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Water Absorption Behaviour of Epoxy-Based Hybrid Composites Reinforced With Glass Fiber And Industrial Waste Fillers

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Abstract
The present work examines the water absorption behavior of epoxy-based hybrid composites reinforced with E-glass fiber and modified with industrial waste fillers such as Coal Dust (CD), Coal Fly Ash (CFA), Marble Powder (MP), CDCFA (Coal Dust + CFA), CDCBPD (Coal Dust + Cement Bypass Dust), and CDMP (Coal Dust + Marble Powder). Laminates were fabricated using the hand lay-up technique with filler additions of 2.5, 5, 7.5, and 10 wt.%, and their moisture uptake was evaluated in distilled, mineral, ground, and sea water in accordance with ASTM D570 standards. The results reveal that water absorption strongly depends on the type of filler, its proportion, and the immersion medium. Distilled water produced the highest overall uptake, where GE50 absorbed 9.64%, while GECDCBPD5 showed the lowest at 0.56%. In mineral water, GECFA7.5 exhibited the least absorption (0.52%), whereas GECD10 recorded the maximum (2.47%). Ground water led to the greatest variation, with GE50 reaching 14.56% and GECFA2.5 maintaining the lowest at 0.52%. In sea water, GE60 demonstrated superior resistance (0.66%), while GECD10 absorbed the most (2.71%). These outcomes highlight the roles of filler porosity, interfacial bonding, and matrix hydrophilicity. The study establishes that industrial waste fillers can effectively reduce moisture ingress in epoxy composites, enabling their use in structural, marine, and humid-environment applications.

Keywords: *Epoxy-based hybrid composites, E-glass fiber reinforcement, Industrial waste fillers (CD, CFA, MP, CBPD), Water absorption (ASTM D570), Moisture resistance, Filler porosity and interfacial bonding, Marine and structural applications.*

1. INTRODUCTION

Polymer matrix composites (PMCs) have emerged as one of the most versatile classes of engineering materials over the last few decades due to their superior balance of mechanical, physical, and environmental properties. Their high specific strength, corrosion resistance, low density, and excellent tailorability have enabled their widespread use in demanding sectors such as aerospace, marine, automotive, defense, and civil infrastructure. Within this broad category, epoxy-based composites reinforced with E-glass fibers occupy a prominent position because they combine excellent mechanical performance, ease of processing, dimensional stability, and relatively low cost. However, despite these advantages, the long-term durability of epoxy–glass fiber composites in aggressive service environments remains a critical challenge [1-2].

One of the most severe degradation mechanisms encountered in these composites is moisture absorption when exposed to humid, saline, or aqueous environments. The ingress of moisture molecules into the polymer matrix is a diffusion-controlled process that can cause a series of detrimental effects, including swelling of the matrix, plasticization of the polymer chains, micro-cracking, and eventual de-bonding at the fiber–matrix interface [3-4]. This interfacial weakening disrupts stress transfer efficiency between the fiber and the matrix, leading to a progressive reduction in mechanical strength, stiffness, and fatigue life. Consequently, the structural reliability and service life of fiber-reinforced composites are significantly compromised in applications involving marine exposure, high humidity, or fluctuating environmental conditions.

To mitigate these limitations, researchers have focused on tailoring the polymer matrix by incorporating particulate fillers that act as diffusion barriers and improve the interfacial bonding between fibers and the matrix. Fillers reduce the free volume within the polymer network, alter the morphology of the resin, and obstruct the pathways available for water molecule transport [5-6]. Moreover, certain fillers can also improve dimensional stability, thermal resistance, and toughness, thereby enhancing the overall performance of the composite system. While conventional fillers such as silica, alumina, and titanium dioxide have been studied extensively, recent trends emphasize the adoption of industrial waste-derived fillers as sustainable, cost- effective, and environmentally friendly alternatives [7].

The valorization of industrial by-products not only reduces environmental burden but also provides a dual advantage of enhancing material performance while promoting circular economy principles. Wastes such as Coal Dust (CD), Coal Fly Ash (CFA), Marble Powder (MP), and Cement Bypass Dust (CBPD) are abundantly available, inexpensive, and possess distinct micro-structural characteristics such as fine particle size distribution, irregular morphology, high surface activity, and diverse chemical compositions rich in oxides and carbonates [8-9]. These attributes make them attractive candidates for incorporation into epoxy matrices to restrict moisture diffusion and improve interfacial adhesion. Furthermore, hybrid combinations of these fillers (e.g., CD + CFA, CD + MP, CD + CBPD) can provide synergistic effects by combining complementary properties of individual wastes, thereby offering greater improvements in water resistance and mechanical integrity compared to single fillers [10-11].

Despite these promising developments, comprehensive and systematic studies addressing the influence of different industrial waste fillers both individually and in hybrid combinations on the water absorption characteristics of glass epoxy composites remain scarce. Most available investigations have focused either on mechanical or thermal properties, with relatively limited attention to long-term durability in aqueous environments [12-14]. Additionally, the influence of immersion medium, such as distilled water, mineral water, ground water, or sea water, on moisture absorption behavior has not been adequately explored, even though these environments represent real-world service conditions for structural and marine applications.

The present work aims to address this critical gap by systematically investigating the moisture absorption behavior of E-glass fiber-reinforced epoxy composites modified with industrial waste fillers [15]. The study involves both single and hybrid filler systems, with varying weight percentages, exposed to different aqueous environments. The objectives are:

- To quantify the effect of filler type and loading percentage on water uptake.
- To evaluate the role of hybrid fillers in suppressing diffusion and enhancing resistance to moisture ingress.
- To compare the performance of composites in different immersion media, reflecting practical service conditions.
- To establish filler environment–loading interrelationships that can guide the design of durable and sustainable composite materials.

By bridging material development with environmental sustainability, this research not only provides insight into the functional utility of industrial wastes in advanced composites but also contributes to the development of cost-effective, durable, and eco-friendly alternatives for critical engineering applications, particularly in marine and structural domains.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, epoxy resin (LY556) was selected as the matrix material due to its excellent combination of mechanical strength, chemical resistance, and superior adhesive properties, which make it a widely used thermosetting polymer in structural composite applications. The curing of epoxy was achieved using triethylenetetramine (TETA) as the hardener, mixed in the recommended stoichiometric ratio to ensure complete cross-linking and optimum performance of the matrix.

E-glass fiber mats were employed as the primary reinforcement owing to their favorable balance of properties, including a density of 2.54 g/cm^3, high tensile strength, and resistance to environmental degradation. Their cost-effectiveness and compatibility with epoxy systems make them a suitable choice for fabricating composites aimed at structural and marine applications [16].

To further enhance the performance of the composites, particularly in terms of moisture resistance, various industrial waste fillers were incorporated into the matrix. These fillers were collected from local industries and carefully processed before use to achieve the desired particle size. Coal Dust (CD), obtained from thermal power plants, was sieved to a size below 75 µm. Coal Fly Ash (CFA), collected from electrostatic precipitators, was refined to a particle size of less than 63 µm. Marble Powder (MP), a by-product of marble cutting and polishing industries, was ground and sieved to achieve particles smaller than 63 µm. Cement Bypass Dust (CBPD), sourced from cement manufacturing plants, was processed and sieved to below 75 µm to ensure uniformity.

In addition to the individual fillers, hybrid filler combinations were also prepared to investigate possible synergistic effects. These hybrid systems included CD+CFA, CD+CBPD, and CD+MP, each mixed in equal proportions by weight. The inclusion of hybrid fillers was expected to improve the barrier effect against moisture ingress and provide enhanced mechanical and durability properties compared to single-filler composites.

2.2. Fabrication of Composites

The fabrication of the composites was carried out using the conventional hand lay-up technique, which is widely adopted in polymer composite processing due to its simplicity, flexibility, and suitability for producing laminates with controlled fiber orientations and filler distributions. To further improve the quality of the laminates and minimize the presence of voids, the lay-up process was followed by compression under a uniform load. This ensured better compaction, improved filler dispersion, and enhanced interfacial bonding between the fibers and the matrix. Flow chart shown in Fig.1 is the fabrication process.

The process began with the preparation of a clean, flat mold. The mold surface was thoroughly coated with a releasing agent to prevent adhesion of the cured laminate to the mold and to facilitate easy removal after curing. E-glass fiber mats were then carefully cut to the required dimensions and placed sequentially in the mold in a layer-by-layer arrangement. The reinforcement architecture was maintained consistently throughout to achieve uniform structural properties across the laminate.

The epoxy resin (LY556) was mixed with the appropriate amount of curing agent (TETA) in the recommended stoichiometric ratio, ensuring thorough stirring to achieve a homogeneous mixture. To this resin system, the per-processed industrial waste fillers were added at predetermined weight fractions of 2.5, 5, 7.5, and 10 wt.% with respect to the resin content. Each filler, whether single or hybrid, was dispersed in the resin using mechanical stirring to minimize agglomeration and promote uniform distribution. The prepared resin–filler mixture was then poured evenly over the E-glass fiber mats during the lay-up process.

A hand roller was used at each stage of lay-up to gently compress the fiber–resin layers, ensuring uniform impregnation of resin into the fiber mats while simultaneously expelling trapped air bubbles. This step was critical in reducing porosity and enhancing the fiber–matrix interface quality, thereby improving the overall mechanical integrity and moisture resistance of the composites. After the required number of layers had been laid up and impregnated, the entire assembly was subjected to compression under a uniform load. This additional compaction step further reduced voids, promoted resin flow, and provided smooth laminate surfaces.

The curing of the fabricated laminates was carried out at ambient room temperature for a duration of 24 hours to allow the initial cross-linking of the epoxy network. Following this, the laminates were post-cured in a hot air oven at 80°C for 3 hours. Post-curing is essential in epoxy systems as it enhances the degree of cross- linking, improves thermal stability, and ensures dimensional stability of the final composites.

Once cured, the laminates were carefully removed from the mold and subjected to finishing operations. Specimens of the required dimensions were cut from the laminates using a precision diamond cutter to avoid edge damage and to maintain dimensional accuracy. All specimens were prepared in accordance with ASTM D570 standards, which specify the requirements for water absorption testing of plastics and composites. The specimens were then polished and conditioned prior to testing to ensure consistency and repeatability in experimental evaluation.

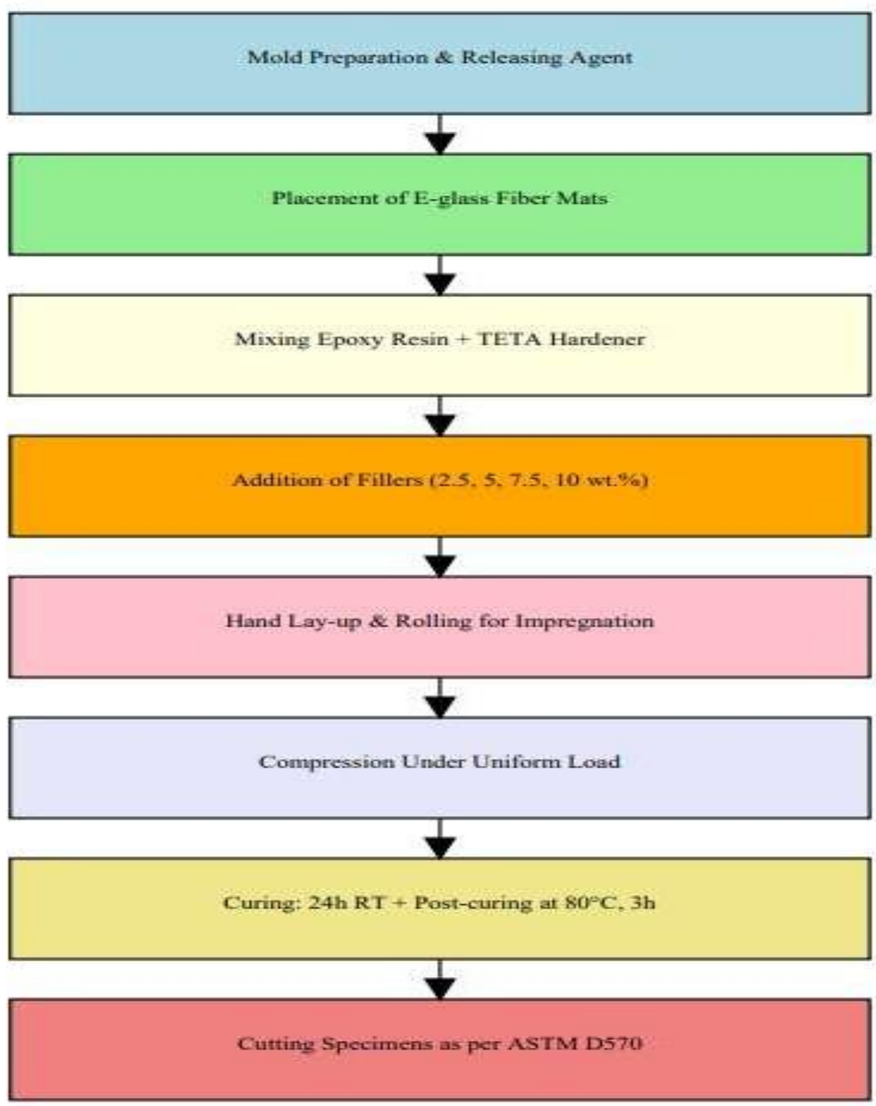

Fig. 1: Fabrication Process Flow Diagram

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2.3. Water absorption Behaviour of Composites

The water absorption characteristics of the fabricated composites were examined in accordance with ASTM D570 standards. Fig. 2 shows the process of water absorption behaviour of the composites. Prior to testing, all specimens were thoroughly dried in a hot air oven maintained at 50 °C until a constant initial weight (Wo) was obtained, ensuring the complete removal of residual moisture. The dried samples were then immersed individually in four different aqueous environments like distilled water, mineral water, ground water, and sea water maintained at ambient room temperature.

Fig.2: Water Absorption Test Workflow as per ASTM D570

At the end of the specified immersion period, the specimens were carefully removed, surface moisture was gently wiped off using absorbent tissue, and the saturated weight (Wb) was immediately recorded with high precision. The extent of water uptake was determined by calculating the percentage increase in weight using the following relation:

$$\text{Water Absorption (\%)} = \frac{W_b - W_o}{W_o} \times 100$$

where *Wb* is the weight of the specimen after immersion and *Wo* is the oven-dried initial weight. This procedure enabled a systematic evaluation of the influence of filler type and immersion medium on the moisture absorption behavior of the composites.

2.4. Experimental Designation

The composites were designated based on reinforcement and filler type, e.g.:
GE50, GE60: Neat glass–epoxy composites with different fiber ratios.
GECDx: Glass–epoxy with x wt.% coal dust.
GECFAx: Glass–epoxy with x wt.% coal fly ash.
GEMPx: Glass–epoxy with x wt.% marble powder.
GECBPDx: Glass–epoxy with x wt.% cement bypass dust.
GECDCFAx, GECDCBPDx, GECDMPx: Hybrid filler composites.
This systematic methodology enabled the comparative evaluation of water absorption across filler types, loadings, and immersion environments.

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3. RESULTS AND DISCUSSION

The water absorption characteristics of polymer matrix composites are critical in determining their long-term durability, especially for applications in marine, structural, and humid environments. Table 1 presents the comparative water absorption behaviour of neat glass–epoxy laminates and those modified with single and hybrid industrial waste fillers when immersed in four different aqueous media: distilled water (DW), mineral water (MW), ground water (GW), and sea water (SW).

Water uptake in composites primarily occurs through diffusion of water molecules into the polymer matrix, capillary action through micro-cracks or voids, and interfacial transport at the fiber–matrix interface. The extent of absorption is influenced by several factors such as matrix hydrophilicity, filler characteristics, interfacial bonding, and the nature of immersion medium.

The baseline composites (GE50 and GE60) without filler modification exhibited the highest water absorption, particularly in ground water (14.56%) and distilled water (9.64%), which can be attributed to the hydrophilic nature of the epoxy and the absence of barrier phases to hinder diffusion. These results are consistent with previous studies reporting that unmodified glass–epoxy composites are highly susceptible to moisture ingress, leading to swelling and deterioration of interfacial adhesion.

In contrast, filler-modified composites demonstrated significantly reduced water uptake across all immersion media. The incorporation of Coal Dust (CD), Coal Fly Ash (CFA), Marble Powder (MP), and Cement Bypass Dust (CBPD), individually and in hybrid combinations, acted as diffusion barriers and improved the packing density of the matrix, thereby reducing free volume available for water transport. Hybrid fillers such as CD+CFA, CD+CBPD, and CD+MP showed superior performance in certain cases, suggesting a synergistic effect where differences in particle size and morphology contributed to effective pore blocking and improved interfacial stability.

Table 1: WATER ABSORPTION BEHAVIOUR OF COMPOSITES

S. NO	Composite Designation	Immersed in Distilled water (DW)		Immersed in Mineral water (MW)		Immersed in ground water (GW)		Immersed in sea water (SW)		Water Absorption Percentage			
		Wb	Wo	Wb	Wo	Wb	Wo	Wb	Wo	DW	MW	GW	SW
1	GE50	3.63	3.98	3.62	3.79	3.64	4.17	3.64	3.88	9.64	4.70	14.56	6.59
2	GE60	4.73	4.80	4.01	4.06	4.68	4.73	4.58	4.61	1.48	1.25	1.07	0.66
3	GECD2.5	3.47	3.50	3.39	3.44	3.53	3.58	3.84	3.87	0.86	1.47	1.42	0.78
4	GECD5	3.04	3.07	3.46	3.53	3.28	3.36	3.57	3.64	0.99	2.02	2.44	1.96
5	GECD7.5	3.94	3.99	3.91	3.99	4.13	4.22	3.54	3.60	1.27	2.05	2.18	1.69
6	GECD10	3.35	3.39	3.64	3.73	3.81	3.86	3.69	3.79	1.19	2.47	1.31	2.71
7	GECBPD2.5	3.48	3.53	3.75	3.79	3.27	3.31	3.75	3.81	1.44	1.07	1.22	1.60
8	GECBPD5	3.39	3.43	3.76	3.79	3.88	3.93	3.82	3.87	1.18	0.80	1.29	1.31
9	GECBPD7.5	3.62	3.69	3.42	3.48	3.91	3.94	3.64	3.68	1.93	1.75	0.77	1.10
10	GECBPD10	3.61	3.65	3.68	3.71	3.63	3.69	3.59	3.64	1.11	0.82	1.65	1.39
11	GECFA2.5	3.50	3.56	3.14	3.20	3.81	3.83	3.70	3.78	1.71	1.91	0.52	2.16
12	GECFA5	3.20	3.26	3.01	3.07	3.11	3.22	3.30	3.41	1.87	1.99	3.54	3.33
13	GECFA7.5	3.43	3.47	3.85	3.87	3.65	3.70	3.65	3.72	1.17	0.52	1.37	1.92
14	GECFA10	3.31	3.53	3.27	3.37	2.89	3.04	3.26	3.37	6.65	3.06	5.19	3.37

15	GEMP2.5	3.68	3.75	3.54	3.57	3.77	3.80	3.46	3.51	1.90	0.85	0.80	1.45
16	GEMP5	3.41	3.46	3.42	3.47	3.63	3.66	3.49	3.54	1.47	1.46	0.83	1.43
17	GEMP7.5	2.87	2.96	2.89	2.95	2.82	2.96	2.78	2.88	3.14	2.08	4.96	3.60
18	GEMP10	3.58	3.63	3.41	3.45	3.83	3.86	3.76	3.81	1.40	1.17	0.78	1.33
19	GECDCFA2.5	3.82	3.86	3.78	3.83	3.94	3.99	3.75	3.81	1.05	1.32	1.27	1.60
20	GECDCFA 5	3.32	3.37	3.16	3.21	3.13	3.20	3.36	3.43	1.51	1.58	2.24	2.08
21	GECDCFA 7.5	3.52	3.59	3.82	3.86	3.76	3.80	3.67	3.74	1.99	1.05	1.06	1.91
22	GECDCFA10	3.52	3.57	3.45	3.52	3.45	3.53	3.79	3.85	1.42	2.03	2.32	1.58
23	GECDCBPD2.5	3.49	3.55	3.39	3.44	3.71	3.76	3.58	3.62	1.72	1.47	1.35	1.12
24	GECDCBPD 5	3.54	3.56	3.52	3.58	3.76	3.83	3.61	3.65	0.56	1.70	1.86	1.11
25	GECDCBPD 7.5	3.50	3.58	3.73	3.78	3.82	3.87	3.76	3.81	2.29	1.34	1.31	1.33
26	GECDCBPD10	3.57	3.61	3.40	3.46	3.67	3.70	3.53	3.58	1.12	1.76	0.82	1.42
27	GECDMP2.5	3.43	3.47	3.16	3.23	3.22	3.25	3.61	3.67	1.17	2.22	0.93	1.66
28	GECDMP5	3.30	3.35	3.38	3.41	3.18	3.23	3.24	3.32	1.52	0.89	1.57	2.47
29	GECDMP7.5	3.74	3.80	3.56	3.60	3.24	3.29	3.71	3.76	1.60	1.12	1.54	1.35
30	GECDMP10	3.64	3.70	3.69	3.77	3.56	3.62	3.64	3.69	1.65	2.17	1.69	1.37

The type of immersion medium also influenced absorption behaviour. Ground water and distilled water caused higher moisture uptake compared to mineral and sea water, possibly due to variations in ionic content and osmotic pressure effects. The higher absorption in ground water may be attributed to dissolved salts and minerals enhancing micro-crack propagation, whereas the saline environment of sea water may have restricted additional diffusion due to ionic equilibrium effects at the interface.

Overall, the results indicate that the introduction of industrial waste fillers mitigates moisture absorption in glass–epoxy composites by restricting diffusion pathways, enhancing filler–matrix bonding, and reducing micro-voids. This improvement is most pronounced at optimized filler loadings (2.5–7.5 wt.%), beyond which agglomeration of fillers may create localized defects, slightly increasing absorption in some cases (e.g., 10 wt.% filler loadings).

3.1. Discussion on Water Absorption Behaviour in Distilled Water (DW)

The water absorption behaviour of composites immersed in distilled water (DW) shown in Fig.3, reveals significant variations depending on the composite designation and reinforcement content. Among all the composites studied, GE50 exhibited the highest water absorption (9.64%), which indicates poor resistance to moisture ingress in the absence of additional fillers. This suggests that the plain glass-epoxy system without hybrid reinforcement tends to absorb more water due to the hydrophilic nature of the epoxy matrix and the micro voids formed during fabrication.

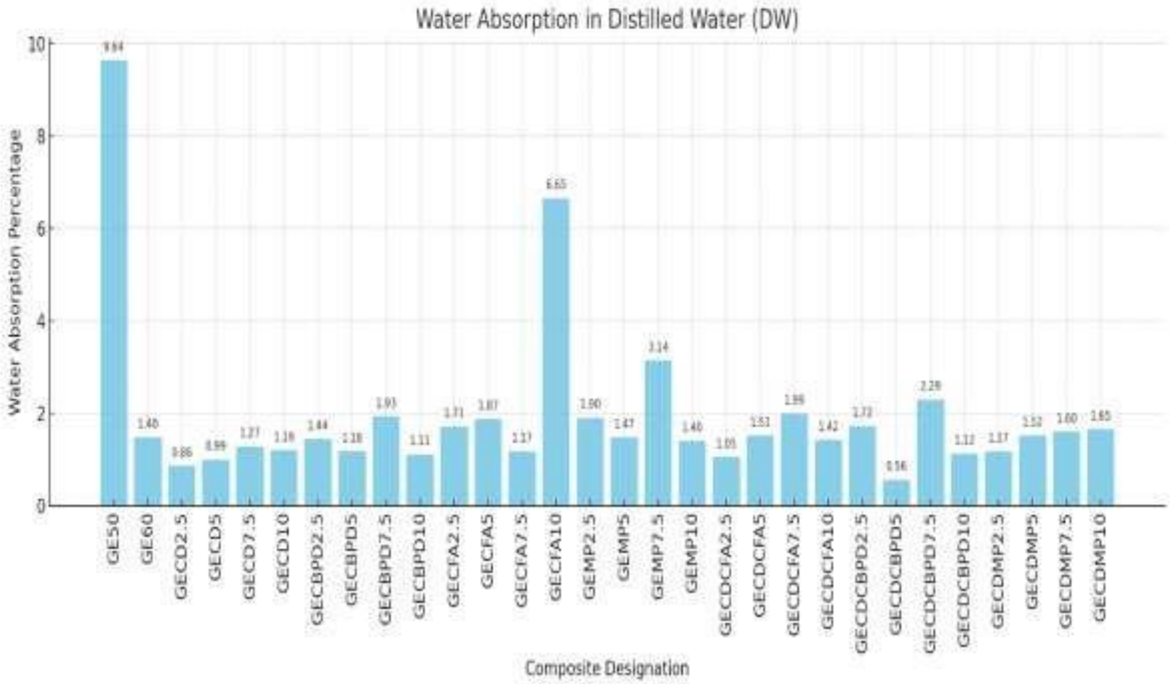

Fig.3: Water Absorption Behaviour of composites in Distilled Water (DW)

In contrast, composites with hybrid fillers such as GECD2.5, GECD5, GECBPD5, and GECDCBPD5 showed much lower absorption values (close to or below 1%). This demonstrates the beneficial role of particulate fillers like coal dust, fly ash, cement bypass dust, and marble powder in reducing the free volume and blocking the diffusion pathways for water molecules.

Interestingly, composites with intermediate filler content (5–10 wt.%) generally showed reduced water absorption compared to the neat matrix, indicating that the filler-matrix interaction improves barrier properties. However, a few cases such as GECFA10 (6.65%) and GEMP7.5 (3.14%) showed relatively higher absorption values than their lower filler counterparts. This anomaly may be attributed to agglomeration of fillers at higher loading, leading to micro-cracks and interfacial de-bonding, which in turn increases water penetration.

Overall, the distilled water absorption data suggest that the incorporation of industrial waste fillers into glass- epoxy composites significantly enhances their moisture resistance by improving matrix densification and reducing void content. The trend confirms that an optimal filler content (typically around 2.5–5 wt.%) is most effective in minimizing water absorption, while excessive addition can deteriorate performance due to poor dispersion.

3.2. Discussion on Water Absorption Behaviour in Mineral Water (MW)

The water absorption behaviour of composites immersed in mineral water (MW) shows a different trend compared to distilled water IN Fig.4 due to the presence of dissolved salts and minerals. In general, the absorption percentages in MW are lower than those in distilled water, indicating that ionic interactions with the composite surface may partially restrict water diffusion.

Among all composites, GE50 exhibited a relatively higher absorption value (4.70%) compared to the other systems, consistent with its poor barrier properties observed in distilled water. In contrast, most of the hybrid composites demonstrated absorption values below 2%, highlighting the beneficial effect of filler addition. For example, GECBPD5 (0.80%), GECFA7.5 (0.52%), and GEMP2.5 (0.85%) absorbed the least amount of water, suggesting that these filler systems effectively blocked the transport of water molecules.

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The composites reinforced with coal dust, fly ash, and marble powder at moderate loadings showed improved water resistance, as the filler particles filled micro voids in the epoxy matrix and restricted water penetration. However, higher filler content (10 wt.%) in some systems, such as GECD10 (2.47%) and GECDCFA10 (2.03%), showed an increase in absorption, which can be attributed to filler agglomeration and weaker filler– matrix interfacial bonding.

The results indicate that 2.5–7.5 wt.% filler loading is generally optimal for reducing water absorption in mineral water. The slightly higher values in some composites compared to distilled water suggest that ionic species present in mineral water may interact with hydrophilic groups of the epoxy resin, thereby influencing diffusion characteristics.

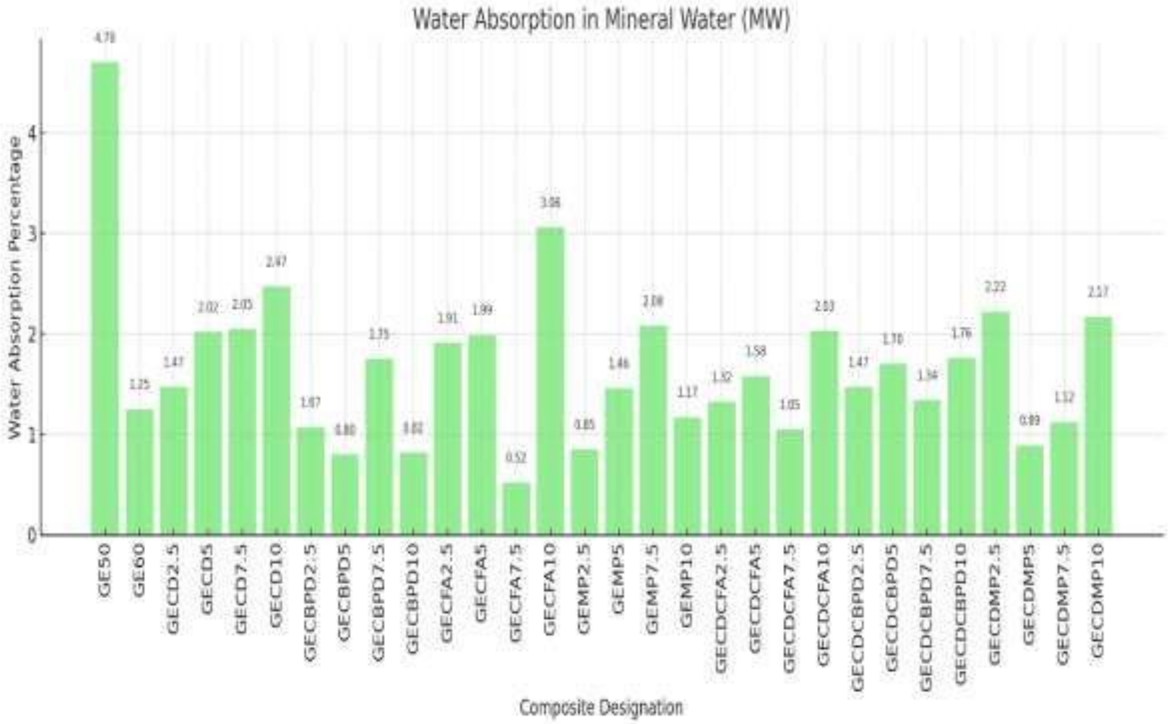

Fig.4: Water Absorption Behaviour of composites in Mineral Water (MW)

In summary, the study confirms that mineral water immersion results in lower and more controlled water absorption compared to distilled water, with the most effective resistance observed in composites containing fly ash (7.5%), cement bypass dust (5%), and marble powder (2.5%) reinforcements.

3.3. Discussion on Water Absorption Behaviour in Sea Water (SW)

The water absorption behaviour of composites immersed in sea water (SW) shows an intermediate trend between distilled water and ground water as shown in Fig. 5. Sea water, being saline and rich in dissolved ions, has a dual effect: on one hand, the presence of salts can partially block free water diffusion into the matrix; on the other hand, prolonged exposure may promote osmotic pressure and micro-crack formation, leading to moderate absorption levels.

Among all composites, GE50 again demonstrated relatively high absorption (6.59%), confirming the poor resistance of neat glass–epoxy composites to aqueous environments. This value, though lower than in ground water, is still significantly higher than in mineral water, highlighting the susceptibility of unmodified epoxy to seawater ingress.

In contrast, most hybrid composites showed absorption values between 1% and 3%, indicating

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that fillers such as coal dust, fly ash, cement bypass dust, and marble powder improved the barrier properties by blocking capillary channels and reducing free volume within the epoxy matrix. Notably, GECBPD5 (1.31%), GECDCBPD5 (1.11%), and GECD10 (2.71%) displayed relatively low absorption values, suggesting that moderate levels of filler incorporation are effective in enhancing seawater resistance.

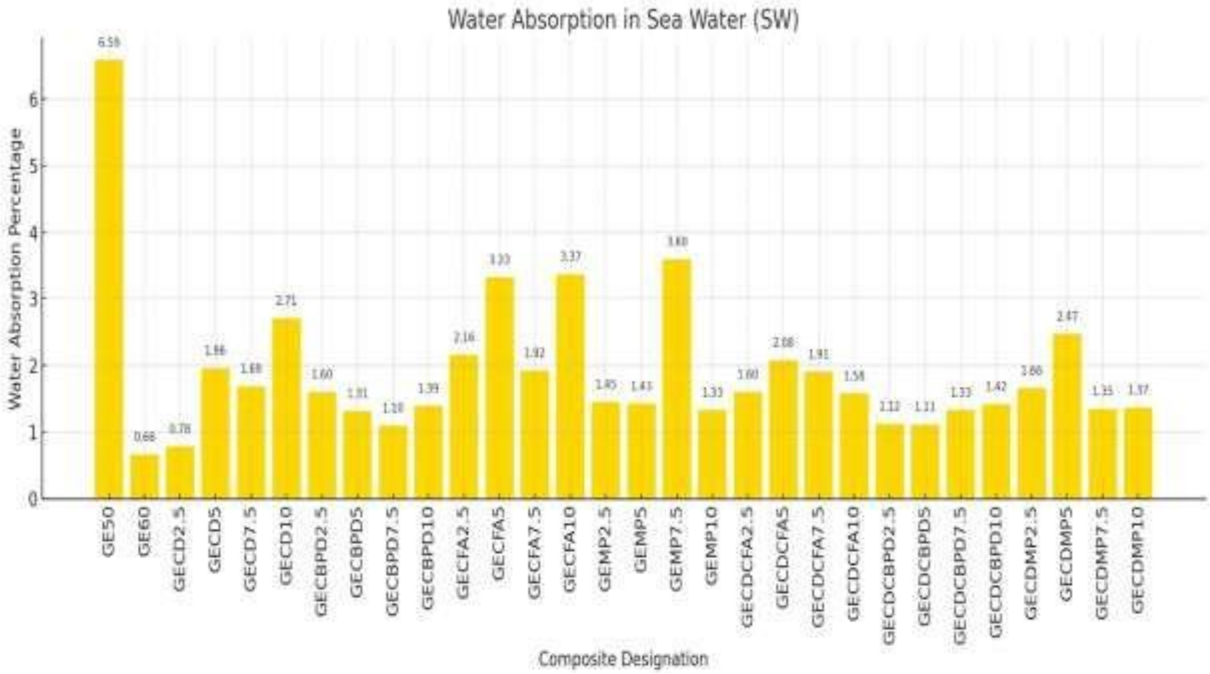

Fig.5: Water Absorption Behaviour of composites in Sea Water (SW)

However, in some cases such as GEMP7.5 (3.60%) and GECFA5 (3.33%), absorption values were higher than expected, likely due to non-uniform filler dispersion and micro void formation at intermediate or higher loading levels. This highlights that filler type and compatibility with the epoxy matrix play a critical role in moisture resistance under saline conditions.

Overall, sea water immersion results indicate that the addition of 2.5–5 wt.% of fillers is most effective in minimizing water absorption. Beyond this range, agglomeration effects dominate and reduce the protective barrier action. The results also suggest that while seawater absorption is less aggressive than ground water, it still poses a significant challenge to long-term durability, particularly in marine and coastal applications.

In summary, composites immersed in sea water demonstrated improved performance with filler reinforcement, but their effectiveness depends strongly on the type of filler and its dispersion quality. For applications in saline environments, optimized filler loading is essential to maintain structural integrity and minimize water-induced degradation.

3.4. Discussion on Water Absorption Behaviour in Ground Water (GW)

The water absorption behaviour of composites immersed in ground water (GW) shown in Fig.6 exhibited a more pronounced variation compared to distilled and mineral water. This is mainly due to the higher presence of dissolved salts, minerals, and impurities in ground water, which can enhance the diffusion of water molecules through the polymer matrix and along the filler–matrix interfaces.

The most striking observation is that GE50 absorbed the highest amount of water (14.56%) among all composites and all immersion conditions, highlighting the vulnerability of neat glass–epoxy composites to moisture ingress. This exceptionally high value can be attributed to the hydrophilic nature of the epoxy resin and the absence of fillers to restrict micro-crack formation or block water transport pathways.

In comparison, hybrid composites demonstrated significantly lower absorption values, mostly within the range of 0.5% to 3%, confirming the effectiveness of fillers in restricting water penetration. For example, GECFA2.5 (0.52%), GEMP2.5 (0.80%), and GECBPD7.5 (0.77%) showed the lowest absorption, illustrating that small filler additions create an effective barrier against ground water intrusion.

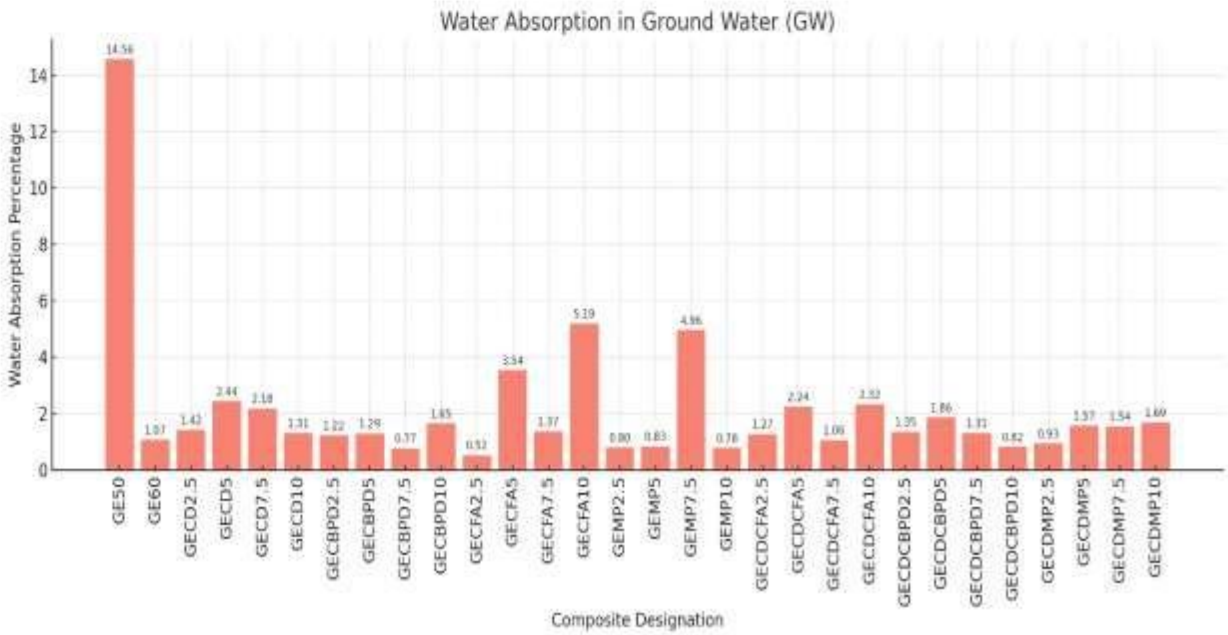

Fig.6: Water Absorption Behaviour of composites in Ground Water (GW)

However, higher filler loading sometimes resulted in increased absorption. For instance, GECFA10 (5.19%) and GEMP7.5 (4.96%) showed relatively high-water absorption compared to their lower filler counterparts. This behaviour is likely due to agglomeration of fillers at high weight fractions, leading to micro voids and weak filler–matrix bonding, which serve as entry points for water molecules.

Overall, the results clearly indicate that ground water leads to the most aggressive water absorption behaviour among the tested environments. While hybridization with industrial waste fillers significantly improves resistance, an optimal filler loading (2.5–5 wt.%) is necessary to balance filler dispersion, mechanical integrity, and water resistance.

In summary, composites immersed in ground water demonstrate the highest sensitivity to environmental conditions, emphasizing the importance of proper filler selection and loading to mitigate moisture-related degradation in real-world applications where composites may be exposed to underground or untreated water sources.

3.5. Overall Comparison

- GE50 (neat glass–epoxy) consistently exhibited the highest absorption across all environments, confirming its poor resistance to aqueous media.
- Hybrid composites demonstrated significant improvement in water resistance, with 2.5–5 wt.% filler loadings emerging as the optimal range.
- Ground water was the most aggressive medium, followed by sea water, distilled water, and finally mineral water as the least aggressive.
- Excessive filler content (>7.5 wt.%) often led to agglomeration and micro-structural defects, reducing

the beneficial effect of fillers.

4. CONCLUSION

The study confirms that incorporating industrial waste fillers into glass–epoxy composites effectively reduce water absorption and enhances durability in different aqueous environments. Among the tested media, ground water exposure was the most severe, while mineral water caused the least absorption. The findings strongly suggest that an optimal filler loading of 2.5–5 wt.% provides the best balance between filler dispersion and matrix integrity, ensuring improved resistance to moisture-induced degradation in practical applications.

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