

# Sustainable Boatbuilding: Evaluating the Feasibility of Recycled HDPE as a Structural Material

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**Abstract.** The boatbuilding industry is increasingly shifting toward environmentally sustainable materials. High-Density Polyethylene (HDPE) has become a highly viable alternative material because of its outstanding chemical and impact resistance, as well as its low-carbon manufacturing process. This makes it a practical substitute for traditional materials such as wood and fiberglass-reinforced plastic for constructing small vessels. However, the substantial generation of HDPE waste poses a significant challenge in maritime manufacturing. In response, this study presents a solution for the plastic waste produced during boatbuilding by recycling HDPE sourced from the Non-Metal Workshop at the Shipbuilding Institute of Polytechnic Surabaya (PPNS) and evaluating its suitability for use as a manhole cover. The compliance of recycled HDPE (r-HDPE) as a structural material was assessed based on the BKI (Biro Klasifikasi Indonesia) Standards for Thermoplastic Vessels, Volume 2, 2023 Edition. The mechanical testing of r-HDPE showed a tensile strength of 24.50 MPa and a flexural strength of 41.93 MPa. Finite Element Analysis using ANSYS showed that increasing the cover thickness from 6.5 mm to 12.5 mm significantly reduced deformation and stress, resulting in a safety factor of 8.29 under a maximum load of 1470 N. Therefore, 12.5 mm thick r-HDPE is structurally viable and supports sustainable shipbuilding by reducing waste.

Keywords: Ansys, Bending Test, HDPE, Manhole, Tensile Test.

## 1 Introduction

Small vessels measuring up to 30 meters in length are still widely used in Indonesian waters for many purposes, including fishing vessels, cargo and passenger vessels for inter-island crossings, water ambulances, patrol boats, and others. However, the availability of materials for boatbuilding poses a significant challenge to the sustainability of these small vessels in Indonesia. While wood remains the primary material, sourcing high-quality wood that meets

the necessary dimensions for construction is becoming increasingly difficult [1]. Additionally, deforestation due to wood exploitation is widely recognized as a contributor to global warming [2]. Conversely, Fiber-Reinforced Polymer (FRP), which has been introduced more than a decade ago as an alternative material, presents its own environmental challenges [1]. FRP presents considerable recycling difficulties, and its degradation results in microplastics that are harmful to aquatic ecosystems. The production processes for FRP boats also involve health risks, as toxic substances are used during manufacturing. In Indonesia, the majority of FRP boat production employs the hand lay-up method in open-air workshops, where operators are often provided with inadequate personal protective equipment. Furthermore, waste from FRP boatyards is poorly managed, despite its classification as hazardous waste. Currently, there is no effective solution for handling FRP waste in shipyards. It is usually sent to licensed B3 (hazardous and toxic) waste handlers, yet in many facilities throughout Indonesia, this waste is left to accumulate or is burned openly.

Nowadays, High-Density Polyethylene (HDPE) is increasingly employed as an alternative in small vessel construction, influenced by environmental concerns associated with the use of wood and FRP [3]. Patrol vessels within the Indonesian National Armed Forces (TNI) have started utilizing HDPE, and fishing vessels in various regions are also beginning to adopt HDPE material. This shift is due to HDPE's outstanding properties, which include remarkable impact strength, resistance to chemicals and corrosion, and a low-carbon emission production process [4]. Furthermore, HDPE provides an environmentally friendly material because its thermoplastic properties allow repeated melting and remolding, thereby facilitating recycling several times [5]. Plastic recycling also plays a crucial role in environmental preservation, primarily by reducing the consumption of fossil fuels required to make virgin plastic materials [6]. Moreover, recycling HDPE waste significantly reduces the accumulation of non-biodegradable plastics and subsequently offers a practical approach to addressing environmental challenges.

A significant challenge is that recycled HDPE (r-HDPE) often exhibits reduced mechanical properties and lower chemical stability than its virgin state (v-HDPE). This degradation is attributed to the service life, natural aging, and thermo-mechanical stresses during recycling [7]. A previous study showed that the mechanical performance of r-HDPE decline after several cycles of mechanical recycling. [8]. Despite the limitation, r-HDPE remains a promising alternative for small vessel applications, especially when its mechanical properties approximate those of virgin HDPE [9]. One potential application of r-HDPE in small vessels is for manufacturing manhole covers. These covers serve as access points for fuel and ballast tanks, as well as various ship compartments. Additionally, they enable crew members to perform maintenance, inspections, and repairs.

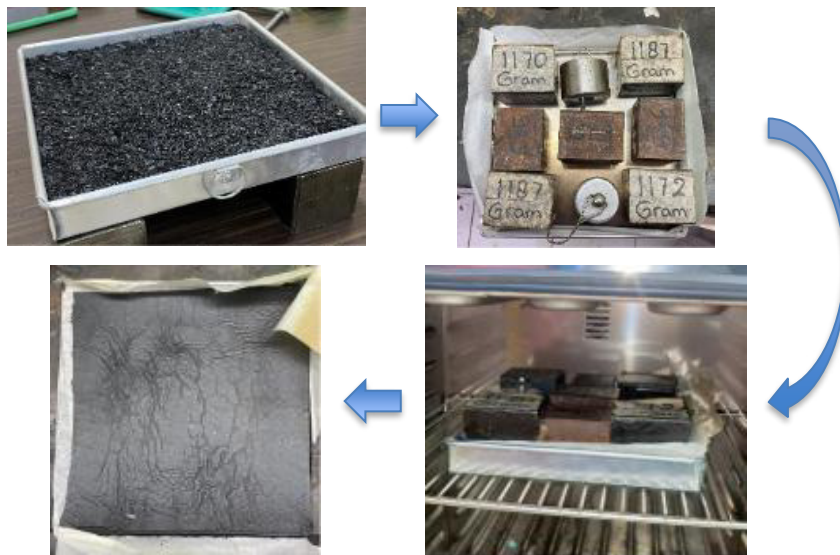
This research aims to assess the feasibility of recycling HDPE waste into manhole covers for a small boat. Mechanical testing of r-HDPE, including tensile and flexural testing, was conducted and compared with the BKI (Biro Klasifikasi Indonesia) standard (2023). Finite element analysis was also conducted out to assess the distribution of stress and deformation of the r-HDPE manhole cover under applied loading conditions.

## **2. Materials and Methods**

### **2.1 Manufacturing of HDPE sheets**

The HDPE waste used in this research was sourced from the waste produced during ship fabrication at the Non-Metal Workshop of the Shipbuilding Institute of Polytechnic Surabaya. Virgin HDPE sheets (v-HDPE) with a thickness of 6 mm originated from Agru. The recycled HDPE (r-HDPE) was first crushed into smaller pieces to facilitate the melting and compression process, then washed to eliminate any remaining contaminants, and

subsequently dried overnight. A total of 250 g of waste HDPE flakes was placed into an aluminum mold to produce r-HDPE sheets with dimensions of 200 × 200 × 30 mm. The fabrication process for the r-HDPE sheet is illustrated in Figure 1. The r-HDPE sheet was fabricated using a manual hot compression molding process under a load of 88.2 N at a temperature of 200 °C for 15 minutes, utilizing a Memmert Laboratory Oven located in the Metallurgy Laboratory of the Department Mechanical Engineering at Sepuluh Nopember Institute of Technology. Following the melting process, the pressure was continuously maintained during cooling to ensure solidification and to prevent distortion, resulting in a solid structure of r-HDPE.



**Fig 1.** Fabrication process of the r-HDPE sheet

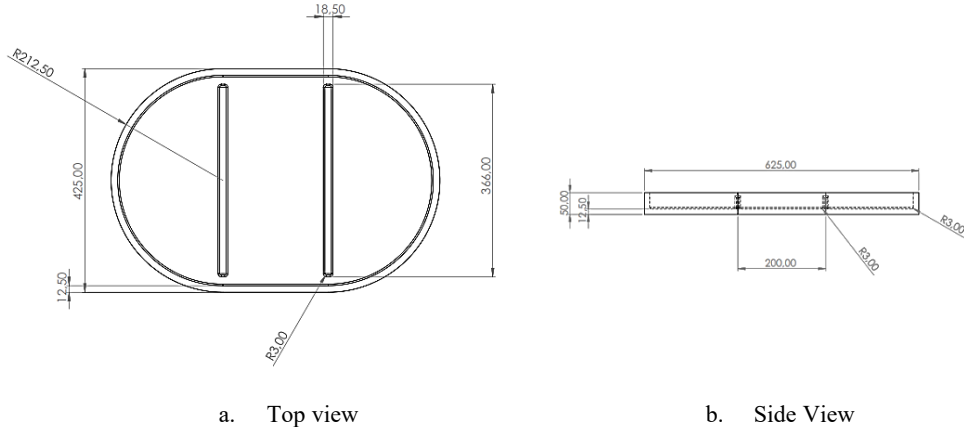
## 2.2 Mechanical Testing

The r-HDPE and v-HDPE sheets were respectively cut and prepared for mechanical properties testing in accordance with the ASTM D638 standard. The specimen dimensions were classified as Type I for the r-HDPE material and Type III for the v-HDPE material. The tensile test was conducted to measure the yield strength (MPa), elongation (%), and modulus of elasticity (MPa) for both r-HDPE and v-HDPE materials. The specimens were evaluated using a Universal Testing Machine in the Mechanical Engineering Department Laboratory at Sepuluh Nopember Institute of Technology, Surabaya. Additionally, flexural (bending) testing was performed in accordance with ISO 178, using the three-point bending method to measure flexural strength (MPa) for both r-HDPE and v-HDPE.

## 2.3 Manhole Structural Analysis

The structural simulation was conducted using ANSYS software on a manhole model measuring 600 mm × 400 mm. Figure 2 shows the geometry of the manhole cover, with all dimensions specified in millimeters. The thickness of the manhole cover was varied to 6.5 mm, 9.5 mm, and 12.5 mm, in accordance with the recommended range specified in ASTM

F-1144. The 3D model was created as a solid body, with the base of the manhole cover representing the section attached to the ship’s deck and defined as a fixed support.



**Fig 2.** Geometry of the manhole cover

The properties of r-HDPE were determined through experimental mechanical tests and were modeled as homogeneous, isotropic, and linear elastic materials. Key parameters included an elastic modulus of 347 MPa, a yield strength of 24.502 MPa, a Poisson's ratio of 0.35, and a density of 0.96 g/cm<sup>3</sup>, all of which were incorporated into the ANSYS material library.

Boundary conditions were applied to simulate the attachment of the cover to the deck by defining the base region of the manhole cover as a fixed support. A uniformly distributed load was applied to the top surface of the cover at two levels, 980 N and 1470 N, corresponding to the weight of one to two individuals.

A grid independence test (GIT) was performed to ensure that the finite element results are independent of the selected mesh configuration. The mesh was systematically refined by decreasing the overall element size from 10 mm to 1 mm. As a result, the 2 mm mesh with 515,704 elements, as presented in Table 2, was selected as the optimal choice for all subsequent analyses. This selection ensured computational efficiency while maintaining result accuracy within the convergence criterion of a change of less than 0.5%.

**Table 1.** Grid Independence Test

No.	Mesh size (mm)	Elements	Max deformation (mm)	Error (%)
1	10	16,161	15.338	—
2	9	18,829	15.414	0.49
3	8	24,064	15.606	1.23
4	7	31,556	15.881	1.73
5	6	43,867	15.926	0.28
6	5	70,290	16.022	0.60
7	4	99,962	16.095	0.45
8	3	201,689	16.173	0.48
<b>9</b>	<b>2</b>	<b>515,704</b>	<b>16.225</b>	<b>0.32</b>
10	1	2,268,841	16.261	0.22

The primary simulation outputs were equivalent (Von Mises) stress and total deformation, which evaluate stress concentration zones and maximum deflection under human loading. These parameters provide a direct assessment of structural integrity by comparing peak stresses with material limits and deflections against acceptable serviceability

thresholds. The safety factor (SF) is the key metric for determining structural adequacy, as shown in Equation 1.

$$SF = \frac{\sigma_y}{\sigma_{max}} \tag{1}$$

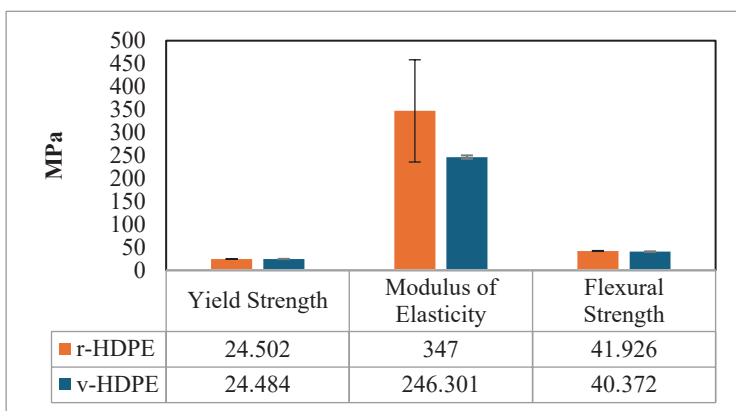
### 3. Result and Discussion

#### 3.1 Mechanical Properties Evaluation

Tensile and bending tests were used to assess the mechanical properties of r-HDPE and v-HDPE samples. The tensile tests provided values for tensile strength, elongation, and elastic modulus, which are detailed in Table 2. Meanwhile, the bending tests offered data on flexural strength, reported in units of MPa or N/mm<sup>2</sup>.

**Table 2.** Tensile and Bending Test Results

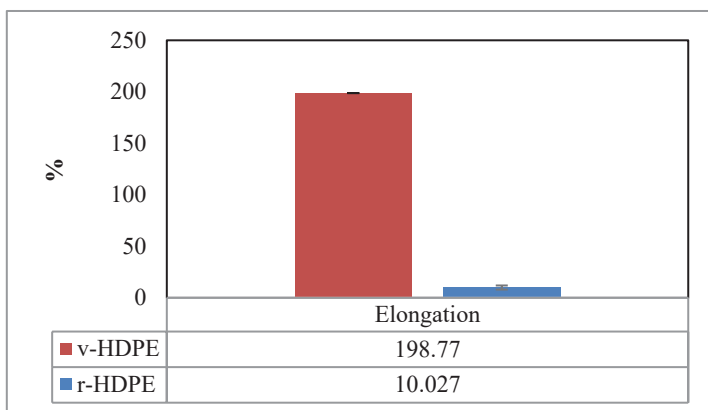
Materials	Yield Strength (MPa)	Modulus of Elasticity (MPa)	Flexural Strength (MPa)	Elongation (%)
r-HDPE	24.502	347	41.926	10.027
v-HDPE	24.484	246.301	40.372	198.770



**Fig 3.** The yield strength, modulus of elasticity, and flexural strength of r-HDPE and v-HDPE

According to Fig 3, the yield strength of r-HDPE (24.502 MPa) and v-HDPE (24.484 MPa) is nearly identical. This similarity can be attributed to an effective recycling process, which allows recycled HDPE to maintain its mechanical properties. The recycling process can alter the crystallinity of materials, occasionally leading to a slight increase in their tensile strength, but might also lead to brittleness as the recycling process continues [10] This behavior aligns with findings from research conducted by Chrysafi et al. [11], in which the r-HDPE exhibits higher tensile strength than v-HDPE. Additionally, they also observed that r-HDPE tends to become more brittle compared to v-HDPE following the recycling process.

The most notable difference was observed in elongation at break, as illustrated in Fig 4. The v-HDPE demonstrated a very high elongation of 198.770%, indicating its ductility. In contrast, the r-HDPE exhibited significantly lower elongation (10.027%), indicating greater brittleness. This reduction in ductility properties was likely due to the recycling effect, where the heating process can break polymer chains and alter the crystallinity, thereby affecting brittleness [10].



**Fig 4.** Elongation at break

The r-HDPE demonstrates a higher elastic modulus and flexural strength, with the values of 347 MPa and 41.926 MPa, respectively, in comparison to v-HDPE, which has values of 246.301 MPa and 40.372 MPa. The increased modulus of elasticity of r-HDPE indicates that the material is stiffer and more rigid. The increased rigidity may also result from the recycling process, which could alter the crystalline structure.

According to the BKI standard [12], "Guidelines for Thermoplastic Vessels, Volume 2, 2023 Edition," the minimum tensile yield strength required for HDPE to qualify as a structural material for the hull is 17 N/mm<sup>2</sup> or MPa. The r-HDPE achieved a tensile yield strength of 24.502 MPa, as seen in Table 3, surpassing the minimum standard by 44.13%. It indicates that the r-HDPE possesses adequate strength for these applications. For tensile elongation at break, the BKI standard allows a wide range from 10% to 1500%. The v-HDPE exhibits a higher elongation at 198.770%, demonstrating excellent ductility. In contrast, the r-HDPE exhibits an elongation of 10.027%, meeting the minimum required level standard. Additionally, the flexural strength also shows a similar trend, with a value of 41.926 MPa for r-HDPE, slightly above the minimum requirement of 40 MPa. This implies that r-HDPE is more brittle and has a lower capacity to stretch before fracturing. It aligns with its lower elongation, indicating a less flexible material structure.

Table 3. Mechanical Properties of r-HDPE and HDPE (BKI)

No	Properties	Unit	r-HDPE	HDPE (BKI)
1.	Tensile Yield Strength	MPa	24.502	17
2.	Tensile elongation at break	%	10.027	10 to 1500%
3.	Flexural Strength	MPa	41.926	40

### 3.2 Manhole Structural Analysis

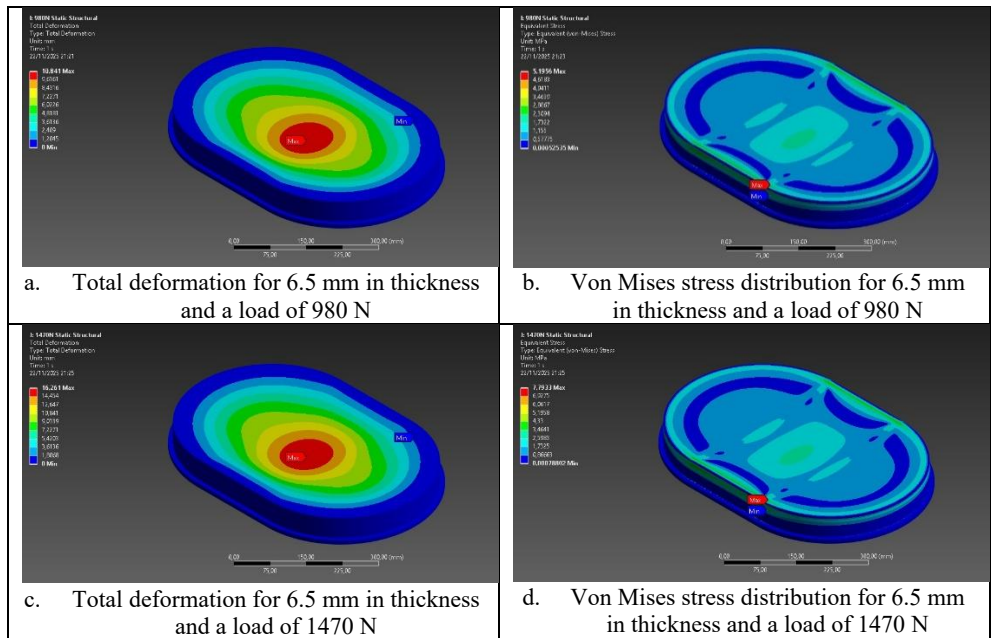
The finite element method (FEM) simulation was performed using ANSYS software. The analysis was performed on the manhole design shown in Figure 2 by applying load variations of 980 N and 1470 N to different manhole thicknesses of 6.5 mm, 9.5 mm, and 12.5 mm. A FEM simulation within ANSYS Workbench was performed to assess the mechanical behavior of a manhole composed of r-HDPE under tensile loading. The main goals of this simulation were to assess the distribution of Von Mises stress, total deformation, stress concentration areas, and the material's safe working limit prior to failure. The material properties of r-HDPE obtained through tensile testing were used as simulation parameters. These included an elastic modulus of 347 MPa, a yield strength of 24.502 MPa, a Poisson's ratio of 0.35, and a density of 0.96 g/cm<sup>3</sup>. The results of the ANSYS simulation are presented

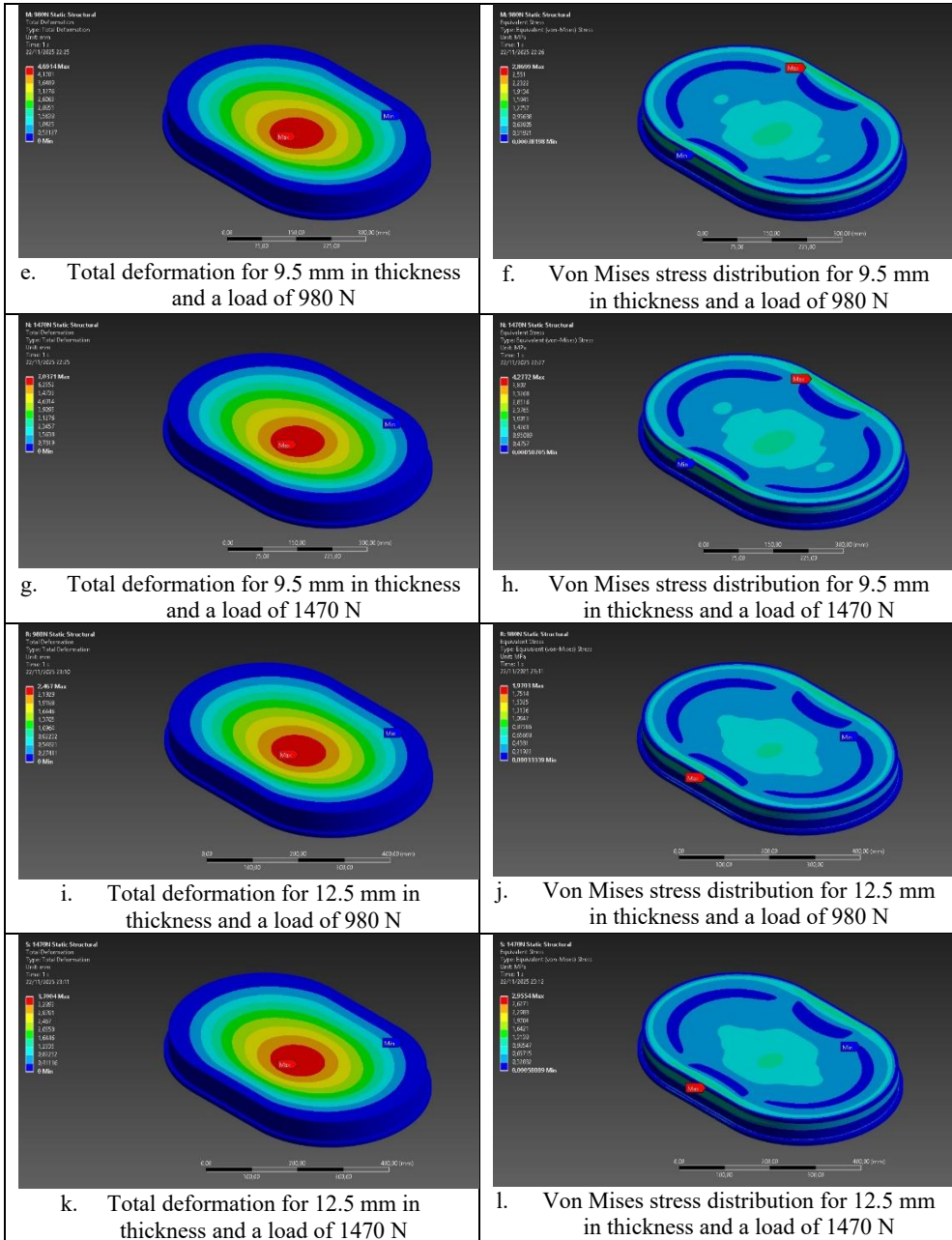
in Table 4 and Figure 3. The finite element analysis (FEA) provides a structural representation of the r-HDPE manhole under variations of thickness and applied loading. The primary analysis parameters include total deformation contours and equivalent Von Mises stress, which serve as the basis for evaluating deformation characteristics and the resulting stress distribution from human-induced loading.

Table 4. ANSYS Simulation Results on r-HDPE Manhole Cover

Thickness (mm)	Load (N)	Maximum Total Deformation (mm)	Minimum Equivalent Stress (Von Mises) (MPa)	Maximum Equivalent Stress (Von Mises) (MPa)
6.5	980	10.841	$5.254 \times 10^{-4}$	5.195
9.5		4.691	$3.820 \times 10^{-4}$	2.869
12.5		2.467	$3.334 \times 10^{-4}$	1.970
6.5	1470	16.261	$7.880 \times 10^{-4}$	7.793
9.5		7.037	$5.071 \times 10^{-4}$	4.277
12.5		3.700	$5.001 \times 10^{-4}$	2.955

The simulation results indicate that increasing the recycled HDPE plate thickness from 6.5 mm to 9.5 mm and 12.5 mm results in a significant reduction in the equivalent (Von Mises) stress under all loading conditions tested. This phenomenon suggests that increasing plate thickness improves stress distribution and reduces stress concentration in critical areas. Previous studies have reported that increasing the cross-sectional dimensions, particularly thickness, can enhance the mechanical stability of recycled plastic panels and reduce stress responses to external loads [13]. Furthermore, other research has highlighted that thicker r-HDPE sections provide better structural performance [14]. Based on the simulation results, the 12.5 mm thick r-HDPE plate configuration is considered the most effective and suitable option for use as a manhole cover plate within the loading range of 980 N to 1470 N.





**Fig 5.** Total Deformation and Von Mises Stress Distribution of r-HDPE Manhole Cover

The analysis of deformation and stress distribution demonstrates a significant influence of plate thickness on structural performance. In the case of a 6.5 mm thick plate, maximum deformation occurs at the load application area, with contour colors transitioning from dark blue (demonstrating minimum deformation) to red (demonstrating maximum deformation), as illustrated in Figures 5a and 5c. This indicates considerable deformation values, particularly under a 1470 N load. The contour pattern displays a color gradient from dark blue in the support area, representing the minimum deformation, progressing to yellow and red around the loading point, where the maximum deformation reaches 16.261 mm. This

distribution pattern is consistent with thin-plate theory, which suggests that deflection is most significant at the center of the span and approaches zero at the supports. Additionally, the Von Mises stress is concentrated around the support region and the geometric transition zones, as depicted in Fig 5b and 5d. Notably, the maximum stress is greater under the 1470 N load compared to the 980 N load, measuring at 7.793 MPa. Red-to-orange stress contours represent these critical areas, while the remaining regions fall within the blue-to-green range. These simulation results are consistent with the theory of geometric discontinuities and plate behavior under bending conditions, which states that maximum stresses typically occur in the regions of direct contact .

As the thickness increased to 9.5 mm, deformation decreased substantially, as evidenced by predominantly blue-green contour colors (Fig 5e). This indicates lower deflection and a more uniform distribution of deformation, with the maximum deformation measuring 7.097 mm (1470 N). The Von Mises stress also decreases, and the stress contour pattern is predominantly represented by blue-to-green colors (Fig 5d and 5f), indicating a more uniform stress distribution.

For a thickness of 12.5 mm, deformation is minimized, with contour colors dominated by blue-green (Fig 5i and 5k). This configuration demonstrates significantly improved load distribution and a notable increase in plate stiffness. Fig 5k shows a significant reduction in deformation to 3.700 mm, with contours predominantly colored blue to green, while yellow appears only locally around the loading point. This condition aligns with principles of structural mechanics, where increasing the plate thickness results in a cubic enhancement in flexural stiffness [15]. Increasing the thickness of panels made from recycled plastic effectively reduces deflection under loading [13]. Additionally, the maximum Von Mises stress diminishes in comparison to other configurations, reaching a lower maximum value of 2.955 MPa. This indicates a safe and stable state under operational loads. This stress reduction suggests that increasing the thickness enhances the load distribution area and reduces local stress concentration. Panels made from recycled plastic with greater thickness demonstrate improved structural performance in terms of stress distribution [13].

**Table 5.** Safety Factor of r-HDPE Manhole Covers

Thickness (mm)	Load (N)	Maximum Stress (MPa)	Safety Factor	Remarks
6.5	980	5.1956	4.716	Structurally safe in terms of stress
9.5		2.8699	8.538	Safe, suitable for light loading conditions
<b>12.5</b>		<b>1.9703</b>	<b>12.436</b>	<b>Highly safe, recommended configuration</b>
6.5	1470	7.7933	3.144	Safe, but at the lower limit of acceptability, less optimal
9.5		4.2772	5.729	Safe under moderate loading
<b>12.5</b>		<b>2.9554</b>	<b>8.291</b>	<b>Safest configuration, recommended design</b>

The safety factor calculation results, presented in Table 5, indicate that all plate thickness variations made from r-HDPE exhibit safety factor values greater than 3. Under the highest loading condition of 1470 N, the lowest SF value is observed at a thickness of 6.5 mm, with a value of 3.14. An SF value of  $\geq 2$  is considered to meet the structural safety requirements for both non-structural and semi-structural components under static loading conditions [15]. From a material strength perspective, all tested plates are considered safe against failure due to stress. It has been demonstrated that increasing the plate thickness enhances the safety factor. For example, under a load of 980 N, the safety factor increases from 4.72 to 12.44 as

the thickness rises from 6.5 mm to 12.5 mm. A similar tendency is observed under the 1470 N load, where the SF increases from 3.14 to 8.29 with the same thickness variation. This observation aligns with the theory of mechanics of materials, which states that increasing the cross-sectional dimensions enhances stiffness and reduces local stress distribution [13]. The mechanical performance of r-HDPE improves when applied in configurations with greater cross-sectional thickness [14]. Recycled plastic panels can perform optimally when the panel thickness is sufficiently designed to ensure stress stability under light to moderate loading conditions [13]. Consequently, although the 6.5 mm thickness theoretically meets the safety factor requirement ( $SF > 2$ ), the 12.5 mm thickness is optimal because it yields the highest SF, providing enhanced safety and improved design reliability to accommodate variations in operational loads and potential long-term material degradation.

#### 4. Conclusion

The results of this study suggest that recycled HDPE (r-HDPE) has strong potential as a suitable material for manhole covers in small vessels. Mechanical testing revealed that r-HDPE exhibits superior tensile strength, elastic modulus, and flexural strength compared to virgin HDPE, highlighting the increased rigidity resulting from the recycling process. Although a significant reduction in elongation was observed, indicating greater brittleness, r-HDPE demonstrated a yield strength of 24.502 MPa, exceeding the minimum requirement specified by BKI (17 MPa), thus confirming its appropriateness as a lightweight structural material. Additionally, the flexural strength of virgin HDPE was 40.372 MPa, whereas that of r-HDPE was 41.926 MPa, slightly above the minimum threshold of 40 MPa. This indicates that r-HDPE is more brittle and has a lower capacity for stretching before fracture, as evidenced by its lower elongation of 10.027%, suggesting a less flexible material structure.

The FEM simulation performed with ANSYS showed that increasing the plate thickness from 6.5 mm to 12.5 mm significantly decreases both deformation and Von Mises stress, while simultaneously increasing the safety factor from 3.14 to 8.29 under a maximum load of 1470 N. Although all thickness variations were considered safe ( $SF > 2$ ), the 12.5 mm configuration was identified as the most optimal design. The use of r-HDPE contributes to sustainable shipbuilding practices by reducing non-biodegradable plastic waste generated during construction and encouraging the use of environmentally friendly materials within the maritime sector. For future studies, it is advisable to evaluate the long-term performance of r-HDPE in marine environments, analyze its behavior under cyclic dynamic loads, and explore potential enhancements to its structural properties through the addition of fillers or hybrid composite configurations.

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