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Original research article

Epoxy/unsaturated polyester blends via post-curing process for marine applications

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ABSTRACT

Epoxy resins and unsaturated polyester resins are widely used thermosetting polymers with applications in construction, electronics, and maritime industries. However, their respective limitations, such as brittleness in epoxy and reduced mechanical strength in unsaturated polyester, hinder their broader utilization. To address these challenges, blending the two polymers offers a promising approach to enhance their performance. This study investigates the mechanical and thermal properties of epoxy/unsaturated polyester blends enhanced through a post-curing process with stepwise temperature increases. The blends were characterized using FTIR, tensile, impact, and hardness tests in accordance with ASTM standards. Results demonstrate a synergy between the two polymers, with certain compositions (e.g., 90% epoxy/10% unsaturated polyester) achieving improved tensile strength, flexibility, and impact resistance. The highest tensile strength (54.45 N/mm²) was recorded in blends with > 50% unsaturated polyester, while optimal impact toughness (0.1438 J/mm²) was achieved with 90% epoxy and 10% unsaturated polyester. FTIR analysis revealed specific interactions between functional groups that contribute to the improved properties. These findings highlight the potential of epoxy/unsaturated polyester blends for demanding industrial applications, particularly in marine environments requiring high thermal stability and mechanical performance.

1. Introduction

Epoxy and unsaturated polyester resins are the most widely used thermosetting polymers in various industrial applications, including electronics, construction, and maritime [1]–[4]. Maritime structures and components are constantly subjected to harsh operational environments, including prolonged exposure to moisture, saline water,

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temperature fluctuations, and mechanical stress from wave impacts and dynamic loads [5]. These conditions pose significant challenges, such as corrosion, material degradation, delamination, and fatigue failure. Consequently, materials used in marine applications must exhibit superior mechanical strength, chemical resistance, and thermal stability to ensure durability and long-term performance [6], [7]. Overcoming these challenges requires developing advanced polymer systems or blends with optimized properties tailored specifically for maritime conditions.

In recent years, significant research has focused on improving the toughness of epoxy resins without compromising thermal stability or abrasion resistance [8]. Many existing polymeric materials have limitations in terms of thermal stability and mechanical properties. Although previous studies have shown improved properties through modification, there remains a need for better materials to meet the higher demands of industrial applications [8]–[10]. By combining several polymers with unique properties into a single component, polymer blends can offer superior properties compared to the base materials [11]. Epoxy resins are often used in applications requiring high strength and environmental resistance, but their brittle nature can be a limitation. Blending with unsaturated polyester (UP) can reduce brittleness, although it may compromise some mechanical properties [12], [13]. Epoxy/unsaturated polyester blended polymers are used to improve mechanical properties and heat resistance [14]–[16].

Some polymer blends, such as bio-phenolic/epoxy blends with 20% bio-phenolic by weight, can increase tensile strength, flexural strength, and impact strength [17], [18]. Polymer blend research has become a key focus of research trends. Many studies have explored polymer blends for various purposes, including improving thermal stability, mechanical properties, and chemical resistance. With enhanced properties, epoxy/UP blends have a wide range of potential applications in the maritime industry, such as manufacturing components that require resistance to corrosion, moisture, and high mechanical loads [12], [19].

The optimized mechanical and thermal properties of epoxy/unsaturated polyester blends offer significant advantages for maritime applications. In harsh marine environments, materials are frequently exposed to moisture, salt corrosion, and mechanical fatigue due to wave and load impacts. The enhanced impact resistance and tensile strength of these blends ensure structural durability, while improved thermal stability supports performance under fluctuating temperatures [20], [21]. These properties make the blends suitable for boat hull reinforcements, marine coatings, and structural components in shipbuilding, where long-term reliability and resistance to degradation are critical [22], [23].

To better understand the structure–property relationship, Fourier-transform infrared spectroscopy (FTIR) analysis plays a critical role in identifying functional group interactions that influence polymer network formation. The degree of cross-linking, hydrogen bonding, and esterification or amine-epoxy reactions can be observed through characteristic peaks in FTIR spectra. These chemical interactions govern the stiffness, flexibility, and impact behavior of the blend. For instance, strong amine-epoxy linkages may enhance hardness but reduce ductility, while ester-rich regions from unsaturated polyester may improve elongation and tensile strength [24]–[26]. Therefore, correlating FTIR data with mechanical performance provides crucial insights into how chemical structure affects material behavior under stress, particularly in maritime environments where both thermal and mechanical integrity are essential.

Although much research has been conducted on polymer blends, the use of post-curing temperature stages has not been extensively explored. Post-curing can enhance the mechanical and flame-retardant properties of epoxy and unsaturated polyester blends. By optimizing curing conditions, such as temperature and time, polymer blends can achieve a better balance between mechanical and flame-retardant performance [1], [27], [28]. Based on this, the researcher proposes blending epoxy and unsaturated polyester and improving their properties through a post-curing method with various temperature stages.

2. Material and method

2.1. Materials

Nippon Paint epoxy resin and hardener were obtained from Nipsea Paint and Chemical, Jakarta, Indonesia. Yukalac 157 BQTN-EX polyester resin was obtained from Justus Kimiaraya, East Java, Indonesia. Methyl Ethyl Ketone Peroxide (MEKP) catalyst was obtained from Justus Kimiaraya, East Java, Indonesia. Table 1, Table 2, and Table 3 show the properties of epoxy glue, unsaturated polyester, and MEKP. Whereas Fig. 1 shows the strcuture of the coressponding materials.

Table 1
Properties of Nippon paint epoxy glue

Paint type	Epoxy
Color	Transparent
View	Matt
Solid volume	98.5% w/w (mixed)
Specific gravity (SG)	1.00 ± 0.05 kg/L
Theoretical spreadability	6.5 – 9.5 m^2/kg/layer

Table 2
Yukalac 157 BQTN-EX unsaturated polyester resin properties

Properties	Value
Viscosity (cP, 25°C)	400 – 600
Density (gr/cm^3)	1.1 – 1.2
Gel Time (minutes, with MEKP catalyst)	10 – 20
Color	Transparent to light yellow
Styrene Content (%)	~35–40
Flash Point, °C	< 32
Volatile content (%)	< 35

Table 3
MEKP catalyst properties

Properties	Value
Shape	Transparent Liquid
Color	Colorless to yellowish
Smell	Sharp, ketone-like
Density (gr/cm^3)	1.17 – 1.19 (at 25°C)
Viscosity (cP)	20 – 30 (at 20°C)
Flash Point, °C	< 60

Table 4
Formulation and labelling of each sample

Label	Epoxy resin (%)	Unsaturated polyester resin (%)
Epo-100	100	0
Epo-90	90	10
Epo-80	80	20
Epo-70	70	30
Epo-60	60	40
Epo-0	0	100

2.2. Blend polymer manufacturing

The epoxy resin was stirred manually using a small electric drill at approximately 300 rpm for 30 seconds while the unsaturated polyester resin was slowly added to prevent clumping. After the initial homogenization, the epoxy hardener (60:40 weight ratio to epoxy) and MEKP catalyst (1 wt% to UP) were added sequentially, followed by further mixing for 20 seconds at the same speed. The resulting mixture was poured into silicone rubber molds (150 mm × 150 mm × 10 mm) that had been coated with mold release agent to facilitate demolding. Curing was carried out at room temperature (27 ± 2°C) for 24 hours. Post-curing was performed in a laboratory oven with staged heating: 50°C for 2 hours, followed by 70°C for 1 hour, and 100°C for 1 hour. After the heating stages, specimens were allowed to cool naturally inside the oven (turned off) for 3 hours until room temperature was reached. The heating ramp rate was not controlled and followed the oven's standard heating profile. The Blend Polymer formulation is shown in Table 4.

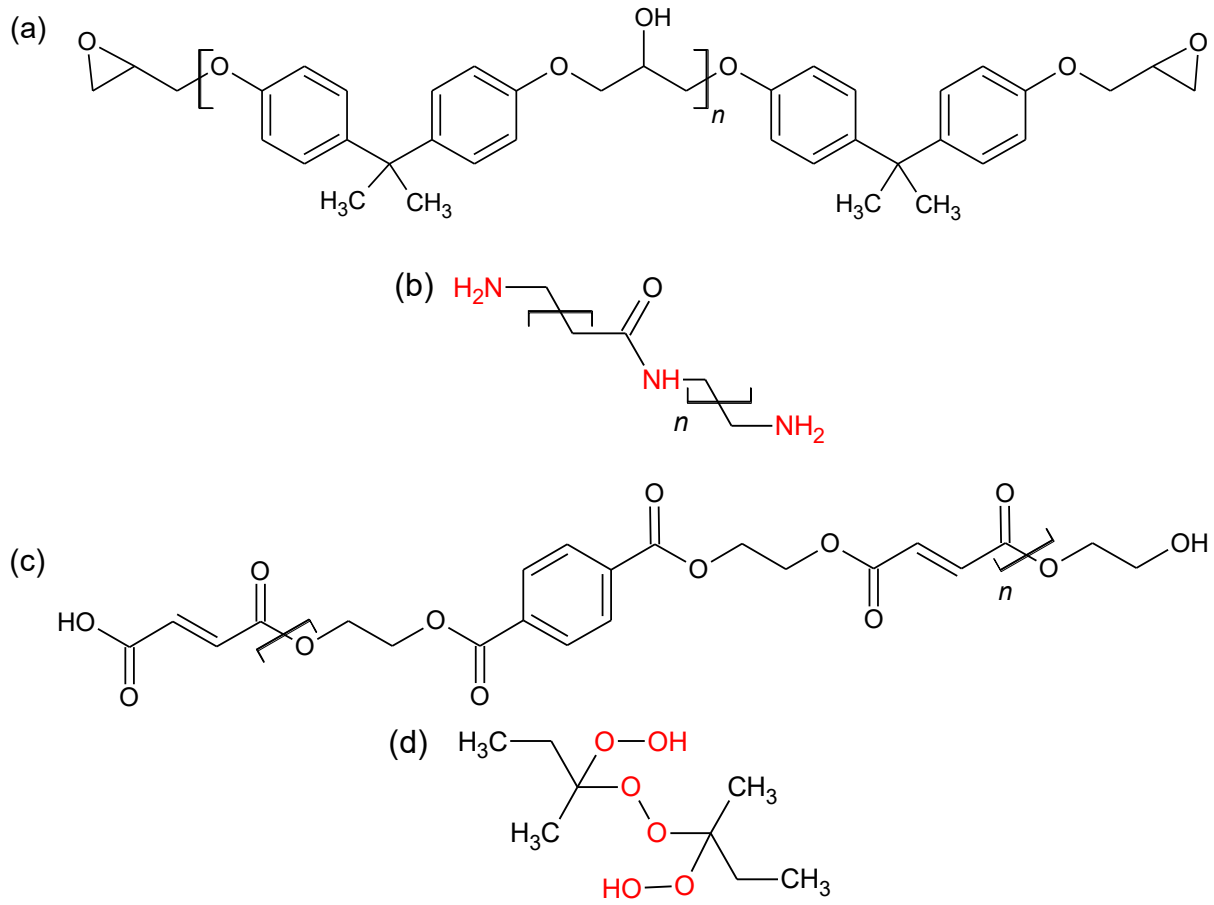

Fig. 1. (a) Nippon Paint epoxy resin type DGEBA [29], (b) Epoxy Hardener [30], (c) BQTN Type 157 Unsaturated Polyester [31], (d) Methyl Ethyl Ketone Peroxide (MEKP) Catalyst [32].

2.3. Characterization

2.3.1. FTIR test

The FTIR test, conducted in accordance with the ASTM E 2412 standard, analyzes the functional groups present in the sample. The sample, a thermoset solid, is crushed into a powder form. The fundamental principle of FTIR involves the production of infrared rays by the sample, which are then detected and recorded by a detector.

2.3.2. Tensile test

The tensile test adheres to the ASTM D 638 standard and utilizes a Shimadzu Autograph-type Universal Testing Machine with a 30 kN load capacity. Samples are prepared using a cutting tool to dimensions of 165 mm x 13 mm x 7 mm. The test is performed at a speed of 2 mm/minute with a gauge length of 50 mm under room temperature conditions. Five repetitions are conducted for each formulation, and the average value is calculated.

2.3.3. Impact test

The impact test is performed using a Plastic Impact Testing Machine in compliance with the ASTM D 6110 standard. Samples are cut to dimensions of 125 mm x 10.16 mm x 10 mm using a cutting tool. Each formulation undergoes five repetitions, with the impact value determined by calculating the average of the test results.

2.3.4. Hardness test

The hardness test follows the ASTM D 2240 standard and employs Shore D hardness test equipment. Samples are shaped with a diameter of 50 mm and a thickness of 20 mm using a cutting tool. Five repetitions are carried out for each formulation, and the average hardness value is calculated from the test results.

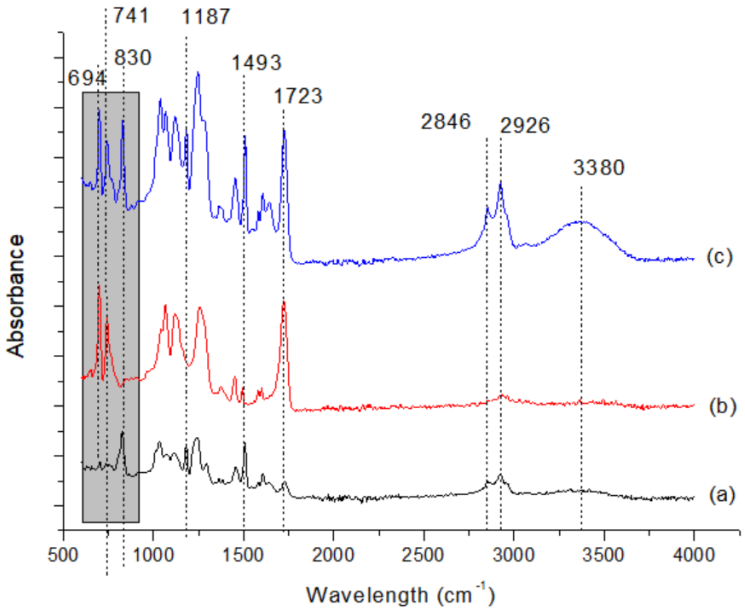

Fig. 2. FTIR curves of (a) Epoxy, (b) Unsaturated Polyester, and (c) Epoxy: Polyester blend polymer.

3. Results and discussion

3.1. Functional group analysis on FTIR

FTIR spectrum of the epoxy thermoset (Fig. 2(a)) shows characteristic functional groups related to the epoxy system and amine-based hardener. The peak at wave number 3380 cm^{-1} (N-H stretching) indicates the presence of primary aliphatic amine groups, indicating the reaction between epoxy groups and amines during the hardening process. This is reinforced by strong peaks at 2926 cm^{-1} and 2846 cm^{-1}, which indicate the presence of amine groups in the form of both amine salts and alcohols.

A weak peak at 1723 cm^{-1}, associated with C-H bending, indicates the presence of minor aromatic fragments in the epoxy system. Furthermore, the peaks at 1187 cm^{-1} and 1117 cm^{-1} (C-N stretching) indicate the presence of amine structures involved in forming the thermoset polymer network. Meanwhile, the strong peak at 830 cm^{-1} (C-H bending) reflects the aromatic fragments of the epoxy, which contribute to the stiffness and thermal stability of the material. This spectrum corresponds to the fully polymerized structure of epoxy, where the interaction between epoxy and amine groups results in a strong network resistant to mechanical and thermal loads.

The FTIR spectrum of the unsaturated polyester thermoset (Fig. 2(b)) is dominated by peaks reflecting the presence of ester groups and carbon-carbon double bonds. The strong peak at 1723 cm^{-1} (C=O stretching) indicates carbonyl groups, an integral part of the ester structure in unsaturated polyesters. The presence of carbon-carbon double bonds typical of unsaturated polyesters was identified through peaks at 1600 cm^{-1} (C=C stretching) and 694 cm^{-1} (C=C bending). The peak at 1245 cm^{-1} (C-O stretching) corroborates the presence of ester groups, which play an essential role in the polymerization process and network formation. Combining these carbonyl groups and double bonds gives unsaturated polyesters high reactivity properties in crosslinking reactions, which contributes to forming strong and stress-resistant materials.

The FTIR spectrum of the polymer blend (Fig. 2(c)) shows a unique combination of epoxy and unsaturated polyester characteristics. The peak at 3380 cm^{-1} (N-H stretching) reflects the contribution of the epoxy component. However, its intensity is lower than pure epoxy, indicating the minor role of amine groups in this blend. The presence of strong carbonyl groups at 1723 cm^{-1} (C=O stretching), as well as carbon-carbon double bonds at 1600 cm^{-1} (C=C stretching) and 694 cm^{-1} (C=C bending), confirmed the dominance of unsaturated polyester in the blend composition. A strong peak at 1245 cm^{-1} (C-O stretching) indicates the presence of significant ester groups, while the peak at 830 cm^{-1} (C-H bending) indicates aromatic fragments of the epoxy.

3.2. Tensile strength analysis of polymer blend materials

Table 5 shows the results of the characterization test, which shows the mechanical properties of samples. Tensile strength increases with decreasing fraction of epoxy in the blend, reaching a maximum value at Epo-0 (54.45

N/mm²), which consists entirely of unsaturated polyester. This highest tensile stress value indicates that unsaturated polyester has a higher intrinsic tensile strength than epoxy. However, in blends such as Epo-90 (36.09 N/mm²) to Epo-60 (38.13 N/mm²), there is an increase in tensile stress compared to pure epoxy (Epo-100 at 27.23 N/mm²), indicating that the addition of polyester strengthens the epoxy network by forming synergistic cross interactions. The decrease in value in Epo-100 indicates the dominance of amine-epoxy-based crosslinks, which are less flexible to stress.

Fig. 3 shows the stress and strain curves for all the samples. The tensile strain increases as the polyester content in the blend increases, reaching a maximum at Epo-0 (3.06%). The more flexible, unsaturated polyester gives more significant deformation before fracture. In the blended system, the tensile strain was 1.98% to 2.42%, reflecting a balance between the epoxy's stiffness and the polyester's flexibility. Epo-100 had the lowest tensile strain value (2.39%), indicating higher stiffness of the pure epoxy network.

Young's modulus indicates the material's stiffness, with the highest value shown in Epo-0 (1.84 GPa). Pure unsaturated polyester systems have a higher Young's modulus due to their stiffer intrinsic properties than epoxy. In blends such as Epo-90 (1.82 GPa) and Epo-70 (1.66 GPa), Young's modulus was higher than the other blends, indicating an increase in stiffness due to the synergy between the cross-linked structure of epoxy and unsaturated polyester. In contrast, Young's modulus values decreased in Epo-60 (1.45 GPa) and Epo-80 (1.52 GPa), reflecting changes in the distribution and dominance of the respective phases.

Compared to previous studies, the tensile strength of the Epo-0 sample (54.45 N/mm²) is superior to that reported by Chakradhar et al. [10], where epoxy/polyester nanocomposites achieved a maximum of approximately 48 N/mm². Similarly, Paluvai et al. [15] recorded tensile values around 50 N/mm² in UP-toughened epoxy systems with nanoclay. Although the tensile strength in blends such as Epo-90 (36.09 N/mm²), Epo-80 (38.17 N/mm²), and Epo-70 (39.51 N/mm²) is lower than in pure UP systems, it still outperforms the pure epoxy matrix (Epo-100 at 27.23 N/mm²) and aligns with the performance reported by Ruban et al. [28], who achieved ~35–38 N/mm² in nanosilica-filled epoxy-UP systems. This indicates that the post-curing technique used here can generate synergistic improvements even without nanofiller additives.

Table 5
Mechanical properties of unsaturated epoxy/polyester blend polymers

Label	Tensile**s** **s**tress (N/mm²)	Tensile **s**train (%)	Young's **m**odulus (GPa)	Impact resistance (J/mm²)	Hardness (HD)
Epo-100	27.23	2.39	1.32	0.1278	80.7
Epo-90	36.09	1.98	1.82	0.1438	75.7
Epo-80	38.17	2.25	1.52	0.1316	76.7
Epo-70	39.51	2.39	1.66	0.1174	78.1
Epo-60	38.13	2.42	1.45	0.1128	79.1
Epo-0	54.45	3.06	1.84	0.1196	77.3

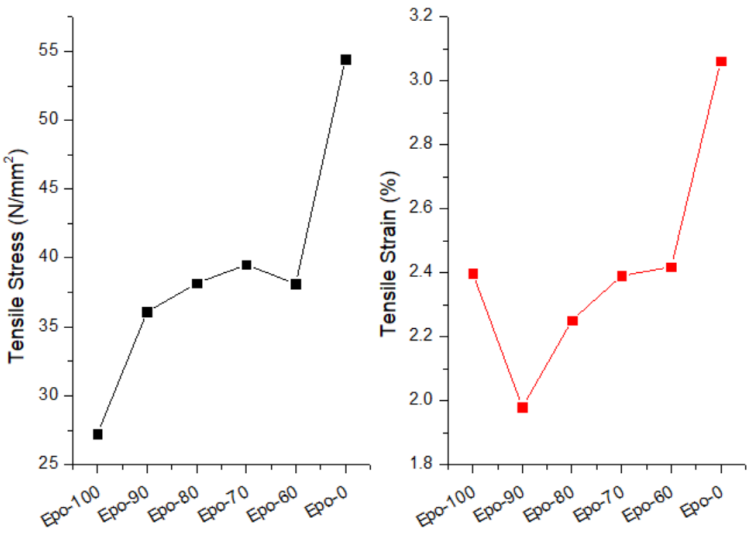

Fig. 3. Stress and strain curves of polymer blend material.

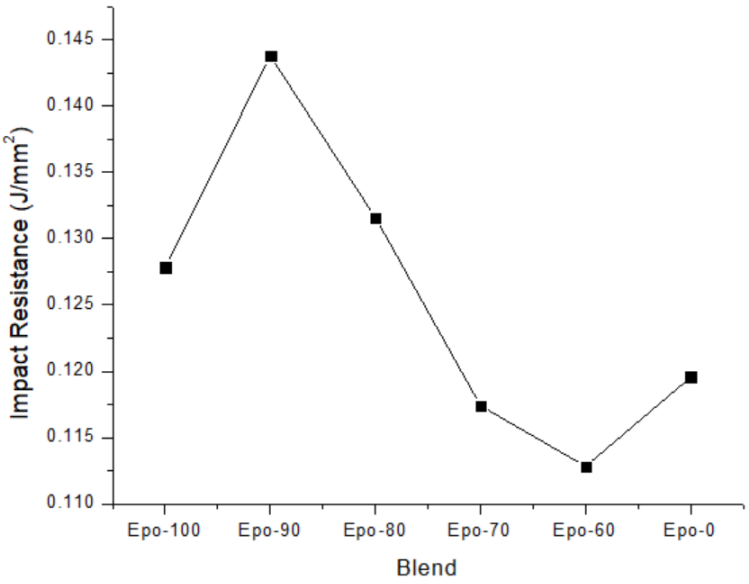

Fig. 4. Impact resistance curve of polymer blend material.

The post-curing process with staged temperatures (50°C, 70°C, and 100°C) is believed to enhance the degree of cross-linking between the epoxy and polyester matrices. For blends such as Epo-90 and Epo-80, this staged thermal treatment likely promoted interphase compatibility and network homogenization, resulting in higher tensile stress compared to pure epoxy. The curing profile enables gradual chain mobility and reactive group alignment, which enhances the polymer network integrity and contributes to the mechanical improvement. For Epo-60, a slight decrease (38.13 N/mm²) is observed, possibly due to the phase incompatibility threshold, yet it remains within the reported effective range. The overall trend suggests that UP inclusion contributes significantly to tensile enhancement, and although reductions occur in intermediate blends, their performance remains competitive with prior optimized systems.

3.3. Impact toughness analysis of thermoset materials

Fig. 4 shows the impact of resistance of polymer blend material. Impact resistance describes the ability of a material to absorb energy before fractures. The highest impact resistance value was observed in Epo-90 (0.1438 J/mm²), indicating that the blend with 90% epoxy and 10% polyester proportion has an optimal balance between stiffness and flexibility. The lower impact resistance in Epo-0 (0.1196 J/mm²) and Epo-100 (0.1278 J/mm²) reflects the brittle nature of the respective pure materials. Blends such as Epo-80 (0.1316 J/mm²) and Epo-70 (0.1174 J/mm²) have relatively stable impact resistance, indicating the contribution of each component in absorbing energy. The optimal impact resistance value (0.1438 J/mm² in Epo-90) is also higher than values reported by Ruban et al. [4], where amine-functionalized CNT-toughened systems only reached ~0.12 J/mm². The current results suggest that even simple polymer blending with post-curing staging can achieve comparable or better toughness, which is promising for simplifying the fabrication process for maritime composite components.

The superior impact resistance observed in Epo-90 (0.1438 J/mm²) may also be attributed to the role of the post-curing stages in relieving internal stresses and improving energy dissipation pathways within the blend. Gradual thermal curing facilitates better molecular interdiffusion and reduces the formation of brittle microphases, especially in epoxy-rich formulations. This results in an optimized balance between stiffness and flexibility, which is essential for impact resistance in marine applications. The decrease observed in Epo-60 (0.1128 J/mm²) might be due to reduced interfacial adhesion as polyester dominates, which aligns with observations from Gao et al. [27] on mechanical performance deterioration at high polyester ratios. Despite the decline, the result remains functionally relevant for applications where moderate impact tolerance is acceptable.

3.4. Hardness analysis of polymer blend materials

Material hardness (HD) indicates the surface properties of the material. Epo-100 has the highest hardness (80.7 HD), reflecting the greater surface rigidity of pure epoxy. Hardness values decreased in Epo-90 (75.7 HD) and Epo-80 (76.7 HD) as the polyester content increased. At Epo-0 (77.3 HD), the hardness value was slightly higher than that of specific blends, reflecting the contribution of polyester in providing moderate surface stiffness.

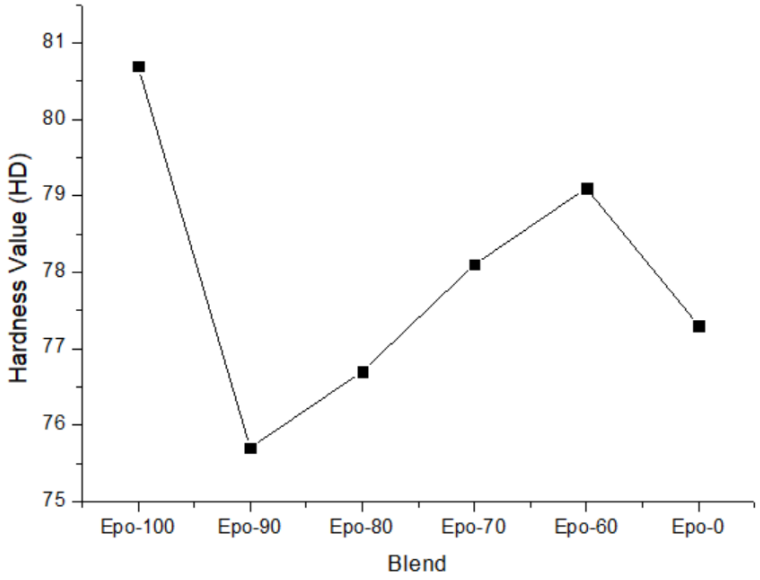

Fig. 5. Hardness value curve of polymer blend material.

Test results in Fig. 5 show that each blend composition has specific mechanical advantages, which depend on the proportion of epoxy and unsaturated polyester. Unsaturated polyester significantly contributed to tensile strength, strain, and Young's modulus. Meanwhile, the epoxy contributed to the overall hardness and mechanical stability. The Epo-90 blend showed optimal mechanical properties with the highest impact resistance (0.1438 J/mm²) and high Young's modulus (1.823 GPa). This shows that at a specific composition, the synergistic interaction between epoxy and polyester can be maximized, creating a strong material with good energy absorption. Pure unsaturated polyester (Epo-0) is the best choice for highly stiff applications. In contrast, pure epoxy (Epo-100) suits applications requiring high hardness. Controlling the unsaturated epoxy-polyester composition enables the design of materials with mechanical properties tailored for specific needs, such as structural composite materials, protective coatings, or high-energy materials. The post-curing stages also play a role in determining surface hardness. The high hardness in Epo-100 (80.7 HD) can be linked to a dense crosslinked epoxy network enhanced by thermal treatment, while the reduction in blends reflects the softening effect of UP, albeit still influenced by the heat-induced structural stabilization during curing.

The optimal mechanical properties observed in specific blend ratios have direct implications for marine applications. For instance, the Epo-90 blend, which demonstrated the highest impact toughness (0.1438 J/mm²) and high Young's modulus (1.82 GPa), is suitable for components that require energy absorption under dynamic loads, such as boat interiors, hatch covers, or structural reinforcements exposed to wave impacts. The high hardness of Epo-100 (80.7 HD) makes it ideal for use in abrasion-prone surfaces like ship flooring or protective outer coatings. Meanwhile, the Epo-0 formulation, with its highest tensile strength (54.45 N/mm²), is advantageous for rigid panels or hull reinforcements where tensile stress resistance is critical. These applications benefit from enhanced durability, corrosion resistance, and thermal stability resulting from the post-curing process, which are essential for long-term performance in harsh marine environments.

4. Conclusions

This study shows that blending epoxy resin and unsaturated polyester (UP) through the blending method and optimization of the post-curing process produces materials with superior mechanical and thermal properties. FTIR analysis showed synergistic chemical interactions between the functional groups of epoxy and UP, resulting in a more stable polymer network resistant to mechanical stress. Mechanical test results showed that adding UP resin significantly increased the tensile strength to 54.45 N/mm² in the Epo-0 formulation. At the same time, blends such as Epo-90 provided an optimal balance between stiffness and flexibility with the highest impact toughness of 0.1438 J/mm². The increasing trend of Young's modulus and tensile strain further supports the strategic role of UP in strengthening the mechanical properties of materials. The stepwise post-curing process at 50°C, 70°C, and 100°C proved effective in improving the homogeneity of the polymer network and the final properties of the material. With these results, the epoxy/UP polymer blend shows broad application potential, especially in the maritime sector, for manufacturing components that require resistance to corrosion, moisture, and high mechanical loads.

Declaration statement

Fahriadi Pakaya: conducted research and data collection in the laboratory and compiled the research article. **Yurika Nantan**: conducted research and specimen testing. **Marinus S. Tappy**: analyzed the results of the data testing. **Raman GTH Simanjuntak**: conducted research and assisted in compiling the research article. **Jozua Ch. Huwae**: analyzed data to be included in the research article. **M. Yusuf Syam**: conducted testing and took the main material of APM fiber. **Izhary Siregar:** was a laboratory assistant who participated in conducting research in the form of preparing specimens to be tested. **I Nyoman Subawa**: was a laboratory technician who assisted in the preparation of specimens and experimental setup. **Wilfred Yan Krol Urun**: was a student cadet who participated in conducting research and assisting during laboratory testing.

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Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

All data generated or analyzed during this study are included in this published article. Additional data can be requested from the corresponding author at [fahriadi.pakaya@kkp.go.id].

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