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Study the Influence of Nano-Beryllia on Carbon Fabrics Reinforced Epoxy Composites Exposed to Chemical Attack

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Abstract

Hybrid polymer composites are an essential part of modern production. Polymer composite structures may encounter diverse corrosive environments during their operational lifespan, resulting in structural degradation and a decline in their inherent properties. This study examines the impact of using various volume fractions (1%, 2%, and 3%) of beryllium oxide (BeO), which is also known as beryllia, nanoparticles on the mechanical properties of carbon fabric-reinforced epoxy composites in both acidic and alkaline conditions at different exposure times. The investigation focuses on the toughness, tensile features, and hardness values of the prepared hybrid composite before and after immersion in hydrogen chloride (HCl) and caustic soda (NaOH) solutions. Irrespective of the solution type, exposure over time reduces the hardness, tensile strength, and impact strength. Notably, the alkaline solution induces a more pronounced decrease in these features than the hydrogen chloride (HCl) solution. Furthermore, BeO nanoparticles result in a noteworthy enhancement in the mechanical performance of these hybrid composites against these solutions.

Keywords: Acid Solution, Beryllia, Caustic Soda, Carbon Fabrics, Hybrid Composite, Mechanical Properties, Nanoparticles.

1. Introduction

Epoxy resins are frequently used as a matrix in polymer composites reinforced by glass fibers, polyamide fibers, and carbon fibers. The long-term contact of these composites with a chemical environment is a great concern [1]. Additionally, degradation of carbon-epoxy composite was evident at high PH solutions [2]. An increasing interest in utilizing reinforced polymer composites as a viable option in highly corrosive environments, instead of traditional materials like cast iron or stainless steel, particularly in the automotive industry, marine industry, construction and infrastructure, is becoming prevalent [3]. The appeal of employing polymer composites stems from their significant weight reduction, coupled with their high rigidity and specific strength, resilience to impacts, cost-effectiveness, favorable resistance to severe chemical corrosion, and ease of manufacturing. Presently, polymer composites are extensively employed, particularly as pipes, across various sections in the construction industry. [4].

Composites based on fiber-reinforced polymers have become a promising substitute for conventional building materials, which have elevated strength, lightweight nature, and are excellent in resistance to corrosion. These types of materials are utilized across diverse industries including marine construction, automotive, aerospace, and civil engineering. Nevertheless, fiber-reinforced polymer FRP sustained effectiveness and lasting resilience are pivotal factors influencing their appropriateness for most applications [5]. Fiber-reinforced polymer durability relates to its ability to withstand exposure to the environment and processes of deterioration over an extended period of time [6]. Environmental elements such as humidity, temperature fluctuations, exposure to chemical solutions, and radiation have a greater effect on the performance of FRP composites. Moreover, aging processes: microcracking, breaking down, creep, failure due to fatigue, and fiber degradation are a few illustrations of the way a material's characteristics begin to deteriorate [7].

Nevertheless, the rapid flow of solid particles and chemical solutions within glass fiber-reinforced polymer (GFRP) pipelines can trigger various degradation processes, including abrasion, changes in hardness, separation of fibers from the matrix, and deterioration of the matrix [8]. Given these circumstances, there is an immediate need to improve the resilience of the composite pipes made of fiberglass to address different forms of corrosive environments [9].

Tasnim and Shaikh [10] conducted an experimental study examining the impact of solutions of sodium chloride (NaCl), magnesium sulfate ($MgSO_4$), and sulfuric acid (H_2SO_4) on the microstructure and mechanical features of lightweight polymer composites containing recycled polyethylene terephthalate (PET) flakes, recycled tire crumb rubber (CR), and fly ash (FA) as fillers. For periods ranging from one to six months, the lightweight polymer composites were submerged in solutions containing one mol H_2SO_4, one mol $MgSO_4$, and 0.5 mol NaCl. The evaluation included compression stress, modulus strength, densities, and microstructures to assess the composite behavior under the following environments. The results indicated that the majority of the emerged composites from the lightweight polymer type demonstrated improved compression strength residue after exposure to the specified chemical environments. However, mixed outcomes were observed in the modulus strength residue. The density of polymer composites did not exhibit significant changes across various exposure times and media. Microstructural examination showed no signs of degradation in composites and no formation of further reaction products after exposure to these aggressive solutions.[10] .

Pan and Yan [11] studied the impact of carbon-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) hybrid bars in alkaline environments. The assessed impact of CFRP lamina on the longevity of GFRP bars and the behaviors of water absorption for both hybrid fiber-reinforced (HFRP) and GFRP polymer bars were examined. Additionally, the degradation of interlaminar shear strength in HFRP and GFRP beams aged in an alkaline solution was evaluated using a short beam shearing test. It was found that the residual interlaminar shear strengths of HFRP bars were higher than those of GFRP bars after exposure to an alkaline solution. It was also shown that the CFRP/CFRP interface is where HFRP bars in an alkaline solution deteriorate. By postponing water and OH- diffusion in CFRP and utilizing CFRP's better alkaline resistance, the study shows that the CFRP layer increases the durability of GFRP bars in alkaline settings.

Uthaman et al. [4] assessed the long-term exposure of carbon fiber epoxy composite to water, acids, and alkaline environments at various temperatures. Their results revealed that the composite deteriorated under the effect of these solutions, especially in the HCL solution. Moreover, their mechanical properties were reduced.

Chen *et al.* [12] investigated the impact of doping ZrO_2 on carbon fiber dispersed in epoxy fiber. According to their results, they can achieve better corrosion resistance and mechanical features owing to the good properties of ZrO_2.

Al-Zubaydi *et al.* [13] studied the effect of adding nano titanium dioxide as hybrid reinforcement on the mechanical properties and the resistance to chemical attack. They found that the developed material has better mechanical properties and chemical attack resistance.

Yin *et al.* [14] investigated the enduring alkaline stability of a biphenyl polymer based on piperidinium (PBP-PIP) in a high-pH operational setting. The hydroxide conductivity of the PBP-PIP membrane was measured at 80°C and showed 57 ms cm^{-1}, along with a tensile strength of 28.2 MPa. After being submerged in an 80°C aqueous solution holding (1%) mol of NaOH for 750 hours, the PBP-PIP membrane astonishingly showed remarkable resilience to the alkaline conditions, holding onto 76% of its conductivity and 77% of its tensile strength.

Kojnoková *et al.* [15] assessed the influence of thermal and chemical environments on carbon fiber-reinforced epoxy composite. They used aqueous, alkaline, and acidic solutions. Their results revealed that the degradation increases as temperature increases. Click or tap here to enter text.

Wang *et al.* [16] investigated the glass fiber-reinforced polymer's (GFRP) tensile strength in both saline and alkaline conditions. After a year at 60 °C, the results showed that the GFRP rebars' ability to retain tensile strength decreased by 45.9%, 47.2%, 44.2%, 41.1%, 27.6%, 30.3%, and 31.9% in distilled water (pH = 7), seawater (pH = 8.2), sodium hydroxide solutions (pH = 11, 12, or 13), and simulated normal concrete (pH=13.6) respectively. In the Arrhenius equation, the activation energy and residual tensile strength showed a quadratic parabolic decline with decreasing pH. The study unveiled the degradation mechanism by connecting macroscopic tensile strength deterioration and microscopic factors such as diffusion of water/ions and degradation of the fiber/matrix interface. Importantly, this research identified the level of pH, rather than saline ions, as the primary influencing factor for GFRP degradation.

This study investigates the effect of nano-Beryllia on composite materials composed of carbon fiber epoxy exposed to diverse corrosive environments. By enhancing the wettability between the host medium and the reinforcing phase represented by beryllium oxide and thus improving the process of load transfer from the host medium to the reinforcing phase, which leads to improved mechanical and chemical properties in basic and acidic media compared to previous studies that were reviewed.

2. Materials

2.1. Matrix Phase

The matrix employed is an epoxy resin combined with its hardener, triethylenetetramine (TETA), in a 3:1 ratio, obtained from SIROPOL.GP. This choice is based on the epoxy resin's advantageous characteristics, such as superior chemical resistance, high modulus and strength, ease of production, and widespread commercial availability[17]. Refer to Table 1 for a detailed overview of the epoxy resin characteristics utilized in the present study.

2.2. Reinforcing Phase

Two types of reinforcing phases were used in this work. The former was carbon fabric style 284, a 2/2 twill weave from HexForce company, as shown in Fig. 1. It is compatible with polymers like epoxy and vinyl-ester resins. Carbon fabrics are one of the most vigorous and rigid reinforcement materials accessible. Beyond possessing remarkable strength/weight and stiffness/weight ratios, carbon fabrics exhibit low coefficients of thermal expansion and exceptional fatigue behavior [18]. The latter were beryllia nanoparticles provided by the NANOSHEL company, as seen in Fig. 1; their properties are listed in Table 2.

Table 1. Specification of the Epoxy matrix according to the provider (HexForce company).

Epoxy Specification	Value
Tensile strength (MPa)	50-80
Modulus of Elasticity (GPa)	2-5
Modulus of Strength (MPa)	50-65
Elongation %	0.7
Compressive strength (MPa)	160-185
Density g/cm^3	1.55
Glass transition temperature °C	100-130

A: Carbon fabrics. B. Beryllia nanoparticles.

Figure 1. Reinforcing phases: A. carbon fabric, B. beryllia nanoparticles.

Table 2. Specification of beryllia nanoparticles according to the provider (NANOSHEL company).

Property	Value
Molecular formula	BeO
Purity	99.8%
Particle Size	25-50 nm
Density	2.9 g/cm^3
Form	Powder
Color	White
Melting point	2507 ºC

3. Procedure of Hybrid Composite Manufacturing

In this study, three sets of samples were prepared. The initial set (G1) consisted of reference samples containing epoxy resin without additives. The second set (G2) comprised samples with carbon fabric reinforcement in the epoxy matrix, while the third set (G3) involved beryllia nanoparticles filled with carbon fabric epoxy resin. In this study, the hybrid composites and composite materials were manufactured using the hand lay-up method. Epoxy resin and hardener (3:1 ratio) were combined for three minutes in a plastic cup to cure the epoxy resin and prepare the composite materials.

Simultaneously, five layers of carbon fabric with 15% wt. of the weight of epoxy were placed in a metal mold, followed by applying the epoxy mixture using a clean brush. In contrast, the hybrid composites were created by integrating beryllia nanoparticles into the carbon fabric epoxy hybrid composite at various volume fractions (1%, 2%, and 3%, respectively). In this instance, the beryllia nanoparticles were blended thoroughly with the epoxy mixture until a uniform consistency was attained. Subsequently, this mixture was applied to the arranged fabric layers within the mold. To avoid the settling of ceramic particles at the sample's base, it is crucial to introduce the particles before the gelation stage during mixture preparation.

4. Experimental Work

Three samples were made with the required characteristics for each test by shaping the hybrid composite material prepared according to ASTM standards and executing the designated procedures for each specific test.

4.1. Tensile Test

Using the Tinius Olsen universal material testing machine, which has a 100 KN load cell and a strain rate of 10 mm/min, the tensile properties of composites are evaluated in compliance with the ASTM D3039 specification [19]. The obtained data include the elastic modulus, tensile strength, fracture point, and elongation. Three readings were taken for each addition ratio, and the average was taken for each tensile test sample. Fig. 2 shows the samples used for the tensile test.

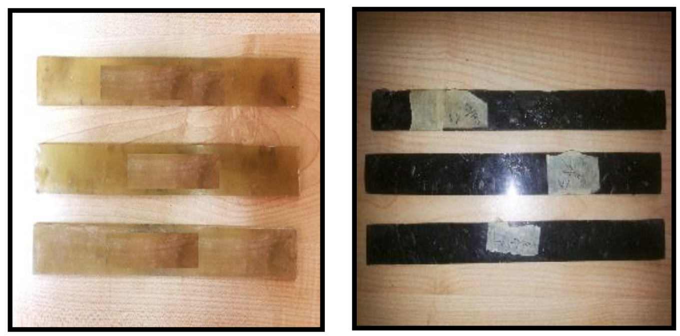


Figure 2. Tensile samples. Left (epoxy resin, right (composite)

4.2. Toughness Test

The hybrid composite's Izod impact strength was assessed using the Time Testing Machines XJU-22's Izod impact device by the ASTM standard D-256. [20]. Three readings were taken for each addition ratio, and the average was taken for each test sample.

4.3. Hardness Measurements

The hardness test employed the W-Tester Amsler Durometer's Shore (D) device, conforming to the DIN 53505-ISO P858 standards. This device, resembling a compass with a central needle, was utilized to calculate the hardness values of the prepared hybrid composites.

For accurate findings, the needle of the device was positioned perpendicularly to the sample's smooth surface, ensuring the needle contacts the surface. The hardness value was obtained by inserting the needle into the material's surface at five points for three seconds, and the readings were then recorded from the device by taking the average of these five readings.

4.4. SEM Characterization

SEM analysis was done using the TESCAN Vega II XMU tool at 30 kV and a working distance of 18 mm, which offers high-resolution images. Before the analysis, the samples underwent cleaning and drying and were subsequently affixed to a metal stub using adhesive. A coating of gold, ranging between 40 and 60 nanometers, was applied to the mounted samples.

5. Results and Discussion

In Figs. 3 to 7, the effects of all groups on hardness, impact strength, and tensile characteristics of epoxy resin were investigated. The results presented in Table 3 indicated that the (G3) group, precisely (G32) with a (2%) volume fraction of beryllia nanoparticles, exhibited superior tensile, elastic modulus, toughness, and hardness values compared to (G2), which already demonstrated high properties in comparison to the reference (G1) group.

The improvement observed in the mentioned characteristics can be ascribed to the inherent qualities of the fabrics utilized. Carbon fabrics, known for their superior tensile strength among various fibers, also possess high-energy absorption properties, thereby enhancing the impact strength of epoxy resin. Also, the effective dispersion of beryllia nanoparticles within the epoxy matrix contributes significantly to these enhancements. The combination of these factors plays a crucial role in bolstering mechanical properties by impeding crack propagation under stress. The characteristics of hybrid composites exhibited an upward trend with the augmentation of the volume fraction of nanoparticles up to (2%), as indicated in Table 3.

Fig.8 and Fig. 9 illustrate the enhanced properties attributed to the good dispersion of BeO nanoparticles within the structure due to ultrasonic dispersion, as shown in the signs of the SEM images displayed. However, beyond this threshold value, a marginal decline in these properties was observed by up to 3%. The most significant property decreases are attributed to the agglomeration of BeO nanoparticles within the epoxy polymer matrix. The elevated viscosity of the mixture at higher volume fractions of the nanoparticles is the primary cause, leading to increased void formation in the microstructure, as seen in the signs in Fig. 10 of the SEM image.

Table 3. Mechanical properties of all prepared groups.

Specimens	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Toughness strength (KJ/m^2)	Micro-Hardness (Unitless)
G1	77	3.1	5.5	70.4	85
G2	132	4.3	7.3	89.3	89
G31	145	4.6	7.1	92.6	92
G32	152	4.9	6.9	96.5	96
G33	143	3.7	6.2	90.8	95

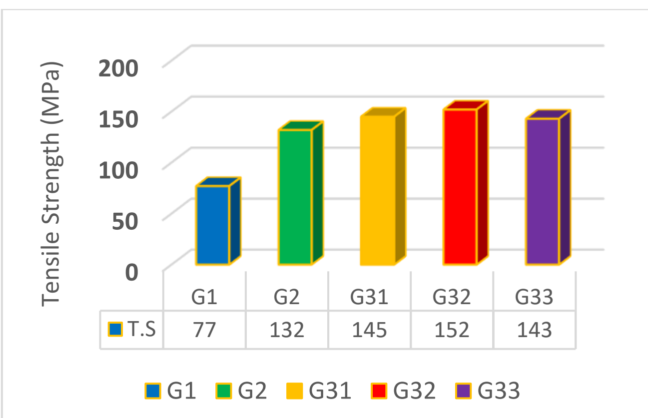


Figure 3. Tensile strength for different composite categories.

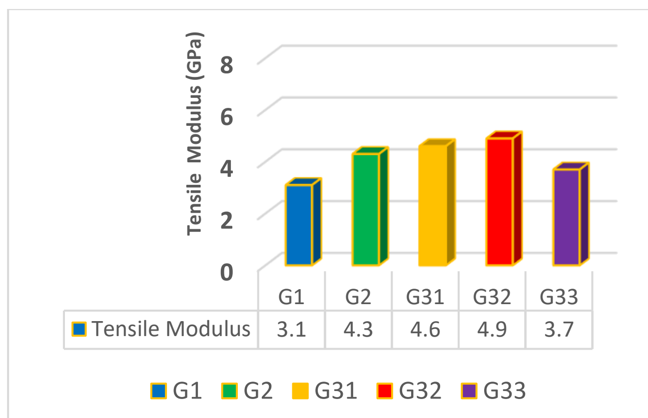


Figure 4. Tensile modulus for different composite categories.

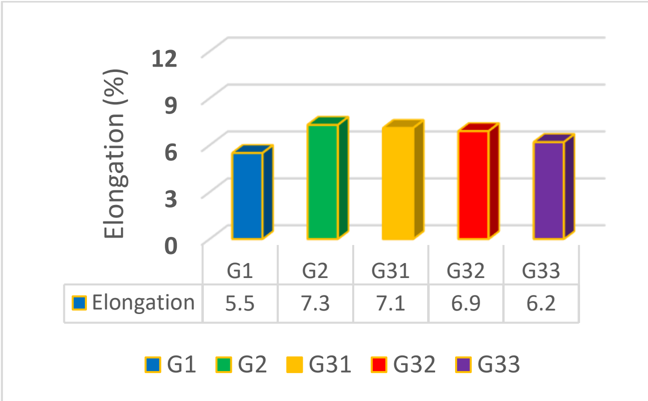


Figure 5. Composite groupings oppose Elongation.

Fig. 11 to Fig. 13 illustrate the response of all sets of prepared composite samples when subjected to immersion in alkaline and acid solutions with a concentration of 15 M over varying exposure durations.

The study employed different periods (one week, two weeks, three weeks, and four weeks). The outcomes indicate a noticeable weight increase up to 28 days for all groups, with similar values observed when the samples were immersed in both alkaline and acid solutions.

This absorption induces matrix deterioration, resulting in the formation of cavities, and during the fabrication of composite materials, micro-stress begins to generate [12].

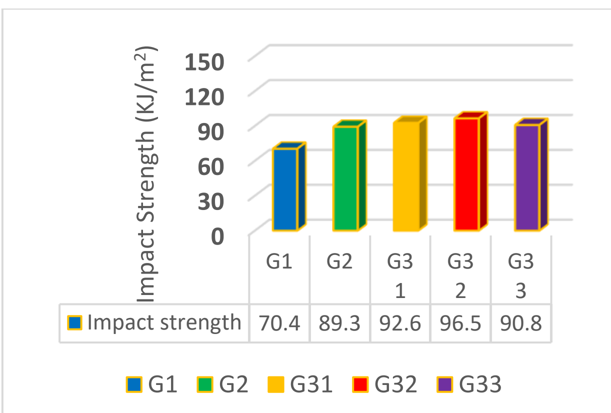


Figure 6. The Impact toughness and composite categories.

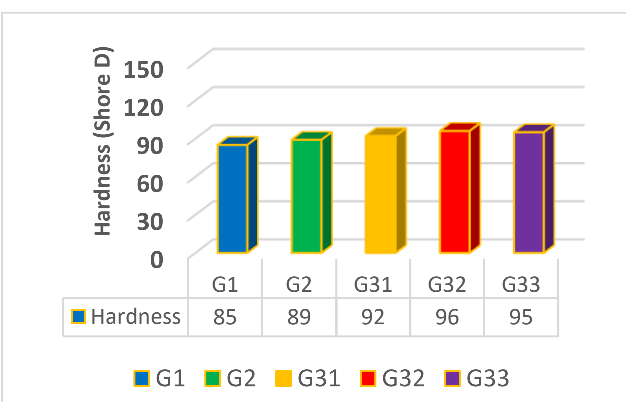


Figure 7. Comparing hardness and composite categories.

Additionally, it was noted that among the three groups, the (G32) hybrid composite with (2%Vf) content of beryllia nanoparticles demonstrated greater resilience to the chemical solutions compared to the (G2) group, which already exhibited notable corrosion resistance in comparison to the (G1) group.

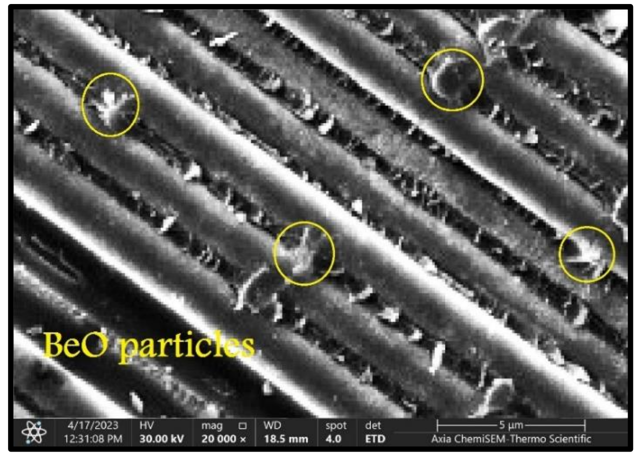


Figure 8. Magnified Image (SEM) (G31) of the hybrid composite.

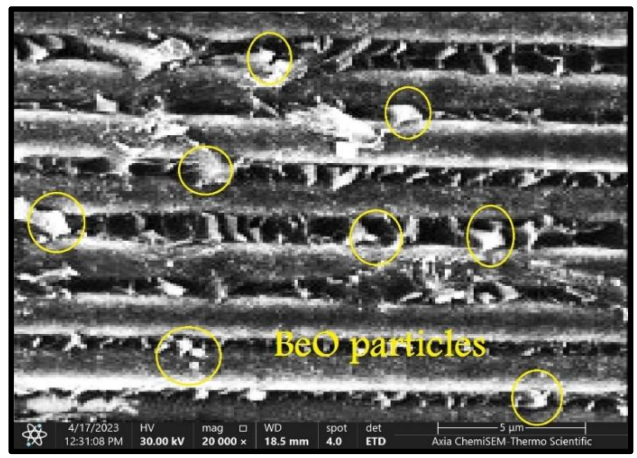


Figure 9. Magnified Image (SEM) (G32) of the hybrid composite.

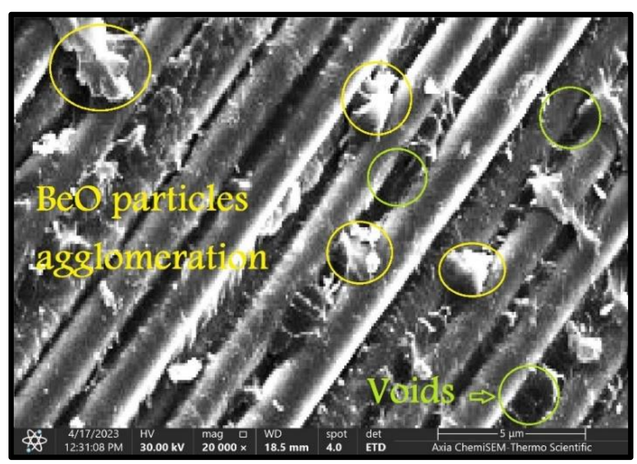


Figure 10. Magnified Image (SEM) (G33) of the hybrid composite.

The improvement in the corrosion resistance of the hybrid composite against chemical solution exposure is attributed to the heightened hardness values. This hardness increase will enhance epoxy resin's resistance to chemical solution penetration, consequently augmenting the epoxy matrix surface hardness. Furthermore, the effective dispersion of nanoparticles plays a crucial role in filling voids within the structure and reducing the absorption rate of solutions within the epoxy structure [5].

Figs. 14 to 18 depict the impact of exposure to acidic and alkaline solutions on hardness, impact strength, and tensile characteristics of the group given the best mechanical properties represented by (G32). It is evident that all these properties declined during immersion in these solutions, and the magnitude of these decreases escalates with prolonged immersion duration.

Furthermore, the outcomes indicate that the (NaOH) solution exerts a more pronounced impact on the indicated properties compared to the hydrochloric acid solution, as shown by the Magnified images (SEM) in Fig.19 to Fig. 20.

Examining Magnified images (SEM) with several pits in the microstructure of epoxy resin, resulting from chemical attacks, induces the generation of microstresses in the prepared hybrid composites. A decline in the mechanical performance can be related to the absorption of chemicals into epoxy resin, diminishing connectivity between the phases and resulting in weakened interphase bonds, ultimately reducing the mechanical features of the composite [17].

Conversely, it can be inferred that the hardness of the hybrid composite experienced a slight increase following seven days of immersion in both chemical solutions. However, the value of composite hardness declined with prolonged duration of exposure (28 days).

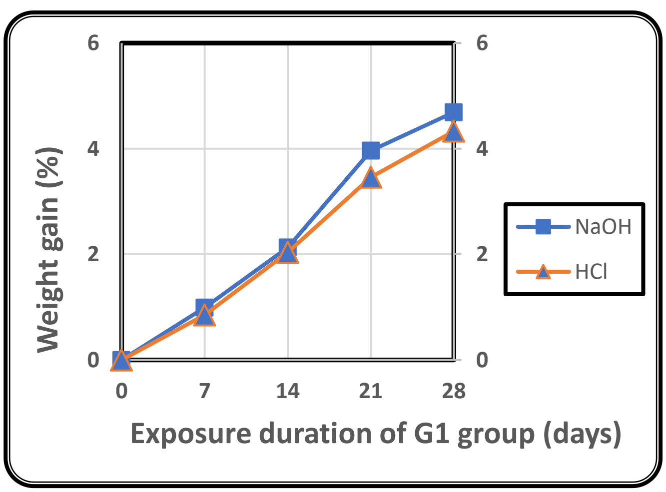


Figure 11. The weight gain at different exposure times for the (G1) group.

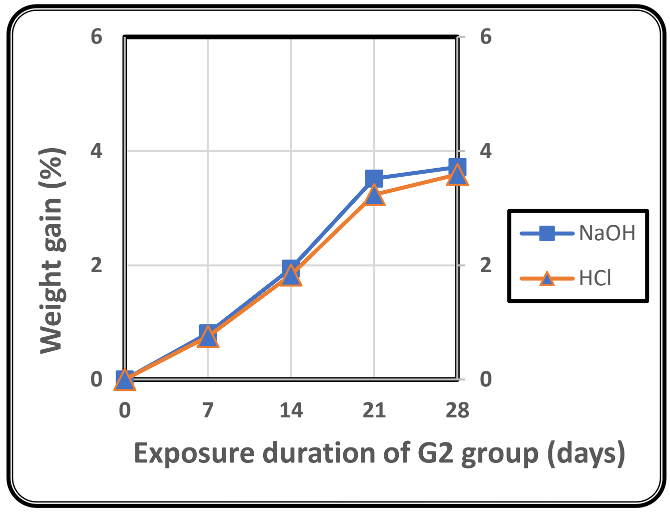


Figure 12. The weight gain at different exposure times for the (G2) group.

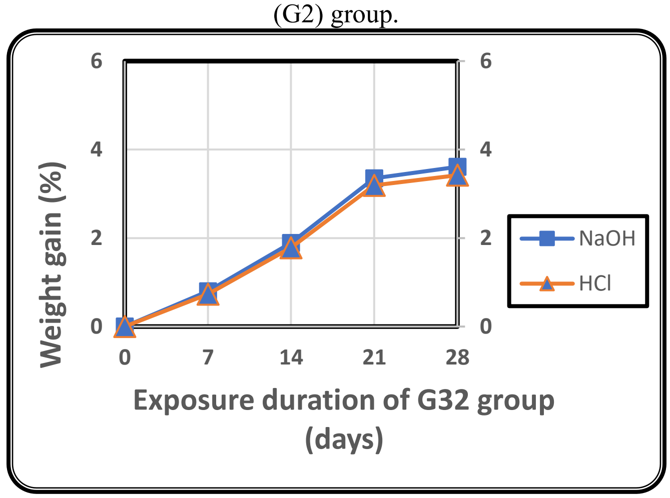


Figure 13. The weight gain at different exposure times for the (G32) group.

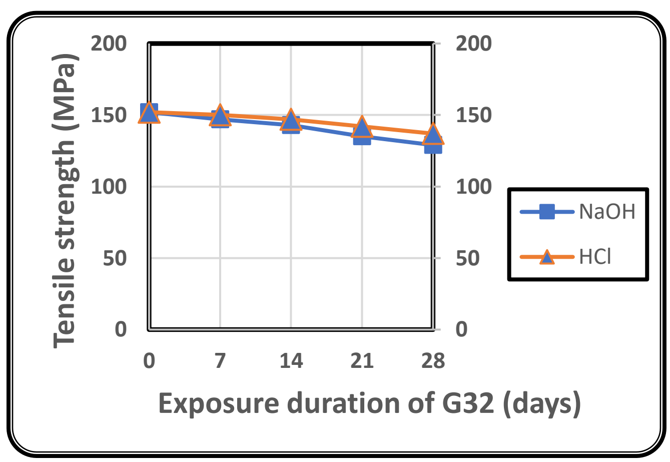


Figure 14. The tensile strength of hybrid composite (G32) at different exposure times**.**

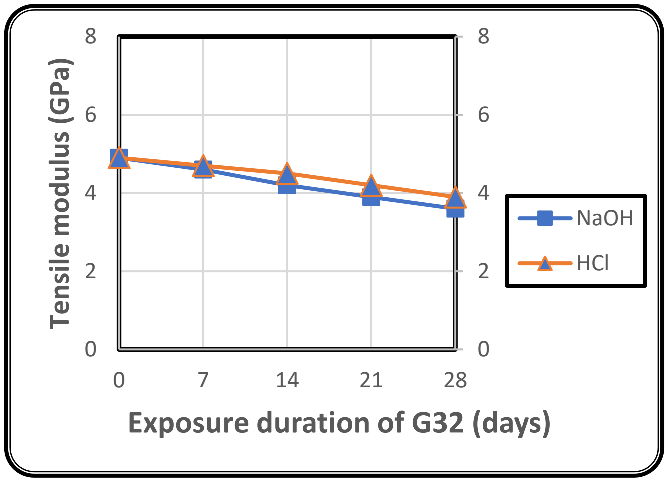


Figure 15. The modulus of elasticity of hybrid composite (G32) at different exposure times.

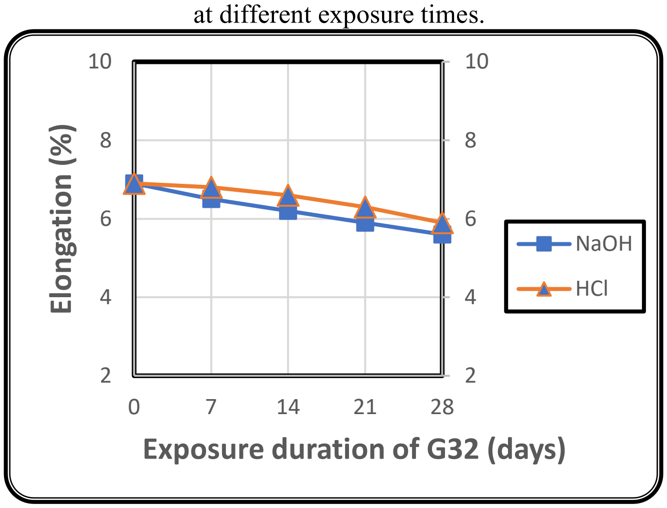


Figure 16. The elongation of hybrid composite (G32) at different exposure times.

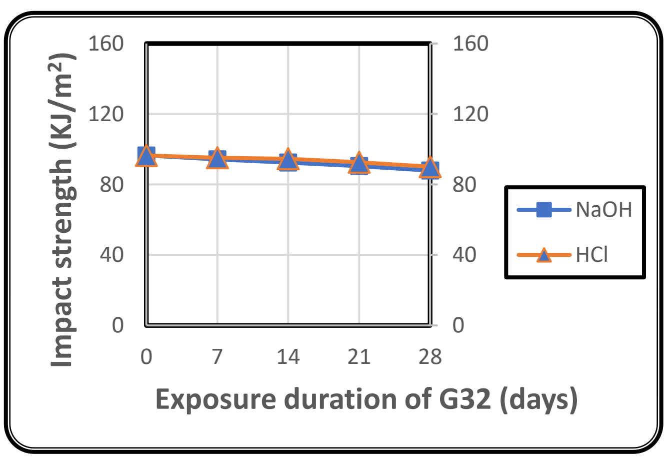


Figure 17. The impact toughness of hybrid composite (G32) at different exposure times.

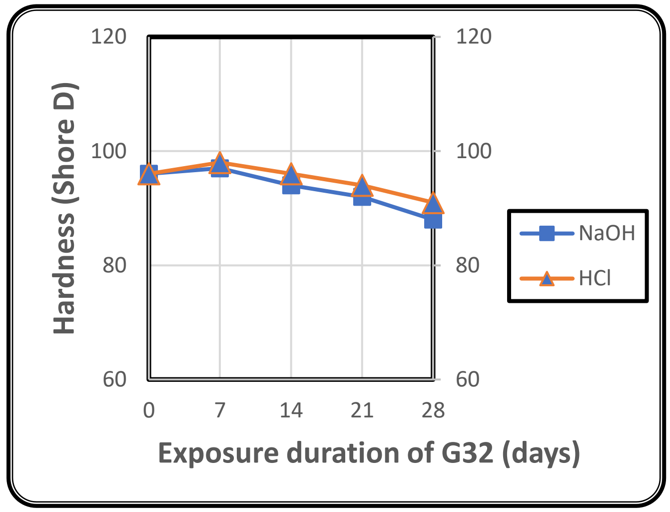
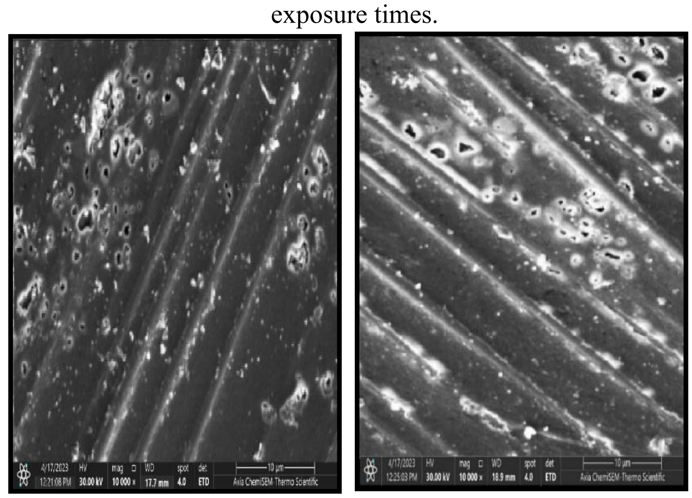
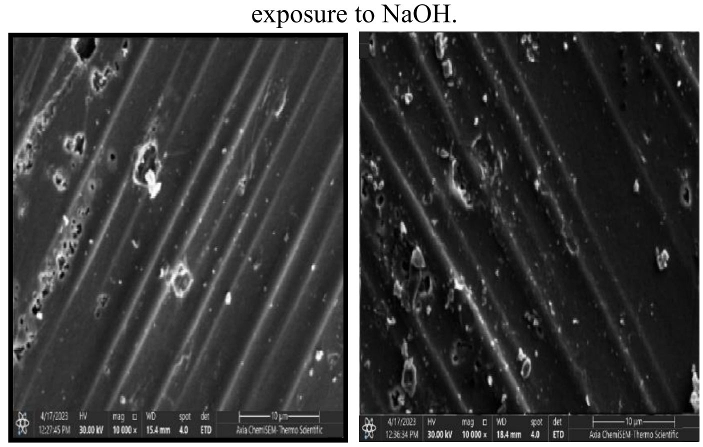


Figure 18. The hardness of hybrid composite (G32) at different exposure times.



14 days **28 days**

Figure 19. Scanning image of hybrid composite (G32) after exposure to NaOH.



14 days **28 days**

Figure 20. Scanning image of the hybrid composite (G32) beyond exposure to HCl.

6. Conclusions

This current work investigated the hardness, tensile features, and impact strength of the beryllia nanoparticles-filled carbon fabric epoxy hybrid composite before and after being submerged in solutions of HCl and NaOH.

The findings indicate that the corrosion environment influences all previously mentioned properties. The degradation of the prepared composite depends on the exposure time. The SEM images demonstrated that the alkaline solution was more aggressive than the acid solution, resulting in the lowest mechanical characteristics.

Additionally, the prepared hybrid composite becomes highly resistant to both (NaOH) and (HCL) solutions due to the positive influence of beryllia nanoparticles by enhancing the surface hardness of the prepared composite and filling the voids within the epoxy structure.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Hamza M. Kamal, Mohammed J. Kadhim, and Layla M. Hasan. The first draft of the manuscript was written by Hamza M. Kamal, and all authors commented on previous versions of the manuscript. All authors read and approved.

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