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Mechanical Properties of Fiberglass-Reinforced Polymer Composites for Reservoir Applications

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***Abstract* - Conventional metal reservoirs suffer from high corrosion rates and severe structural degradation, leading to leakage and elevated maintenance costs. This study evaluates three variations of fiberglass-reinforced polymer (FRP) composites as an alternative material for reservoir walls by investigating the effect of fiber orientation and mass fraction on mechanical properties and corrosion resistance. Three stacking sequences were fabricated using the hand lay-up method: E1 (Mat–Mat–Mat), E2 (Mat–FG 0/90–Mat), and E3 (FG 45–FG 0/90–FG 45). The specimens were evaluated through density testing, Charpy impact testing, tensile testing and three-point bending. The E3 variation achieved the highest density (1.580 g/cm³), the highest tensile strength (89.666 MPa), and the highest elongation (4.333%). The E2 variation yielded the maximum flexural strength (239.51 MPa) and the highest impact toughness (0.160 J/mm²). These findings confirm that a hybrid laminate structure with a woven-fiber core is critical for balancing mechanical performance and environmental durability in fluid storage applications.**

Keywords: corrosion rate, fiber orientation, fiberglass composite, mechanical properties, reservoir.

I. INTRODUCTION

The rapid advancement in materials science and manufacturing technology has progressed significantly, driven by industrial demand for materials that are strong, lightweight, and efficient. Polymer matrix composites (PMCs), specifically fiberglass-reinforced plastics, offer a high strength-to-weight ratio, excellent chemical resistance, and minimal maintenance requirements compared to conventional metals such as carbon steel [1][2]. In fluid storage infrastructure, such as reservoirs, carbon steel is highly susceptible to electrochemical corrosion as a result of continuous interaction with the stored fluid, which leads to wall thinning, leakage, and potential environmental contamination [3].

To overcome these structural limitations, composite materials are increasingly utilized due to their inert chemical properties and tailored mechanical characteristics [4]. The mechanical integrity of a composite structure heavily depends on internal parameters, particularly the orientation angle of the fibers (0°, 45°, 90°) and the fiber mass fraction, which dictate load distribution and material density [5][6]. While a 0° (longitudinal) orientation maximizes tensile strength by ensuring the fibers bear the primary load, multi-axis or mixed configurations can induce complex stress responses and alter the material's structural resilience [5]. The quality of the fiber–matrix interphase also plays a decisive role in translating fiber-level properties into bulk laminate performance [7]. And the internal stress state of a thin-walled storage vessel under hydrostatic loading further dictates the minimum strength requirements that any candidate wall material must satisfy [8].

Although composites resist traditional electrochemical corrosion, they undergo physicochemical degradation such as water absorption, polymer chain scission (hydrolysis), and wicking at the fiber-matrix interface when exposed to fluids over extended periods [9][10]. This study investigated the effect of fiber orientations on the tensile, flexural, impact, and density properties.

II. METHODS

2.1 Materials and Specimen Fabrication

The PMC specimens were fabricated using unsaturated polyester resin as the matrix, mixed with a catalyst (hardener) to initiate polymerization, and E-Glass fibers as the reinforcement. The hand lay-up method was utilized with six distinct stacking variations, as listed in Table 1.

Table 1: Stacking-sequence variations of the fiberglass composite specimens

Code	Stacking Sequence	Description
E1	Mat – Mat – Mat	Pure resin matrix (no fiber reinforcement)
E2	Mat – FG 0/90 – Mat	Woven 0°/90° fiber core, sandwiched between two

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Code	Stacking Sequence	Description
		pure resin outer layers
E3	FG 45 – FG 0/90 – FG 45	45° fiber outer skins with a woven 0°/90° fiber core

Various fiberglass composite laminate configurations were designed to evaluate the influence of fiber orientation and stacking sequence on the material's mechanical characteristics and degradation resistance. The stacking sequence schemes for each composite configuration (E1–E6) are shown in Figure 1.

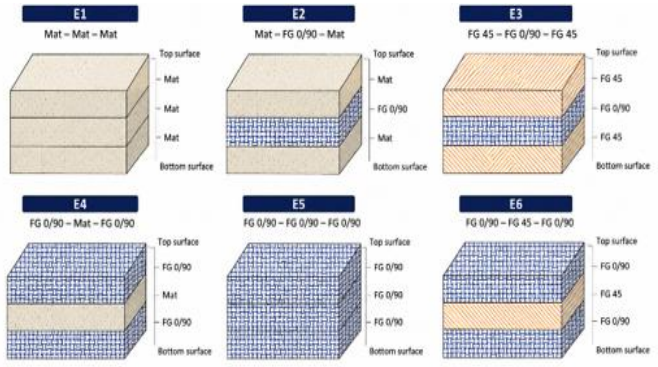

Figure 1: Schematic illustration of fiberglass composite stacking sequences (E1–E6)

2.2 Mechanical and Physical Characterization

Various fiberglass composite laminate configurations were designed to evaluate the influence of fiber orientation and stacking sequence on the material's mechanical characteristics and degradation resistance. The stacking sequence schemes for each composite configuration (E1–E6) are shown in Figure 1.

III. RESULTS AND DISCUSSIONS

3.1 Physical Density

The average density test results for the six composite variations are presented in Table 2.

Table 2: Average density test results of the fiberglass composites

Composite Variation	Average Density (g/cm³)
E1 (Mat – Mat – Mat)	1.458
E2 (Mat – FG 0/90 – Mat)	1.572
E3 (FG 45 – FG 0/90 – FG 45)	1.580

The density test revealed a clear upward trend as fiber reinforcement was introduced. The lowest density was observed in the pure resin matrix specimen (E1) at 1.458 g/cm³, while E2 rose to 1.572 g/cm³ and E3 achieved the highest value at 1.580 g/cm³. Although the difference between E2 and E3 is marginal (0.008 g/cm³), the result confirms that the addition of fiber reinforcement regardless of its angular arrangement consistently increases material compactness. A higher density indicates fewer micro-voids within the laminate, which is essential for preventing fluid seepage through reservoir walls [12]. This behavior is consistent with the rule of mixtures, since E-glass fibers carry a higher specific gravity than the surrounding polyester resin [6].

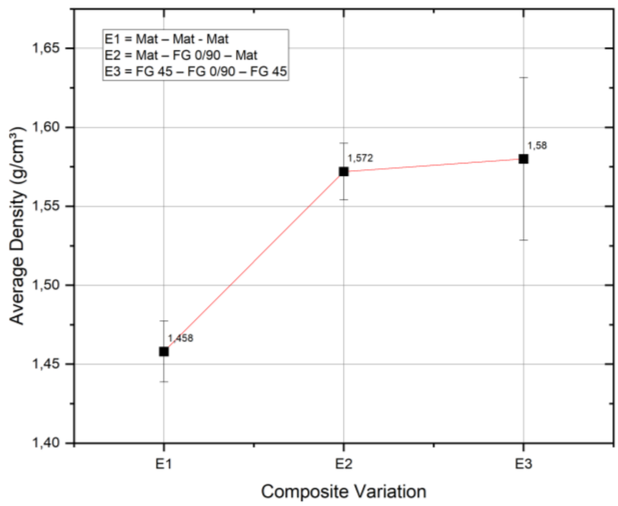

Figure 2: Average density of the fiberglass composite variations

3.2 Impact Toughness

Table 3: Charpy impact test results

Composite Variation	Average Impact Energy (Joule)	Average Impact Value (J/mm²)
E1 (Mat – Mat – Mat)	7.69	0.106
E2 (Mat – FG 0/90 – Mat)	14.12	0.160
E3 (FG 45 – FG 0/90 – FG 45)	11.73	0.150

The E2 variation (Mat–FG 0/90–Mat) achieved the highest impact toughness at 0.160 J/mm², followed closely by E3 at 0.150 J/mm². The unreinforced E1 specimen recorded the lowest value (0.106 J/mm²), indicating high *brittleness* and poor energy absorption. The superior performance of E2 can

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be attributed to the thick outer resin layers acting as an energy-dissipating buffer: upon impact, the compliant resin skin absorbs and distributes the sudden load before it reaches the stiff woven-fiber core, thereby preventing rapid crack propagation. This mechanism is consistent with energy absorption behavior reported for resin-rich composite configurations under blunt loading [13]. In contrast, E3's 45° outer fiber orientation provides some energy dissipation through *shear coupling*, but the stiffer fiber surface is less effective at absorbing transient impulse loads compared to E2's resin skin.

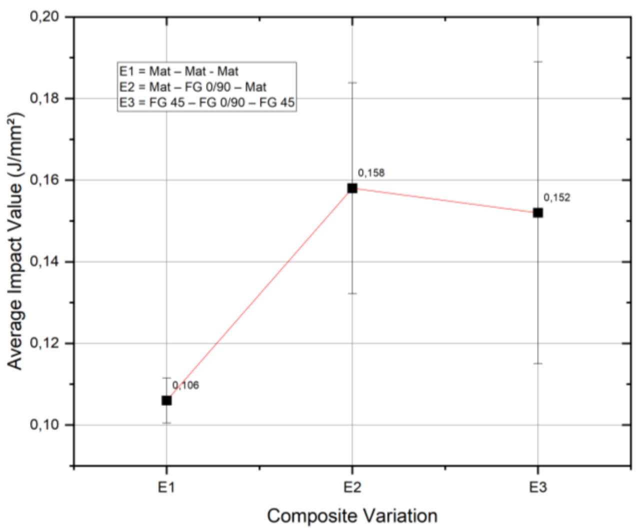

Figure 3: Average Charpy impact value of the fiberglass composite variations

3.3 Tensile Strength

Table 3: Charpy impact test results

Composite Variation	Average Tensile Strength (MPa)	Average Elongation (%)
E1 (Mat – Mat – Mat)	60.041	2.054
E2 (Mat – FG 0/90 – Mat)	54.307	2.439
E3 (FG 45 – FG 0/90 – FG 45)	89.666	4.333

The ability to withstand internal hydrostatic pressure (*hoop stress*) is a crucial parameter for reservoir side walls. The E3 variation (FG 45–FG 0/90–FG 45) achieved the maximum tensile strength of 89.666 MPa, surpassing both the unreinforced E1 (60.041 MPa) and E2 (54.307 MPa). The combined contribution of the 45° outer fiber skins and the 0°/90° core creates a multi-directional load-sharing architecture, allowing the laminate to resist tensile forces from multiple axes simultaneously. This also accounts for E3's significantly higher elongation (4.333%) compared to E2 (2.439%) and E1 (2.054%), as the 45° fiber layers induce a *shear coupling effect* that permits greater elastic deformation before failure. These results agree with previous findings that glass-fiber orientation and volume fraction are the primary determinants of tensile performance in polyester-matrix composites [14]. Notably, E2 exhibited a slightly lower tensile strength than E1, which can be explained by stress concentration at the resin–fiber interface: the abrupt stiffness mismatch between the resin-dominated outer layers and the woven fiber core generates interlaminar shear under axial loading, reducing effective tensile transfer [15].

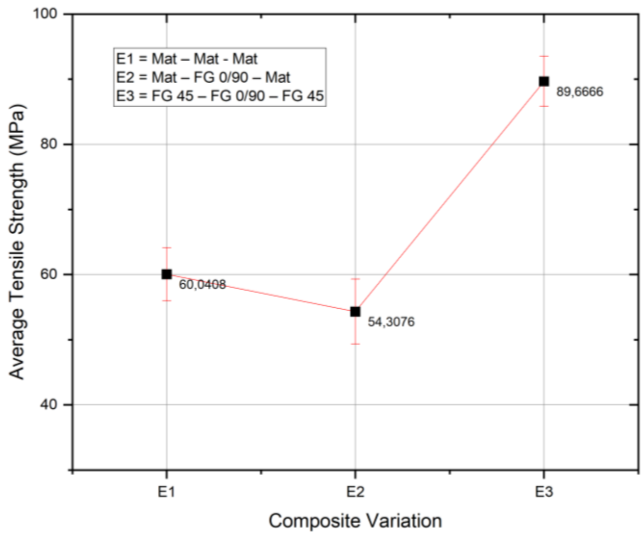

Figure 4: Average tensile strength of the fiberglass composite variations

3.4 Flexural Strength

Table 4: Three-point bending test results of the fiberglass composites

Composite Variation	Average Maximum Flexural Strength (MPa)
E1 (Mat – Mat – Mat)	141.27
E2 (Mat – FG 0/90 – Mat)	239.51
E3 (FG 45 – FG 0/90 – FG 45)	140.47

Flexural testing simulates the load-bearing capacity of the reservoir base under the weight of the stored fluid. The E2 variation (Mat–FG 0/90–Mat) achieved by far the highest flexural strength at 239.51 MPa, nearly 70% greater than both E1 (141.27 MPa) and E3 (140.47 MPa), which performed

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almost identically. The outstanding flexural rigidity of E2 arises from its sandwich architecture: the thick outer resin layers act as stiff skins that resist bending-induced compression and tension at the surfaces, while the woven fiber core provides the shear-carrying web. This structural synergy is analogous to the I-beam principle and is well-established in flexural performance of sandwich composites [16]. By contrast, E3's 45° outer fiber orientation, while beneficial for tensile ductility, offers minimal resistance to bending loads because 45° aligned fibers are poorly oriented to carry the longitudinal bending stresses that dominate under three-point loading, yielding a flexural strength nearly identical to the unreinforced E1.

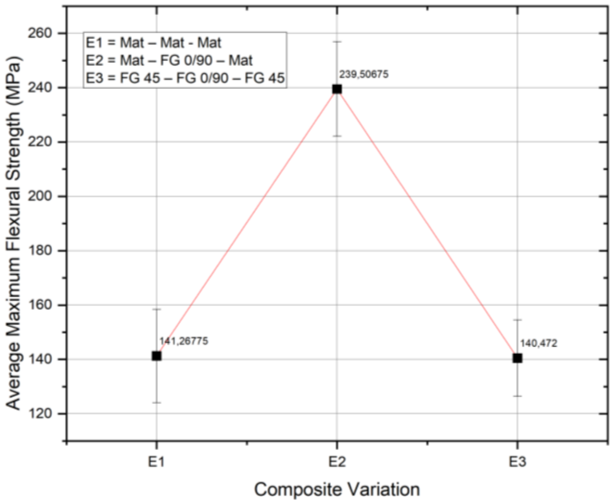

Figure 5: Average maximum flexural strength of the fiberglass composite variations

3.5 Implications for Reservoir Design

Overall, the integration of all tested parameters confirms that no single stacking sequence is absolutely optimal for every reservoir component; the choice of laminate sequence must be matched to the structural position, a design philosophy also echoed in studies on composite reservoir liners exposed to chemically aggressive stored fluids [17] and in fluid–structure interaction analyses of hydraulic storage and discharge structures [18]. The E2 variation (Mat–FG 0/90–Mat) is the most strongly recommended configuration for reservoir applications, as it delivers the highest flexural strength (239.51 MPa) and impact toughness (0.160 J/mm²). The E3 variation (FG 45–FG 0/90–FG 45) may be considered as a supplementary option for components requiring higher tensile strength (89.666 MPa) and ductility (4.333% elongation), such as connecting flanges or sections subject to internal pressure fluctuations. The E1 variation (Mat–Mat–Mat) is not recommended for direct fluid contact applications due to its poor mechanical performance.

IV. CONCLUSION

This study successfully evaluated the effect of fiber orientation and mass fraction on the mechanical and physical properties of three fiberglass-reinforced polymer composite variations (E1, E2, and E3) for fluid reservoir applications. The stacking sequence proved to have a significant and differentiated effect on each measured property. The E3 variation (FG 45–FG 0/90–FG 45) achieved the highest density (1.580 g/cm³), the highest tensile strength (89.666 MPa), and the greatest elongation (4.333%). The E2 variation (Mat–FG 0/90–Mat) delivered the highest flexural strength (239.51 MPa) and the highest impact toughness (0.160 J/mm.

Considering the combined requirements of structural integrity and long-term durability under fluid contact, the E2 variation is the most optimal configuration for reservoir applications, as it provides the best balance of flexural rigidity, impact resistance, and chemical resilience. The E3 variation may be used selectively for pressure-bearing components where higher tensile strength is the primary requirement, provided that adequate surface protection is applied to counteract its elevated degradation tendency.

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