.4 MPa with a standard deviation of 1.5 MPa. In the non-recycled HDPE sample this value was 23.7 MPa. The average of the ultimate strength or the strength at break is 18.6 MPa with a standard deviation of 2.3 MPa for the recycled HDPE sample as against the 20-25 MPa for the non-recycled sample (Bamberger Polymers, 2019). Both the compressive yield strength and the ultimate strength values are similar in both the recycled and non-recycled samples.

3.6 Flexural yield strength and Flexural ultimate strength

The Flexural yield strength and ultimate strength results of the recycled HDPE samples are reported in Table 6 below,

Table 6. Flexural yield strength and ultimate strength of recycled HDPE

Test specimen	Flexural yield strength (MPa)		Flexural ultimate strength (MPa)	
	Y axis (bending on wide edge)	X axis (bending on narrow edge)	Y axis (bending on wide edge)	X axis (bending on narrow edge)
1	33.44	34.27	29.53	37.58
2	35.73	34.30	31.34	38.33
3	35.85	35.53	31.73	38.48
4	36.41	36.04	32.25	38.70
5	36.77	38.00	32.57	39.83
Average	35.61	35.62	31.52	35.57

The Flexural yield strength and ultimate strength of the non -recycled HDPE is 33.9 MPa which is lower than the recycled HDPE sample (Bamberger Polymers, 2019). This is practically indicative of the fact that the flexural properties are better in the recycled HDPE sample rather than in the non-recycled one. Using a material with a high flexural strength can allow the manufacturer to potentially reduce the wall thickness of the extruded article while maintaining the same stiffness. Bearing in mind that the high strength materials are difficult to form, it is of utmost importance to carefully select the material with the desired properties (McKelvey, Menary, Martin, & Yan, 2017).

3.7 Coefficient of thermal expansion

The coefficient of linear thermal expansion of the recycled HDPE sample ranged between 20°C – 80°C averaged 130 µm/(m.°C) and for non-recycled HDPE the value was 142 µm/(m.°C) (Bamberger Polymers, 2019). The resultant increase in thermal expansion is mainly due to the change in HDPE crystalline structure during the process of recycling. The coefficient of linear expansion is a parameter which is related to the molecular weight of the resin chains in a polymer. The coefficient of linear expansion is inversely proportional to the molecular weight (Araújo, Waldman, & De Paoli, 2008). A lower coefficient of linear expansion which yields a higher average molecular weight is predictive of

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greater tensile strength and toughness (Kolařík, Pegoretti, Fambri, & Penati, 2006). The findings of the research hereto presented prove that the coefficient of the linear expansion value is lower in the non-recycled HDPE in contrast to the recycled sample which indicates that molecular weight has reduced during the recycling process.

4 Conclusions

In view of the results, the modulus of elasticity and the tensile yield strength are lower in the recycled HDPE when compared to the non -recycled HDPE. There is no significant difference between recycled and non-recycled HDPE for tensile ultimate strength, compressive yield strength and compressive ultimate strength. Flexural yield strength and flexural ultimate strength properties are better in recycled HDPE compared to the non-recycled HDPE. All in all, in light of the above considerations, it can be concluded that the recycled HDPE can be used as an alternative to the non-recycled HDPE and therefrom provides sustainable solutions for cost-effective production and environmental protection. The study hereto discussed was only limited to the recycled and non-recycled HDPE, and is likely to be further developed by blending different ratios of recycled HDPE and non-recycled HDPE and evaluating the property variations with the blending ratios.

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