

Unsaturated polyester resin synthesis for enhanced fiber-reinforced composite performance

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This research aims to enhance traditional glass fiber composites by utilizing a medium-reactive unsaturated polyester resin (UPR) synthesized from ortho-phthalic anhydride. The UPR is formulated using unsaturated acids, glycols, and styrene monomers, with the reaction tailored to improve mechanical properties beyond those of standard commercial resins. The liquid resin's properties are evaluated for manufacturing viability, and its solidified form demonstrates superior performance compared to industrial benchmarks. The composite, produced via the hand layup technique, features a reduced resin-to-glass fiber ratio. Mechanical property tests confirm its robustness. Additionally, scanning electron microscopy (SEM) analysis reveals the microstructural characteristics to study the UPR performance.

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1. Introduction

In contemporary applications, Unsaturated Polyester (UP) resins play a prevalent role in the fiber-reinforced plastic (FRP) structures, including wind blades, rail car components, automotive bumpers and bonnets, and marine hulls and decks in infrastructure projects. FRP, essentially a composite of fiber reinforcement and a resin matrix, offers multiple resin options including Unsaturated Polyester, Epoxy, Vinylster, and phenolic resins. The growing preference for Unsaturated Polyester resins arises from their cost-effectiveness, ease of manufacturing, rapid curing with dimensional stability, and the adaptability to diverse FRP industry requirements. However, existing market resins face challenges such as poor compatibility with reinforcements, high flammability, elevated costs, and limited support for incorporating fire-retardant additives. The chosen Unsaturated Polyester resin, specifically ortho phthalic-based UPR, was synthesized due to its simplified process compared to other classifications, addressing these challenges in the current resin market.

Glycols, maleic anhydride (MA), and phthalic anhydride (PA) are used in a condensation process to create ortho unsaturated polyester resin (UPR), sometimes referred to as GP UPR [1]. When compared to other acids, the use of ortho phthalic anhydride results in increased structural rigidity at a lower cost. Among glycols, propylene glycol (PG) resins hold greater significance than ethylene glycol and diethylene glycol-based resins. The methyl group in PG reduces resin crystallinity, enhancing compatibility with commonly used reactive diluents [1]. The amalgamation of an aromatic dicarboxylic acid with a polyhydric alcohol yields a viscous liquid. Incorporating a reactive diluent like styrene creates a double bond with unsaturated polyesters, resulting in a heterochain thermoset polymer with a rigid, three-dimensional, crosslinked structure [1]. Methyl ethyl ketone peroxide (MEKP) is a common catalyst that starts the curing reaction at room temperature. It is frequently activated by a cobalt or cobalt-amine system. Additional free radicals, notably benzoyl peroxide (BPO) and cumene hydroperoxide, can be utilised by UPRs [2]. An inhibitor is added to the resin post-synthesis to minimise undesirable colours, odours, or side effects and to speed up curing. Among the inhibitors utilised are hydroquinone, substituted

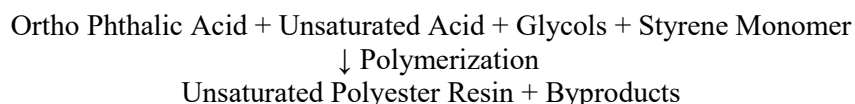
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catechol, and 4,4-dihydroxy biphenyl [3]. Researchers have explored various strategies to enhance the corrosion resistance, thermal stability, mechanical properties, and flame-retardant (FR) characteristics of Unsaturated Polyester Resins (UPRs). Parker et al. proposed that incorporating isophthalic acid improves mechanical properties and corrosion resistance [4]. Watanabe et al. introduced a two-stage production method using dimethyl terephthalate instead of isophthalic acid, addressing essential improvements [5]. In the work conducted by Benny Cherian, Eby Thomas Thachil, and collaborators, superior mechanical qualities were achieved by polymerizing alcohols and acids in the ratio of 30% ethylene glycol to 70% propylene glycol, with a MA/PA ratio of 60/40. Mechanical properties were exclusively examined for cast resin without fiber reinforcement, and all polyesterification reactions were conducted at 30 mg KOH/g [6]. The researchers also diversified constructions by adjusting concentrations of anhydride and alcohol. The synthesis of unsaturated polyester resin yielded the best mechanical characteristics with a 60% MA/PA combination. However, resins with higher concentrations of PA demonstrated increased resilience and flexibility. Similar to the enhanced flexibility and toughness observed with diethylene glycol (DEG), DEG also improved impact strength, albeit at the expense of load-bearing capacity. The combination of an equal mixture of MA and PA with a resin ratio of 20/80 DEG/PG yielded optimal results [7]. Various diols and polyols were blended with bio-derived diesters of unsaturated acids, including fumaric, succinic, and itaconic acids. This resulted in the production of resins with a molecular weight range of M_n 480–477,000 and glass transition temperatures (T_g) extending from $-30.1\text{ }^\circ\text{C}$ to $-16.6\text{ }^\circ\text{C}$ [8]. The solubilities of these resins varied depending on the initial monomers. In the work by Yoon and colleagues, UPR was fixed, and then recycled UPR was developed. Recycled UPR demonstrated faster curing compared to pure resin. Mechanical properties were assessed for both pure resin and blends, revealing that while pure resin exhibited superior qualities, the blend properties were composition-dependent and found to be beneficial in various applications [9]. A Cobalt (Co) curing system was employed with different concentrations ranging from 0.05% to 1%, resulting in a reduction in gel time as Co concentration increased. Gel time decreased by 50% in the presence of 0.05% Co [10]. Investigating the impact of cobalt acetate as an accelerator and MEKP as the initiator, the study assessed how varying volume ratios of the two curing agents influenced gelation and the exothermic behavior of UPR. The study revealed that the resin's start temperature increased during gelation, and the absorptions of the accelerator and initiator had an inverse relationship with gel time [11]. At the curing temperature, the liquid system's viscosity rose; at higher temperatures, however, it dropped. The study found that decreasing M_c increased T_g and heat resistance in the UPR-MEKP system, which was based on the fragility parameter (M_c) of the cured UPR [12]. Kosar and Gomzi used an experimental and theoretical model to study the curing behaviour of unsaturated polyester resin (UPR) [13]. Dynamic and isothermal measurements were utilized to scrutinize the kinetic behavior of the curing system, and the results from both approaches were found to be in complete agreement in terms of reaction heat and kinetic parameters. Heat generated by the reaction was measured using cylindrical molds. The primary reason for the superior heat output in the mould was the difference in heat conductivity between copper and glass. In the context of low-temperature molding methods, a significant challenge is controlling the resin shrinkage of residual monomers. Low-profile additives (LPAs) are employed to mitigate UPR/styrene resin shrinkage under specific processing conditions, although they may lead to higher residual styrene content. Using LPAs, a methodical examination was conducted to examine the effects of the initiator system and reaction temperature on the model morphology, final resin alteration, and resin shrinkage of UPR. The findings showed that two initiators could improve the resin system's final conversion, with the most effect being shown at low temperatures. In the investigation of shrinkage control, LPAs performed better at low ($35\text{ }^\circ\text{C}$) and high ($100\text{ }^\circ\text{C}$) temperatures compared to intermediate temperatures (e.g., $60\text{ }^\circ\text{C}$ - $75\text{ }^\circ\text{C}$). The final shrinkage of the resin caused morphological modifications, the creation of microvoids, and adjustments in the relative response rates between the LPA-rich and UPR-rich phases [14]. Styrene mass percentages in commercial unsaturated polyester resins (UPRs) usually range from 30% to 40%. The composition of the resin determines the miscibility of the resin with styrene; larger amounts of styrene cause more phase separation. The styrene monomer controls the mixture's phase behaviour, which is essential for mechanical qualities and thermal stability [15]. Dynamic Mechanical Analysis (DMA) research

has revealed that cured resin with elevated styrene concentrations undergoes phase separation. The glass transition temperature, influenced by styrene content, thermal stability, and mechanical behavior, varies accordingly [16]. In the context of specific applications such as marble, marine products, gel coats, and buttons, Hildeberto Nava of Poly Composites has delineated various high-performance, low molecular weight resin formulations. These formulations aim to enhance corrosion resistance and thermal performance in the design of composite products [17].

Overall Reaction



The researchers elucidated diverse resin synthesis approaches by altering the ratios of alcohols and unsaturated acids. Most researchers concluded the resin synthesis process when acid values reached 40 mgKOH/g, utilizing limited materials for the synthesis. However, the liquid resin properties and resin cast properties proved inadequate for the inclusion of Flame Retardant (FR) additives. The endeavors of the aforementioned researchers prompted a refinement of the resin synthesis process using varied materials to enhance liquid resin properties, mechanical characteristics, and compatibility for FR additives within the resin matrix system. Propylene glycol (PG), ethylene glycol (EG), diethylene glycol (DEG), maleic anhydride, and ortho phthalic acid are used in the formulation and manufacturing of unsaturated polyester ortho resins. Crucially, the synthetic procedure and raw ingredients used in this investigation are different, even from the mixes that the aforementioned researchers have previously investigated.

2. Resin preparation and testing (experimentation)

2.1. Resin raw materials

Glycols: Propylene Glycol (PG), Diethylene glycol (DEG).

Unsaturated Acids: Phthalic anhydride (PA), and Maleic anhydride (MA)

Monomers: Styrene, Alpha Methyl Styrene, and Methyl Methacrylate.

Processing Catalyst: Triphenyl phosphate (TPP)

Process Inhibitor: Toluhydroquinone (THQ)

Curing Catalyst: Butanox M-50 (9% Active Oxygen) (MEKP)

Preaccelerator: Cobalt Octoate 6%

Promotor: N, N-Dimethylaniline.

Glass fibers: 600 woven roving glass and 300 chopped standard glass fibers.

2.2. Resin preparation

Prior to embarking on the direct resin synthesis, it is imperative to conduct a thorough quality inspection of incoming raw materials to ensure the production of suitable resin. The raw materials are categorized into liquid and solid components, with essential quality checks encompassing boiling point, refractive index, and specific gravity for liquid raw materials, while melting point and acid value tests are conducted for solid raw materials. The synthesis of ortho resin involves a two-step process, initiating the condensation reaction between acids and glycols within a small laboratory reactor equipped with a stirrer, vertical condenser, and bulb condenser, as depicted in Figure 1a below.

Creating resin formations solely from 100% propylene glycol and 100% ortho phthalic anhydride is unfeasible due to the absence of crosslinking sites between them. The use of pure Maleic Anhydride alone in the formulation leads to immediate gelling. Therefore, the combination of glycols, particularly diethylene glycol (DEG) with propylene glycol (PG), assumes significance for cost reduction, achieving high mechanical properties, and ensuring compatibility with the styrene monomer over ethylene glycol (EG). After careful consideration and referencing existing literature, the final composition for the new formulation was established. Initially, maleic

anhydride reacted with an excess of a 10% glycol ratio to compensate for evaporation losses compared to phthalic anhydride and the remaining glycols. The introduction of triphenylphosphate was essential to initiate the reaction in the reactor at a rate of 0.2% per volume of maleic acid.

Subsequently, the reaction mixture undergoes heating for several hours within a temperature-controlled heating mantle, reaching 210°C. During this process, the acid value (mgKOH/g) is monitored every 20 minutes. Maintaining the reaction temperature at 210°C is critical for the isomerization of maleic anhydride, especially when branching secondary glycols such as propylene glycol (PG) are present. At this temperature, cis-configured molecules transform into the less restricted planar trans-fumarate [7]. Fumaric acid (FA) exhibits high reactivity, resulting in the resin showcasing outstanding qualities. The optimal temperature to yield a substantial amount of fumarate is maintained at 210°C with the assistance of a temperature-controlled heating mantle in the reactor.

Upon reaching an acid value of 60 mgKOH/g, the temperature is lowered to 140°C, and an inhibitor (THQ, 1% of MA composition) is introduced into the reactor. This acid value serves as a marker for the reaction intensity, and the reaction proceeds until reaching an acid value of 20 mgKOH/g. The ASTM D 4662-87 method is employed to determine the acid value (mgKOH/g). The mixture undergoes room-temperature cooling, and upon reaching 80°C in the reactor, 0.02 wt% of inhibitor and paraffin wax (0.2–0.3 wt%) are added to the styrene. The inclusion of paraffin wax prevents oxygen contact with the resin, hindering the synthesis process's crosslinking reaction initiated by oxygen. Hydroquinone acts as an inhibitor to prevent premature polymerization, maintaining the resin's purity and color. The mixture is vigorously stirred to achieve a homogeneous liquid.

Styrene, at the unsaturation site of the polyester chain, forms linear polystyrene chains rather than copolymerizing, resembling a random copolymer. The polystyrene chain elongates until an unsaturated point is reached in one polyester chain, leading to the formation of crosslinks that span two to three monomer units. Reaction water makes up 8% of the total weight of the substance. Subsequently, the raw high molecular resin is transferred to the styrene vessel (as depicted in Fig. 1b) with slow mixing at about 100 rpm. After the final resin preparation, a preaccelerator is introduced, leading to a color change from pale yellow to pale pink, as illustrated in Figure 1c.

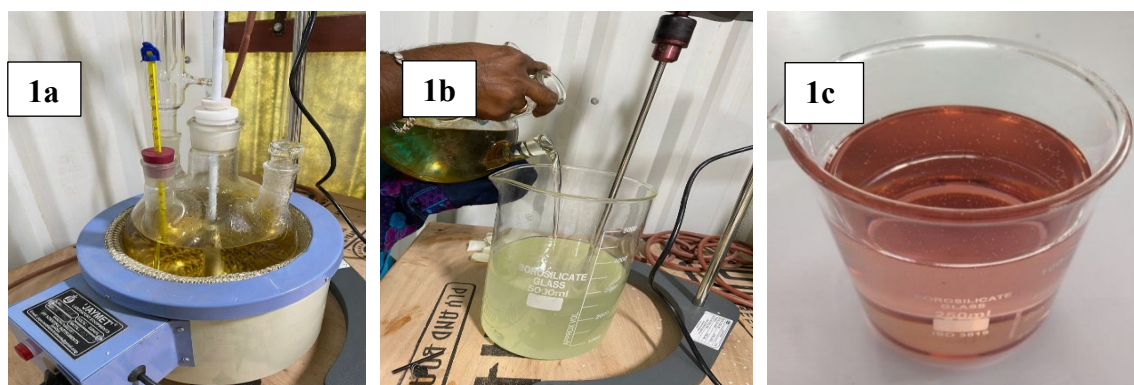


Fig. 1. (a) is the resin at the reactor; (b) is the resin transferring to the styrene monomer vessel, and (c) is the Pre-accelerated resin.

2.2.1 Test results of liquid resin

Upon the addition of the preaccelerator, a noticeable transformation in the resin is observed, manifesting as a shift in color from pale yellow to pale pink. This modification speeds up the gel time as well as the curing process. The promotor plays a pivotal role in fine-tuning the gel to achieve the maximum exothermic temperature. To assess the resin's characteristics, viscosity was measured using a Brookfield viscometer at room temperature (25 °C) with spindle two at 12 rpm, adhering to the ISO2555-2018 standard. Similarly, specific gravity was determined under the same conditions as specified in the ISO2811-2016 standard. The content of volatile components was evaluated through the ISO3251-2019 standard, employing the acid test outlined in ASTM D

4662-87.

Gelation time and exothermic peak temperature readings were conducted in accordance with ISO2535-2001 and ISO584:1982 standards. All tests were performed on the material in its liquid state at 25 °C. Comparative analysis of the obtained test values with those of industrial resin reveals favorable liquid resin properties.

Table 2.1. Shows the liquid state material data at a room temperature of 25 degrees.

Properties	Unit	1	2
Appearance	-	Light pinkish	-
Specific Gravity @25°C	-	1.09	1.11
Viscosity -Brookfield @ 25°C (sp2/12Rpm)	mPa (cps)	197	180
Volatile Content	%	40	45
Acid value	mgKOH/g	18	25
Geltime@25°C	Minutes	44	100
Peak Exotherm Temp.	°C	183	-

1 is the synthesized resin data. 2* The obtained results are validated with the reference 18.*

2.3. Preparation of resin cast

2.3.1. Standard resin cast procedure

Methyl Ethyl Ketone Peroxide (MEKP) was used as the catalyst and cobalt naphthenate (6% solution in styrene) as the accelerator in the manufacture of ortho resin. Initially, 0.25% of 6% cobalt was added to the Synthesized ortho resin, and the mixture underwent an initial cure at room temperature [11]. To attain a satisfactory gel time, for 100 g of resin, 1% of Butanox M/50 is used to measure gel time, cure time, and Peak Exotherm.

Test specimens for impact strength, tensile strength, flexural strength, and heat deflection temperature (HDT) were cast into the proper moulds separately. The specimens needed a full day to finish the drying procedure, which was done at room temperature.

2.3.2 Test results of cured cast

After being cured, the specimens were subjected to a list of tests covering tensile strength, Density, modulus, impact strength, toughness, elongation at break, water absorption and hardness in order to assess their mechanical characteristics. Tensile strength was assessed using a UTM machine following the ISO 527-4 standard. The same UTM machine and ISO 527-4 flexural test were employed to determine flexural properties. The impact values were obtained through the Charpy notched bar impact test ISO 178, while hardness values were measured according to ASTM D-2240. Heat deflection was evaluated following the ASTM D648 method. Additionally, water absorption tests were conducted over seven and 28 days, adhering to ISO62-1999 standards. The testing encompassed all material attributes for both casting resin and laminate materials, with detailed results presented in Tables 2.2 and 2.3. Table 2.2 shows the properties of the cured cast.

Property	units	1	2 [7]	3 Commercial Resin
Tensile strength	N/mm ²	82.60	42.5	38
Tensile Modulus(0.25%)	KN/mm ²	4.73	1.82	14.10
Elongation to break	%	3.07	2.5	2.4
Flexural strength	N/mm ²	123.84	-	-
Flexural Modulus	KN/mm ²	3.53	-	-
Hardness	-	92	87	88
HDT	°C	81.7	-	-
Water absorbtions:7dyas	%	0.17	0.25	0.21
Water absorbtions:28dyas	%	0.22	-	-

1* is the synthesized resin data. 2* & 3* is the referred from reference 7.

2.3.3 Sem analysis of cast

SEM analysis assumes paramount importance in comprehending the microstructure of cured resin casts, offering essential insights into their structural characteristics. Examining the cured resin at magnifications of 80, 40, and additional microns, SEM facilitates a detailed exploration of the material's composition and morphology.

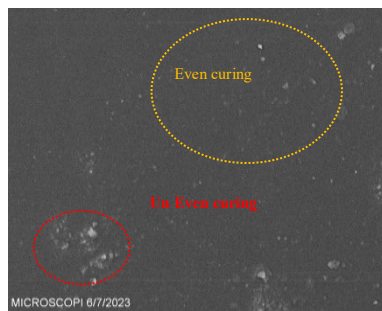


Fig. 2.3.3.1 Sem Analysis of Resin Cast with 80 microns zoom

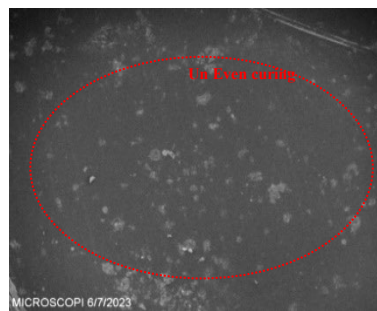


Fig. 2.3.3.2 Sem Analysis of Resin Cast with 40 microns zoom



Fig. 2.3.3.3 Sem Analysis of Resin cast with 20 microns zoom

This proves particularly crucial when investigating defects arising from uneven curing temperatures. The significance of SEM analysis is exemplified in Fig. 2.3.3.1, Fig. 2.3.3.2, and Fig. 2.3.3.3, where the microstructural intricacies, including defects between uneven and even curing boundaries, are visually depicted. These figures underscore the invaluable role of SEM in refining resin processing techniques for uniform curing and enhanced overall integrity in resin casts.

2.4. Composite-making process

Both commercially available resin and the synthesized resins underwent lamination using the hand lamination method, employing a stacking arrangement of Csm300/wr600 x 5. The resin-to-mat ratio was maintained at 1.52, indicating that for every 1 kilogram of overall glass fiber, 1.52 kilograms of resin were utilized. This ensured consistency in the glass fiber content reinforcement, facilitating a meaningful comparison of results with commercial resin.

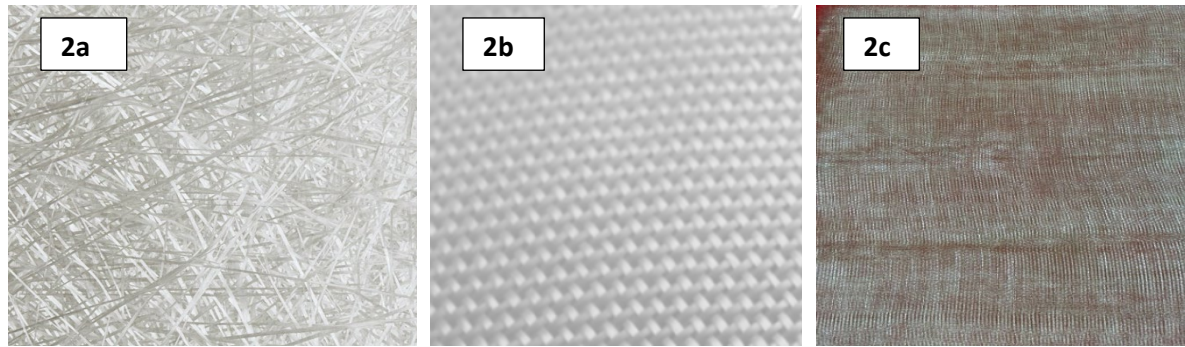


Fig. 2. (a) is the CSM300 glass fiber; (b) is the WR600 glass fiber and (c) is the laminate.

The specimens were cut from the laminate using a trimming blade to meet the tensile specifications outlined in ASTM D3039. The failure occurred within the span length at a load of 26.24 KN, with the sample exhibiting a mean thickness of 3.44 mm and a width of 24.78 mm. The recorded tensile strength for the sample was 308.39 MPa. Each value presented is an average derived from five samples, and the corresponding loading graph is depicted below in Figure 3.

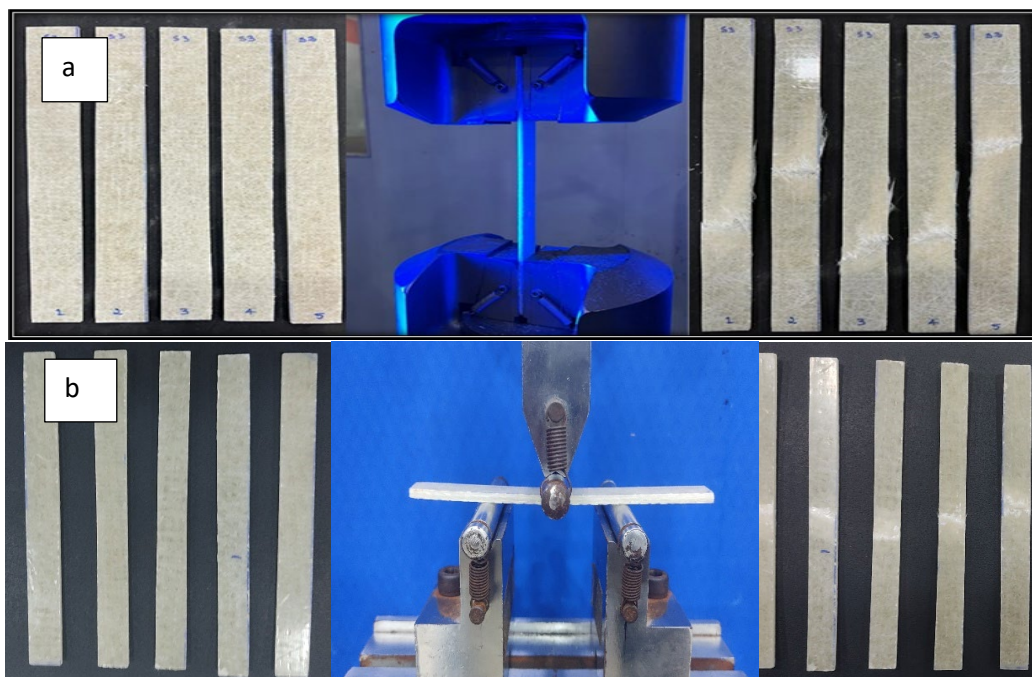
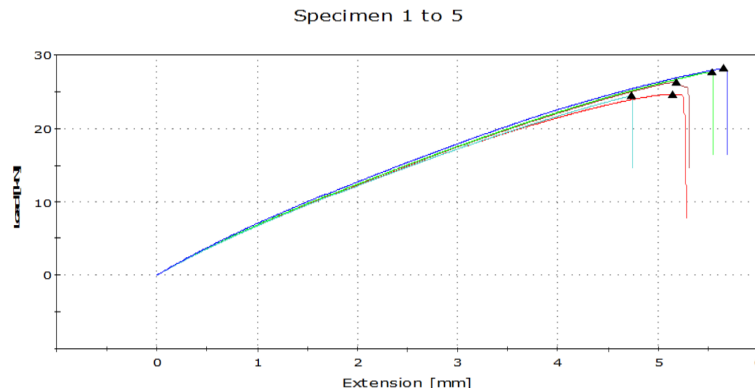
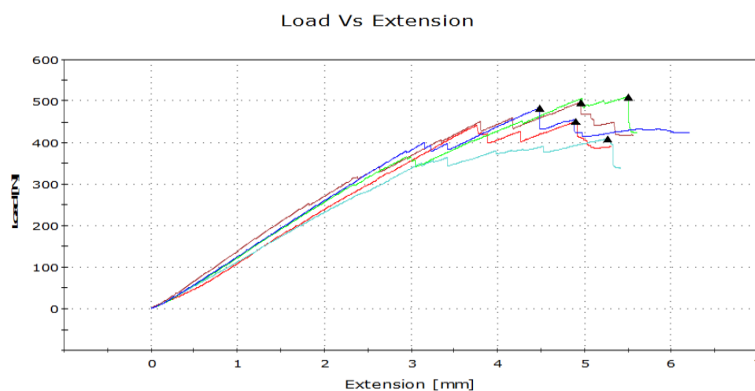


Fig. 3. (a) is the tested specimen of tensile strength; (b) is the tested specimen of flexural strength.



Graph 1. Shows the load Vs. Extension for tensile strength.

The specimens were crafted from the laminate, conforming to the dimensions specified in ASTM D790 for the Flexural test, using a trimming blade. Upon observation, the specimen exhibited an average thickness of 3.52 mm, a width of 11.78 mm, and a span length failure occurred under a load of 470.14 N, resulting in a flexural strength of 282.51 MPa. All reported values represent the means obtained from five specimens, and the loading diagram is presented below.



Graph 2. Shows the load Vs. Extension for flexural strength.

The specimens were crafted from the laminate using a trimming blade, adhering to the dimensions specified in the ISO 179 test for the Charpy impact test. The observed sample had an average thickness of 3.48 mm, a width of 8.51 mm, and recorded an energy value of 7.40 J, resulting in an impact resistance of 2126.83 J/m. The impact strength was measured in kJ/m². All reported values represent the averages obtained from five specimens.

2.4.1. Composite tested values @25°C

The increased presence of crosslinking sites contributes to higher tensile strength and modulus compared to other commercial resins. Propylene glycol (PG) alone lacks sufficient tensile strength properties, but when combined with other glycols like ethylene glycol (EG) and diethylene glycol (DEG), favorable properties are observed. Utilizing a combination of DEG and PG to a certain extent is recommended for various manufacturing processes such as LRTM, infusion, RTM, and vacuum bagging due to its lower viscosity compared to EG.

Table 2.3. Shows the laminate mechanical properties.

Property	Units	1	2
Density	Kg/m ³	1653.2	-
Tensile strength	N/mm ²	308.39	100
Flexural strength	N/mm ²	282.51	170
Flexural Modulus	KN/mm ²	-	9000
Impact Strength	KJ/m ²	249.92	249.92
Glass content	%	39.8	40
Water absorption: 7 days	mg	0.21	-
Water absorption: 28 days	mg	0.27	-

1* is the synthesized resin data. 2* is referred from reference 19.

The PG-DEG combination exhibits more elastic properties and a higher break point compared to the PG-EG combination. However, exceeding 20% DEG with PG leads to a significant decrease in tensile modulus properties [7]. Maleic anhydride (MA) can be incorporated into formulations between 50% and 70% to enhance modulus [6]. Comparative analysis of composite properties, presented in a table, indicates superior performance compared to industrial resin.

2.4.2. SEM analysis of laminate

SEM analysis played a pivotal role in evaluating the glass fiber-reinforced laminate, documented in Fig. 2.4.2.1 (Warp Direction), Fig. 2.4.2.2 (Weft Direction), and Fig. 2.4.2.3 (Trimming Marks during Specimen Preparation). Before mechanical testing, a pre-testing SEM analysis assessed resin-fiber compatibility post-lamination. This crucial step allowed a detailed examination of the composite's microstructure. Subsequently, after conducting tensile and flexural strength tests, a post-testing SEM analysis was performed to scrutinize the microstructure, capturing essential insights. The inclusion of SEM figures provides visual documentation of the laminate's microstructural characteristics at different stages, enhancing the comprehensive understanding of its performance.

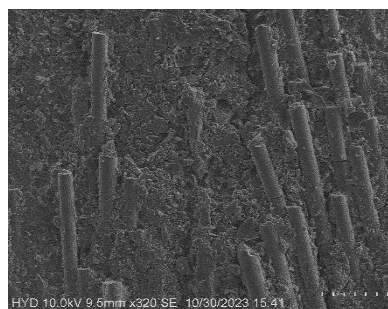


Fig. 2.4.2.1 Warp Direction defects

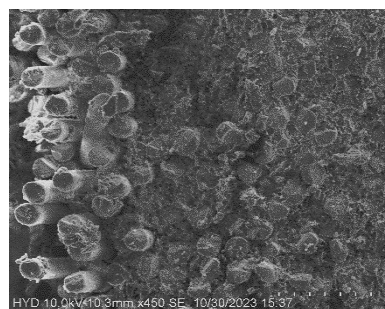


Fig. 2.4.2.2 Weft Direction defects

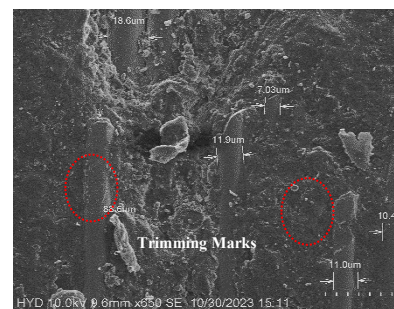


Fig. 2.4.2.3 Tool Marks defects

Following the completion of tensile and flexural strength tests, a post-testing SEM analysis was carried out to scrutinize the microstructure of the laminate. These dual SEM analyses provided valuable insights into both the pre-existing compatibility and the structural changes induced by mechanical stresses, contributing to a comprehensive understanding of the material's performance.

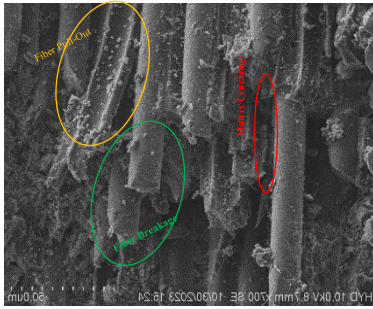


Fig. 2.4.2.4 Warp Direction of Tensile Specimen

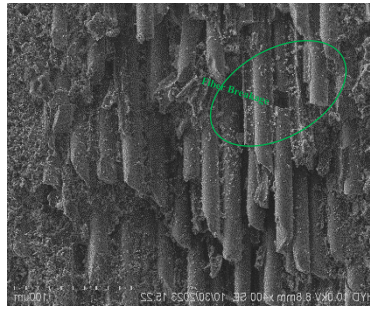


Fig. 2.4.2.5 Weft Direction of Tensile Specimen

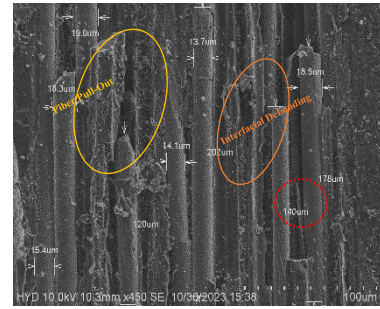


Fig. 2.4.2.6 Defects of GFRP after tensile test

Defects observed during tensile testing of Glass Fiber Reinforced Polymer (GFRP) are visually documented in the following figures:

Fiber Pull-Out (Fig. 2.4.2.4 - Warp Direction): Instances of individual glass fibers pulling out from the matrix along the warp direction are illustrated in this figure. Matrix Cracking (Fig. 2.4.2.5 - Weft Direction): Visible cracks within the polymer matrix in the weft direction are depicted in this figure. Interfacial Debonding & Delamination (Fig. 2.4.2.6): Areas of weakened adhesion between fibers and matrix (interfacial debonding) and separation between layers (delamination) are captured in this figure. Fiber Breakage (Fig. 2.4.2.6): Instances where tensile forces led to the fracture of individual glass fibers are evident in this figure. These specific figures, namely Fig. 2.4.2.4, Fig. 2.4.2.5, and Fig. 2.4.2.6, provide a concise reference for the different defects observed during the tensile testing of GFRP.

In the context of the flexural test for Glass Fiber Reinforced Polymer (GFRP), various defects are visually presented in specific figures:

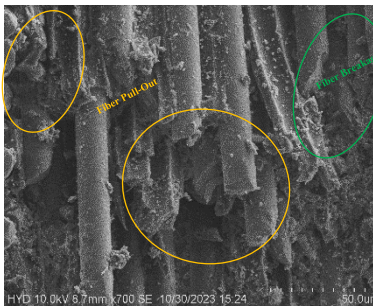


Fig. 2.4.2.7 Warp Direction of Flexural Specimen

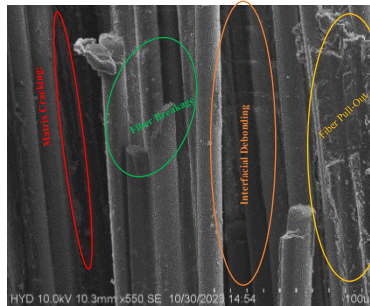


Fig. 2.4.2.8 Weft Direction of Flexural Specimen



Fig. 2.4.2.9 shows the defects Detailing.

Fiber Pull-Out (Fig. 2.4.2.7 - Warp Direction of Flexural Specimen): Instances of individual glass fibers pulling out from the matrix along the warp direction during the flexural test. Matrix Cracking and Fiber Breakage (Fig. 2.4.2.8 - Weft Direction of Flexural Specimen): Visible cracks within the polymer matrix in the weft direction, along with instances of fiber breakage, were observed during the flexural test. Defect Detailing (Fig. 2.4.2.9): This figure provides a detailed view of defects encountered during the flexural test, offering comprehensive insights into the material's response to bending stresses. These specific figures, namely Fig. 2.4.2.7, Fig. 2.4.2.8, and Fig. 2.4.2.9, serve as visual references for the different defects observed in the GFRP material during the flexural testing process.

3. Conclusion

In conclusion, the acid value's crucial role in resin synthesis was highlighted, guiding the formulation for enhanced properties and reaction process termination. The resin's low viscosity, specific gravity, and extended gel time contribute to its versatility and suitability for diverse laminate manufacturing processes. The combination of propylene glycol (PG) and diethylene glycol (DEG) with maleic anhydride (MA) and phthalic anhydride (PA) at 20% DEG yields a resilient, flexible, and impact-resistant resin.

Both the resin cast and composite, with the 60/40 MA/PA and 80/20 PG/DEG configurations, surpass standard resins in mechanical properties. The material, featuring increased phthalic anhydride levels, exhibits remarkable strength and flexibility, outperforming industrial resins. It stands out for its low density and high tensile, flexural, and impact strengths, positioning it as an excellent matrix for FR fillers and additives.

Importantly, SEM analysis played a pivotal role in validating the material's superior performance. Conducted the mechanical testing on the resin cast and FRP laminate, SEM provided crucial insights into the microstructure, confirming enhanced structural integrity. This underscores the significance of SEM analysis in comprehensively assessing the synthesized material's behavior under loading conditions, further solidifying its potential for diverse applications like defense - fiberglass foldable mats, rails – Outer body, etc.,

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