Technology and Science for the Ships of the Future
V. Crupi and V. Bucci (Eds.)

doi:10.3233/PMST250118

Investigation on the Tensile Properties of Virgin and Recycled HDPE for Boatbuilding Applications Through Experimental Tests

Serena BERTAGNA[a,1], Natasha TAUCER MARCHESI[a], Vittorio BUCCI[a], Giuseppe BRANDO[b], Fabio DISTEFANO[b], Vincenzo CRUPI[b] and Alberto MARINO'[a]
[a]*Department of Engineering and Architecture, University of Trieste*
[b]*Department of Engineering, University of Messina*

ORCiD ID: Serena Bertagna https://orcid.org/0000-0002-1100-5048
ORCiD ID: Natasha Taucer Marchesi https://orcid.org/0009-0008-6239-5008
ORCiD ID: Vittorio Bucci https://orcid.org/0000-0001-5929-8655
ORCID ID: Fabio Distefano https://orcid.org/0000-0002-0255-5857
ORCID ID: Giuseppe Brando https://orcid.org/0009-0005-9173-7810
ORCID ID: Vincenzo Crupi https://orcid.org/0000-0001-7498-4733
ORCiD ID: Alberto Marino' https://orcid.org/0000-0001-9878-2941

Abstract. The search for novel materials suitable for the construction of boat structures and components has acquired paramount importance in the last few years, driven by technological developments in terms of processes and formulations. Particularly, specific types of plastics have attracted attention due to manufacturing techniques that are able to exploit the material's mechanical properties at their best while ensuring execution simplicity and precision. This is the case of High-Density Polyethylene, commonly known with its acronym HDPE and increasingly used for the construction of small workboats. The numerous positive features of HDPE for marine applications can be summed up in high flexibility, toughness and durability, anti-corrosion properties, and excellent resistance to marine growth. In addition, HDPE can be recycled in several ways for different applications and may give origin to regenerated polyethylene as well, positioning itself in a market that favours materials capable of increasing the eco-sustainability of the final products. Despite all these benefits, the quite limited knowledge and expertise related to the different formulations of the materials available on the market and the presence of several suppliers can lead to incorrect applications that might jeopardise its large-scale diffusion. Moreover, the properties of regenerated HDPE must be thoroughly investigated to understand its potential scope of use. For these reasons, almost all Ship Classification Societies are still working on proper regulations applicable to this material, with some tentative proposals from RINA and Bureau Veritas. The present paper aims to fit into this context by presenting a mechanical characterisation activity to evaluate tensile properties of both virgin and recycled materials through experimental tests. After describing the different types of HDPE employed, the authors present the testing approach and its results.

Keywords. HDPE, boatbuilding applications, tensile tests, virgin and recycled material.

[1] Corresponding Author: Serena Bertagna, Department of Engineering and Architecture, University of Trieste, sbertagna@units.it.

1. Introduction

Within the shipbuilding sector, as well as all the other industries, growing emphasis on sustainability has led to the exploration of innovative materials that fulfill performance requirements while minimizing environmental impact [1].
In particular, high-density polyethylene (HDPE) has emerged as a valuable structural material in the construction of small and workboats (Figure 1) [2]. This material is characterized by its high chemical resistance, anti-corrosion properties, and mechanical flexibility [3], along with its potential for reuse in both additive manufacturing processes and thermoforming techniques such as rotomoulding [4–6].

HDPE utilized in the marine sector can originate from either virgin polymer or recycled sources. Virgin HDPE, produced directly from petrochemical feedstocks, offers consistent quality, uniform mechanical properties, and high purity, making it suitable for applications requiring stringent performance standards [7,8]. In contrast, recycled HDPE, derived from post-consumer or post-industrial plastic waste, may exhibit greater variability in composition and properties due to previous usage and the recycling process itself [9]. This can result in differences in strength, durability, and long-term performance, which must be carefully evaluated depending on the intended application. Nonetheless, advances in recycling technologies have significantly improved the reliability of recycled HDPE, making it a viable alternative in many non-critical structural and outfitting components within the marine industry [10–12].

Given the relatively novel application of HDPE in the marine environment, a comprehensive understanding of its mechanical performance under different operational and loading conditions is essential [13]. In recognition of this emerging trend, classification societies such as Registro Navale Italiano (RINA) and the French Bureau Veritas (BV) have recently developed and updated technical regulations to address the use of HDPE in hull construction. Specifically, RINA has revised its rules for plastic, aluminum alloy, and wooden hulls [14], while BV has introduced a dedicated rule note covering hulls made from composite and HDPE materials [15].

In this context, the present study focuses on virgin and recycled HDPE and aims at evaluating their tensile properties through experimental tests performed in accordance with ISO and ASTM standards [16,17]. From the analysis of the resuts coming from the testing procedure, the authors performed a detailed comparison among the mechanical properties of both materials as given by several sources and laid the basis for a greater employment of recycled HDPE in marine and boatbuilding applications.

Figure 1. HDPE workboat (https://workboat365.com/wp-content/uploads/2023/11/6.webp).

2. Material and methods

2.1. Materials

For the purposes of the mechanical tests performed within the study, the authors focused on the properties of HDPE "single-skin" panels. They typically have a density of approximately 0.98 g/cm³, a value that ensures their lightweight nature while maintaining good mechanical strength. Commonly available thicknesses range from 1 mm to 50 mm, with different surface finishes depending on their thickness as follows:

- Panels with a thickness between 2 mm and 5 mm feature a glossy finish on both sides, making them ideal for applications requiring a smooth and easily cleanable surface.
- Sheets of 1 mm thickness, as well as those thicker than 6 mm, have one glossy and one matte side, providing greater flexibility in use depending on specific industry requirements.

Among the main applications of HDPE panels in industrial sectors, the most important are the following: chemical engineering and tank construction, industrial machinery, and aquaculture, benefiting from the material's excellent resistance to chemical aggressives, corrosion and saline environments; mechanical engineering, where HDPE is used for lightweight yet durable structural components; vacuum forming industry, where it is employed in the production of packaging and peculiar customized solutions; water treatment and wastewater management, as the material is chemically inert and does not release harmful substances into the environment. For boatbuilding applications, HDPE panels are the most commonly used commercial format due to its ease of thermoforming, cutting, and welding. The ability to process the material using various techniques allows for the production of complex and customized shapes, essential to ensure the proper hulls' curvatures deriving from hydrodynamic requisites.

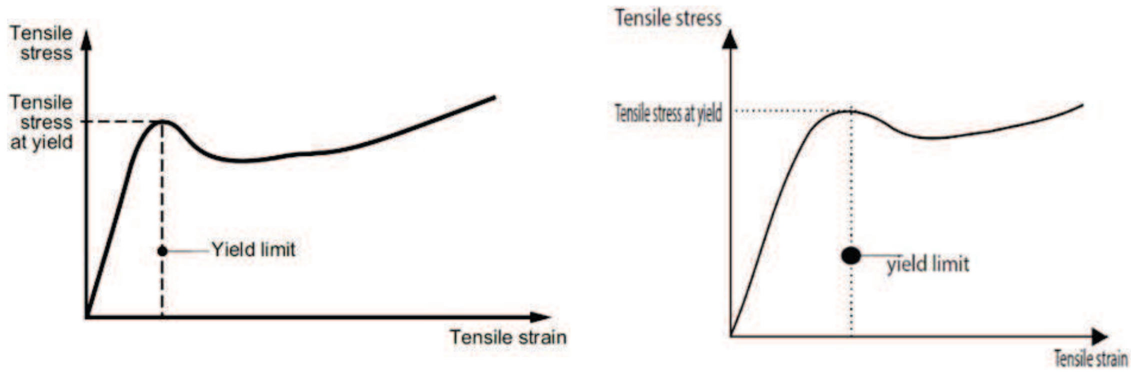
As the present research aims at investigating the tensile properties of virgin and recycled HDPE through the execution of experimental tests, two different materials were selected and employed in the manufacturing of the specimens. For both, the mechanical properties provided by the suppliers in their technical datasheets are reported in Table 1 [18,19]. These quantities will be also compared with the outcomes of the mechanical tests as part of the study, in order to confirm their validity.

As further knowledge, the authors analysed the expected mechanical properties of HDPE provided within the Rules issued by the classification societies Bureau Veritas (BV) and Registro Italiano Navale (RINA) [20]. Both regulations consider the non-linear behaviour of the material, and state that the main mechanical characteristics to be considered are to be defined by the manufacturer and/or by mechanical tests at the yield limit of the material [14,15]. The qualitative trends of HDPE stress-strain curve as given by both the Rules are reported in Figure 2. With specific reference to RINA Rules, currently the adoption of recycled HDPE is not allowed for structural applications. This aspect represents one of the driver of the present research, as the authors aims at deepening the knowledge regarding this type of material and its mechanical properties.

In terms of technical characteristics as given by the materials' suppliers, virgin HDPE shows very good welding and processing properties, good chemical resistance, high adhesion in a composite system, and is so highly suitable for tank building. On the other hand, the recycled product offers good wear and permanent UV-resistance, and good antistatic properties.

Table 1. Mechanical properties of virgin and recycled HDPE [18,19].

	Value		
	Virgin	Recycled	
General properties			
Density	0.95	>0.93	g/cm^3
Water absorption	<0.01	<0.01	%
Mechanical properties			
Yield stress	22	>20	MPa
Elongation at break	>50	-	%
Modulus of elasticity	800	>800	MPa
Shore hardness D	63	60÷63	-
Thermal properties			
Melting temperature	+135	+135	°C
Thermal conductivity	0.40	0.40	W/(m·K)
Coefficient of linear thermal expansion	+150 ÷ +230	+200	10^{-6}/K
Service temperature – long term	-50 ÷ +80	-100 / +80	°C
Service temperature – short term	+100	+100	°C
UL 94 Flammability (thickness 3-6 mm) [21]	HB	HB	-



(a) (b)

Figure 2. Stress-strain curve of HDPE as reported in Rules: (a) BV [15]; (b) RINA [14].

2.2. Methods

In compliance with the requirements established by BV and RINA, the authors adopted the testing guidelines provided by the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM). Specifically, the attention was focused on the standards ISO 527-1 “Plastics – Determination of tensile properties - Part 1: General Principles” and ASTM D638-14 “Standard Test Method for Tensile Properties of Plastics” that determine the tensile properties for plastic materials in terms of tensile strength, modulus and stress-strain relationship [16,17].

The testing procedure implies that the specimen is extended along its major longitudinal axis at a constant speed until the specimen fractures or until the stress (load) or the strain (elongation) reaches some predetermined value. During this procedure, the load sustained by the specimen and the elongation are measured. The data acquisition frequency needed for the recording of data (load, elongation) must be sufficiently high in order to meet accuracy requirements. This data acquisition depends on the following quantities:

- v: the test speed, in mm/min;
- L/L_0: the ratio between the actual length and initial reference length;
- r: the minimum resolution, in mm, of the strain signal to obtain accurate data.

The tests were carried out using an Italsigma servo-hydraulic testing machine equipped with a 25 kN load cell, calibrated according to ISO 7500-1 in Class 1. After some preliminary tests based on an actuator speed, a value equal to 10 mm/min was adopted. Furthermore, all the tests were performed in the same preferred atmosphere corresponding to a temperature equal to 23 ± 2 °C and a relative humidity of 50 ± 10%. The shape of the specimens was elaborated by the authors in accordance with the above-mentioned ISO and ASTM standards: specifically, the dog-bone geometry was adapted to the geometric constrains of the testing machine used in terms of overall length and width without altering the proportional ratios given by the standards (Figure 3). Figure 4 shows the pictures of the manufactured specimens in both virgin and recycled HDPE: from the images, the different surface finishes that characterise the two materials can be appreciated (in particular, the recycled material presents a surface slightly rigged). In terms of workability, the specimen manufacturer stated that the recycled material proved to be more challenging to process.

A set of 8 specimens were tested for each material. All the specimens were indexed with a specific alpha-numerical code representing the type of material used (virgin or recycled), the nature of load applied (tensile), the thickness t, and any unique specimen details. Letter meanings are reported in Table 2. Furthermore, each tested specimen was labelled with a number to perform a sequential count, allowing a precise collection of the results. In accordance with the proposed coding system, the specimens tested within the present research were labelled as either VT15S, for those made from virgin HDPE, or RT10S, for those made from recycled material.

Mean values ($\bar{x}$) and standard deviation values were calculated for both the tensile strength (assumed at the yield limit in accordance with the Rules) and Young modulus. For the latter, the value of the modulus, as usual, was considered equal to the slope of regression straight line of the initial stress-strain data drawn from each test. In detail, the initial stress-strain data considered were selected in order to achieve a value of the determination coefficient R^2 at least equal to 0.99.

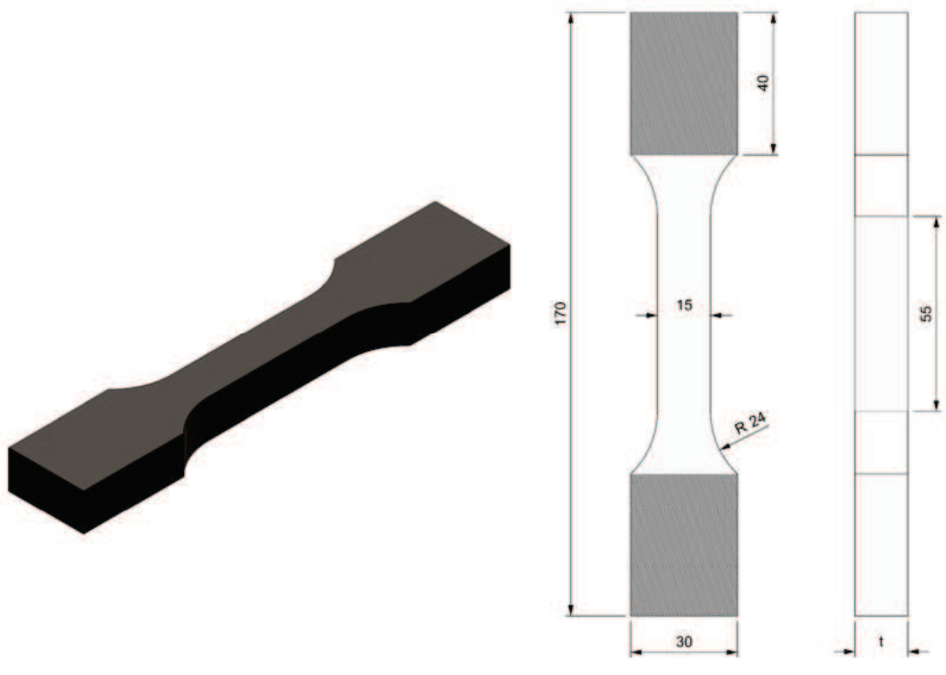
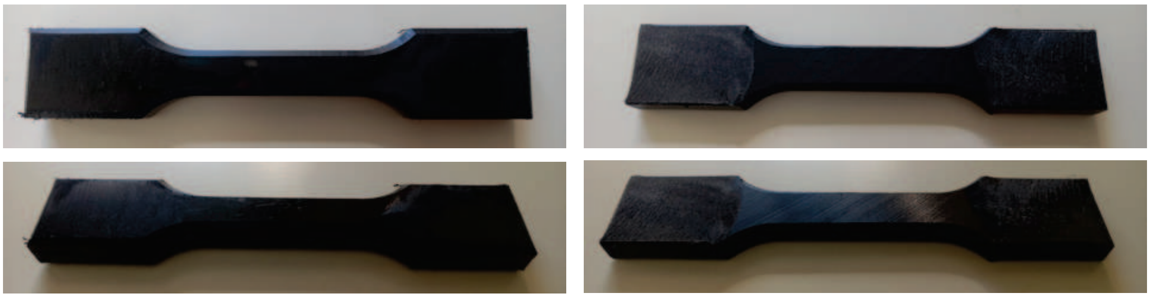


Figure 3. Dog-bone tensile test specimen.



(a) (b)

Figure 4. Dog-bone tensile test specimens: (a) virgin HDPE; (b) recycled HDPE.

Table 2 - Letter meanings of the specimens' code.

Material code	Load type	Thickness t	Details
V Virgin **R** Recycled	**T** Tensile	**15** Thickness of 15 mm **10** Thickness of 10 mm	**S** Simple dog-bone

3. Results and discussions

Eight specimens for each material (virgin or recycled HDPE) were tested. Figure 5 shows a specimen during the tensile test and the reference length L_0 adopted to evaluate the nominal strain.

For each specimen, the test results are priorly represented by the load-elongation graph, then converted into the nominal stress-strain graph through the formulae:

$$Stress\ [MPa]: \sigma = \frac{F}{A_0} \qquad\qquad Strain: \varepsilon = \frac{\Delta L}{L_0} = \frac{(L - L_0)}{L_0} \tag{1}$$

in which F [kN] is the applied load, A_0 [mm^2] is the initial cross-section area of the specimen (equal to $225\,\mathrm{mm}^2$ for VT15S and $150\,\mathrm{mm}^2$ for RT10S specimens), $\Delta L = L - L_0$ [mm] is the elongation evaluated with respect to the reference length $L_0 =\ 50\,\mathrm{mm}$.

Figures 6 and 7 represent the stress-strain graphs for virgin- and recycled-HDPE, respectively. For virgin HDPE, specimen number as 7 was not considered as some problems occurred during the testing procedure.

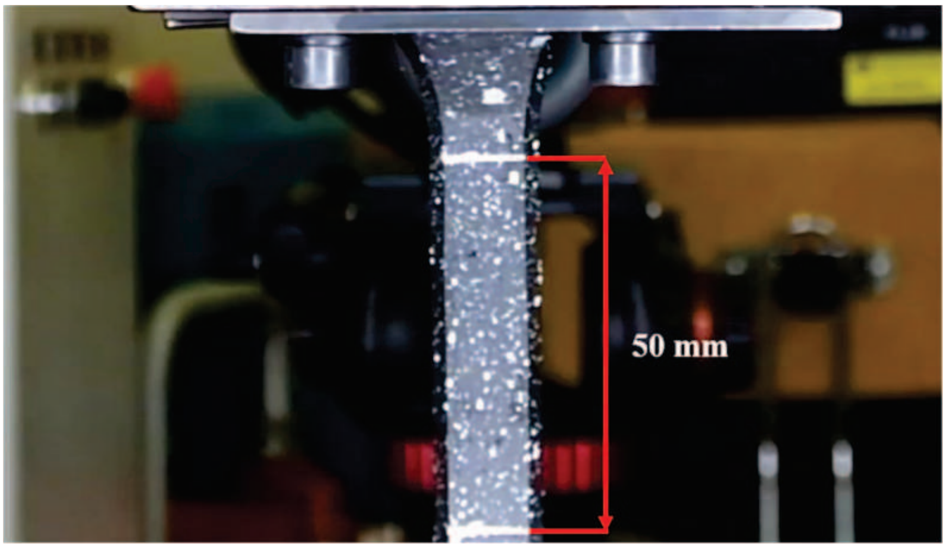


Figure 5. Reference length for the tensile tests.

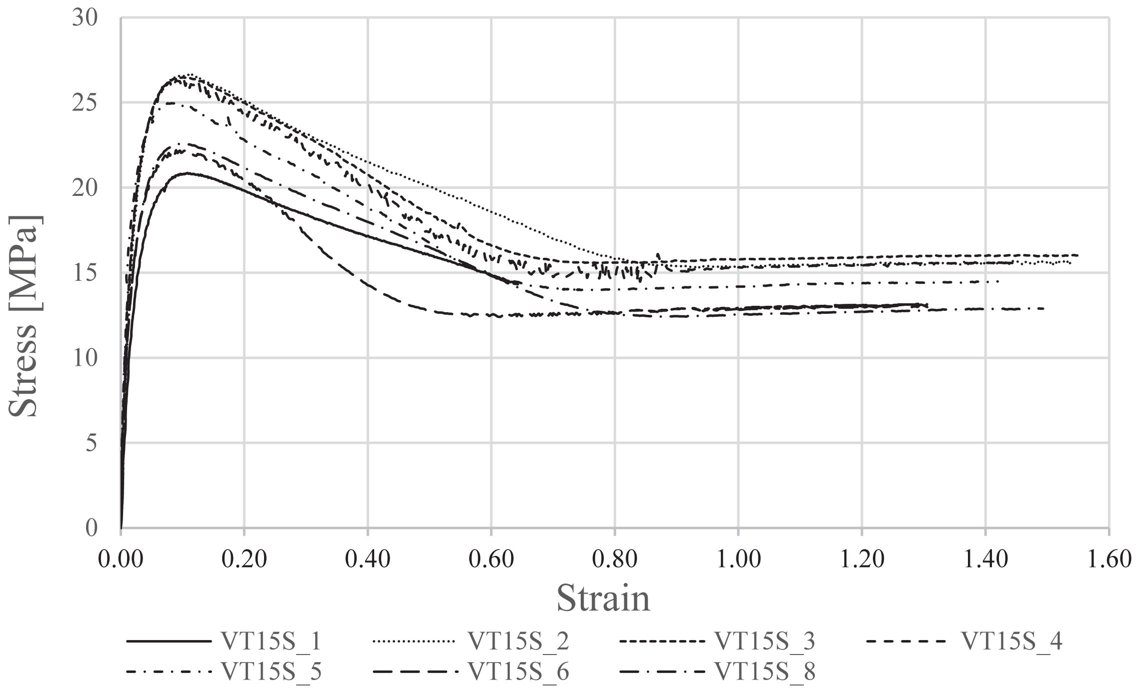


Figure 6. Stress-strain curve for virgin-HDPE specimens VT15S.

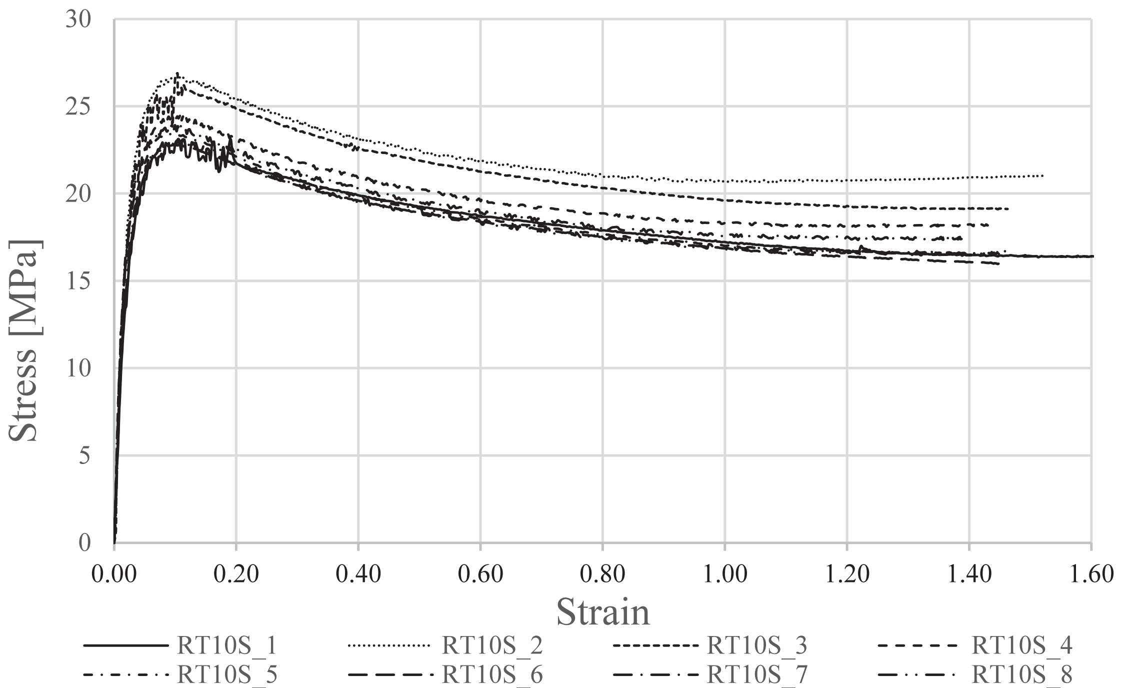


Figure 7. Stress-strain curve for recycled-HDPE specimens RT10S.

Both the types of specimens VT15S and RT10S were subjected to large permanent elongation under tensile loading and did not suffer any fracture; furthermore, the deformation was not recovered after the load was removed.

The quantitative results obtained for the specimens tested are reported in Table 3 for virgin-HDPE specimens (VT15S) and in Table 4 for recycled-HDPE specimens (RT10S). The highest values of load, and relative stress, as well as the value of Young modulus for tensile tests are shown; for stress and Young modulus, the mean values and standard deviations, along with the standard error are also provided.

By comparing the curve provided in both BV and RINA Rules reported in Figure 2 with the stress-strain curves obtained through the tests (Figure 6 and Figure 7), it is evident that the maximum tensile stress measured during the tests corresponds to the yield limit as defined by the Rules. Based on this assumption, Table 5 provides a comparison among the results obtained from the tensile tests in terms of mean values for both maximum stress and Young modulus and the values offered by both the Suppliers' technical datasheets and the Classification Societies' Rules.

From the numerical results, it is evident that the values of yield stress and Young modulus offered by both datasheets and Classification Societies are confirmed. In fact, the test results exhibit mechanical properties that surpass the values reported by the material suppliers, indicating a performance level beyond the expected specifications. Furthermore, it can be seen that there is no significant difference between the mechanical properties of the virgin and recycled HDPE. The same value of maximum tensile stress was obtained for both the types of material. The Young modulus, instead, is slightly higher for recycled HDPE. In terms of standard deviations, the small values observed for both virgin and recycled HDPE reflect a high degree of precision in the results.

Table 3. Results obtained for virgin-HDPE specimens (VT15S).

Specimen	1	2	3	4	5	6	7	Mean value	Standard deviation	Standard error
Max load [kN]	4.7	6.0	6.0	5.9	5.6	5.0	5.1	-	-	-
Max stress [MPa]	21	27	26	26	26	25	22	24.7	2.3	±0.87
Young Modulus [MPa]	908	990	937	947	1064	852	905	943	68.1	±25.8

Table 4. Results obtained for recycled-HDPE specimens (RT10S).

	1	2	3	4	5	6	7	8	Mean value	Standard deviation	Standard error
Max load [kN]	3.5	4.0	4.0	3.7	3.5	3.4	3.6	3.5	-	-	-
Max stress [MPa]	23	27	27	24	23	23	24	23	24.3	1.8	±0.62
Young Modulus [MPa]	975	966	964	992	915	930	997	922	958	31.6	±11.2

Table 5. Comparison among the test results and the values provided by technical datasheets (DS) and Rules.

	Virgin-HDPE VT15S		Recycled-HDPE RT10S		Ship Classification Rules	
	Test mean value	DS [18]	Test mean value	DS [19]	BV [15]	RINA [14]
Max stress [MPa]	24.7 ± 0.87	22	24.3±0.62	>20	24	22
Young modulus [MPa]	943 ± 25.8	800	958±11.2	>800	950	950

4. Conclusions

This study presented a comprehensive analysis of the mechanical properties of virgin and recycled high-density polyethylene (HDPE) materials, with a particular focus on their applicability in maritime contexts. By examining the regulatory frameworks provided by RINA and Bureau Veritas, alongside ISO and ASTM standards, the authors established a foundational understanding of the requirements for materials used in marine applications. Subsequently, an experimental campaign involving tensile tests on standardized dog-bone specimens was carried out to assess the mechanical responses of both virgin and recycled HDPE.

The results indicate that both virging and recycled HDPE show comparable mechanical properties in terms of tensile strength and Young modulus. Furthermore, the measured tensile values are comparable to those provided by the supplier for both virgin and recycled materials. In fact, in several tests, some values exceeded the supplier's data, contrary to the initial expectations of the experimental campaign. With respect to the data provided by Classification Society Rules, these were confirmed as well by the results coming from the mechanical tests.

The findings suggest that recycled HDPE can be considered a viable alternative in specific contexts, contributing to sustainability efforts by reducing reliance on virgin materials. Specifically, the authors aim at presenting the results obtained to the above-mentioned Classification Societies, with particular attention to RINA, and open a discussion related to the possibility of introducing recycled-sourced HDPE for the manufacturing of structural members in boatbuilding applications.

Future research should focus on evaluating the long-term performance of recycled HDPE under marine environmental conditions, including exposure to UV radiation, saltwater corrosion, and cyclic loading. Such studies will be crucial in fully validating the suitability of recycled HDPE for broader applications within the boatbuilding sector.

Acknowledgments

This study was carried out within the consortium iNEST (Interconnected Nord-Est Innovation Ecosystem) CUP J43C22000320006 funded by the European Union Next-GenerationEU (Piano Nazionale di Ripresa e Resilienza (PNRR)—Missione 4 Componente 2, Investimento 1.5–D.D. 1058 23/06/2022, ECS_00000043). This manuscript reflects only the Authors' views and opinions.

References

[1] S. Abeysinghe, C. Gunasekara, C. Bandara, K. Nguyen, R. Dissanayake, and P. Mendis, Engineering Performance of Concrete Incorporated with Recycled High-Density Polyethylene (HDPE)—A Systematic Review, *Polymers (Basel).* **13** (2021) 1885. doi:10.3390/polym13111885.

[2] M. Kafalı, A Research on Design and Production of HDPE Boat Structural Elements, *Proc. 4th Int. Nav. Archit. Marit. Symp.* (2023).

[3] M. Sánchez-Soto, A. Rossa, A.J. Sánchez, and J. Gámez-Pérez, Blends of HDPE wastes: Study of the properties, *Waste Manag.* **28** (2008) 2565–2573. doi:10.1016/j.wasman.2007.10.010.

[4] L.F. Ramos-De Valle, Principles of Polymer Processing, in: Handb. Polym. Synth. Charact. Process., Wiley, 2013: pp. 451–461. doi:10.1002/9781118480793.ch23.

[5] N. Gupta, P. Ramkumar, and V. Sangani, An approach toward augmenting materials, additives, processability and parameterization in rotational molding: a review, *Mater. Manuf. Process.* **35** (2020) 1539–1556. doi:10.1080/10426914.2020.1779934.

[6] M.N. Subramanian, Thermoforming: Processing and Technology, Wiley, 2024. https://books.google.it/books?id=kJsQEQAAQBAJ.

[7] S.M. Al-Salem, and P. Lettieri, Kinetic study of high density polyethylene (HDPE) pyrolysis, *Chem. Eng. Res. Des.* **88** (2010) 1599–1606. doi:10.1016/j.cherd.2010.03.012.

[8] P. Herrera-Franco, A. Valadez-Gonzalez, and M. Cervantes-Uc, Development and characterization of a HDPE-sand-natural fiber composite, *Compos. Part B Eng.* **28** (1997) 331–343. doi:10.1016/S1359-8368(96)00024-8.

[9] Y. Lei, Q. Wu, F. Yao, and Y. Xu, Preparation and properties of recycled HDPE/natural fiber composites, *Compos. Part A Appl. Sci. Manuf.* **38** (2007) 1664–1674. doi:10.1016/j.compositesa.2007.02.001.
[10] W. Amiruddin, and H. Yudo, STUDY ANALYSIS OF THE USE OF HDPE PLASTIC AS A SHELL ON CATAMARAN HULL, *Int. J. Adv. Res. Eng. Technol.* **11** (2020) 121–133. doi:10.34218/IJARET.11.12.2020.013.
[11] I.P. Arta Wibawa, K. Abdullah, . Sumardiono, A. Gafur, E.W. Restu Widodo, and Z. Aris Musthofa, The Analysis of Tensile Strength of High-Density Polyethylene for Shipbuilding, in: Proc. 5th Int. Conf. Appl. Sci. Technol. Eng. Sci., SCITEPRESS - Science and Technology Publications, 2022: pp. 334–336. doi:10.5220/0011769900003575.
[12] S.-G. Ryu, Y.-H. Kwon, J.-H. Ma, K.-D. Lee, and K.-H. Lee, A Study on the Structural Behavior of HDPE Vessels Considering Operational Environment and Thermo-physical Characteristics of HDPE, *J. Korean Soc. Mar. Environ. Saf.* **30** (2024) 699–708. doi:10.7837/kosomes.2024.30.6.699.
[13] P. Wibawa, A. Razzaqi, K. Abdullah, K. Wulandari, S. Sumardiono, E. Restu, and A. Gafur, Analysis of tensile and flexural strength of HDPE material joints in ship construction, *J. Appl. Eng. Sci.* **21** (2023) 668–677. doi:10.5937/jaes0-41924.
[14] Registro Italiano Navale, RES. 22/E Rules for the classification of ships with reinforced plastic, aluminium alloy or wooden hull, 2023.
[15] Bureau Veritas, NR 546 - Hull in Composite,Plywood, and High Density Polyethylene Materials, 2022. https://erules.veristar.com/dy/data/bv/pdf/546-NR_2022-11.pdf.
[16] ISO, ISO 527-1 - Plastics — Determination of tensile properties - Part 1: General Principles, (2012).
[17] American Society for Testing and Materials, ASTM D638-14 Standard Test Method for Tensile Properties of Plastics, 2016. doi:10.1520/D0638-14.1.
[18] G.B. Plast Srl, PEHD300 natural/black Technical Data Sheet, n.d.
[19] Boianoflon Srl, PEHD 3000 (f) recycled, n.d.
[20] S. Bertagna, N. Taucer Marchesi, V. Bucci, and A. Marino', On the Structural Response of Innovative Plastic Materials for Boatbuilding Applications, in: Theory Pract. Shipbuild. - Proc. 26th Symp. (SORTA 2024), Zadar, Croat. 2-5 Oct. 2024, IOS Press, 2024: pp. 1–10. doi:10.3233/PMST240024.
[21] Underwriters Laboratories, UL 94 - Tests for flammability of plastic materials for parts in devices and appliances, 2013. https://standardscatalog.ul.com/standards/en/standard_94_6.