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Mechanical Properties Characterization of Glass/Carbon Fiber Hybrid Multilayer Composite under Environmental Aging Condition

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ABSTRACT

Metallic components in boating industry are being replaced with carbon fiber composites due to their light weight, excellent mechanical properties, and corrosion resistance. However, the carbon fiber cost has obstructed the substitution. Hybridization is suggested to merge carbon and glass fibers in cost-effective composites while maintaining the desired engineering properties. This study experimentally examines the impact of hybridization and seawater aging on the mechanical properties of glass and carbon fibers hybrid composites. A range of composites ([C]6, [CGC]s, [C]3[G]3, [GCG]s, and [G]6) are fabricated and aged in simulated seawater solution before their tensile, flexural, impact, and hardness properties are examined. The results revealed degradation in properties due to the ageing, the degree of degradation is influenced by the s hybridization configuration. The [G]6 sample shows the highest tensile strength reduction of 30% compared to 20% for the [C]6. The remaining samples exhibit reduction percentages falling between these two extremes. A similar behavior is observed in the flexural test, though the extremes values are smaller, 10.2%, and 12.5%. The impact and hardness tests showed an inverse relationship between the glass fiber content and impact strength degradation due to aging, while they exhibited a linear correlation for hardness degradation due to ageing.

1. Introduction

Fiber reinforced composites are more favorable than conventional engineering materials in many applications due to their superior specific strength, specific modulus, lightweight nature, corrosion resistance, and design flexibility. Hence, composite materials have found increased interest in weight sensitive applications like aircraft, boats, and automobile industry [1]. Some composite materials are produced by incorporating two or more fibers to create what is called hybrid composite material which demonstrates improved engineering properties in an affordable cost. Recently, there has been a significant focus on hybrid composites in research, primarily because of their superior properties when compared to traditional single-fiber composites [2]. According to Naveen, et al. [3], hybridization techniques have been shown to bring about significant enhancements in the thermal and mechanical properties of hybrid materials, as well as improvements in their durability. Moreover, versatile composites are developed by effectively integrating the quality of the reinforcing components while adhering to specific criteria such as affordability and low density. [4, 5].

According to Zhao, et al. [6] the incorporation of ultra-high molecular weight polyethylene fiber (UHMWPE) and carbon

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fibers in various hybridization systems within composite laminates has the potential to improve delamination resistance. An improvement in mode I and mode II fracture toughness is reported due to the proposed hybridization technique. Pappu, et al. [7] manufactured hybrid composites using hemp fibres, granulated sisal, and lactic acid aliphatic polyester. The conducted experimental investigation of the developed hybrid composites revealed a considerable enhancement in the composite impact behavior. The study concluded that the developed hybrid composites are excellent environmentally friendly alternative material suitable for applications in agriculture, electronics, and the automotive industry. In another study Wu, et al. [8] studied the mechanical properties of a hybrid composite made of silk and flax fibers. The study highlighted important development in the impact and flexural strengths due to the hybridization.

Rajesh and Bhaskar [9] investigated a hybrid composite contains glass and carbon fibers, to explore its potential as an unconventional material for steel spring application. Flexural testing was performed to evaluate its load-carrying capacity and deflection, and the results showed a significantly improved flexural response compared to traditional materials.

Yashas Gowda, et al. [10] made four-layered epoxy laminates reinforced with areca, carbon, kevlar, and carbon-kevlar fibers combination using different stacking sequences. The laminates subjected to a comprehensive mechanical, thermal, and water absorption characteristics assessment in order to evaluate the hybridization effect. The results showed that the incorporation of synthetic fibers alongside areca fiber has significantly enhanced the mechanical properties. Moreover, improvement in the water absorption behavior and thermal properties were reported due to the ncorporation of the synthetic fibers with areca fiber.

Guo, et al. [11] investigated the hygrothermal characteristics of a pultruded carbon/glass hybrid fiber reinforced polymer through the immersion in deionized water at different temperatures for 135 days. Thermal and mechanical properties were analyzed to evaluate the hygrothermal evolution. The results reported noticeable degradation in mechanical and thermal properties due to the immersion in the deionized water, however the reduction in long-term life of hybrid composite was lower than conventional composites.

Jesthi and Nayak [12] considered different combinations of glass and carbon fibers hybrid composites and compared their mechanical properties with plain glass and plain carbon composites. The composites were first aged in seawater for 90 days before the tensile and flexural strength were investigated. The results demonstrated 14%, 43% and 64% improvement in hybrid composite tensile strength, flexural strength, and modulus, respectively, compared to the plain composite.

Hung, et al. [13] investigated the low-velocity impact behavior of a hybrid glass/carbon fiber composite. The study findings confirmed a considerable reduction in impact induced damage of the hybrid composite with carbon fiber layers on top. Though, a severe damage was reported in samples with glass fiber layers on the surface and carbon fiber in core.

Dadej and Bieniaś [14] conducted experimental and analytical study to evaluate the static and fatigue strength of conventional and carbon/glass fibers reinforced hybrid laminates. The study reported that the hybrid glass/carbon laminates are featured by higher fatigue but lower static strength compared to the glass reinforces laminates.

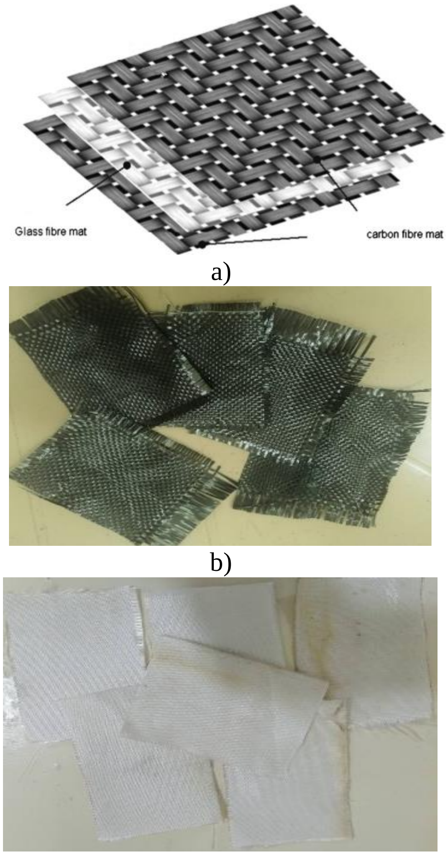
Wu, et al. [15] developed a hybrid composite material by combining carbon and glass fibers both within and in between the composite layers. Investigations were also performed to assess how varying the ratios of these materials impacts the tensile and compressive properties of the composite materials. The findings indicated no significant differences in tensile and compression moduli, for within layers and between layers’ hybrid composites, when the same mixture ratio is maintained. However, the tensile strength greatly outperforms the compression strength. Furthermore, as the carbon fiber content increases, both the tensile modulus and strength show improvement, while compression values remain relatively stable.

In boating and pipelines industry, metal parts are being replaced with carbon fiber composites due to its light weight, and excellent corrosion properties. The high cost of the carbon fiber has obstructed the substitution, and hybridization is suggested to merge carbon and glass fibers in cost-effective composites while maintaining the desired engineering properties. Applications like boating involve material exposure to salty wet conditions for prolonged periods which may degrade the material properties. Hence, this paper aims to provide mechanical properties characterizations of hybrid polymer composites made of carbon and glass fiber fabrics under seawater aging condition. Different composites are made and aged in a simulated sea water solution. These samples encompass those composed solely of carbon, others featuring different combinations of carbon and glass layers, and yet others consisting exclusively of glass. Tensile, bending, impact, and hardness tests are done to perform the characterization before and after the aging process.

1. Materials and methods

1.1. *Specimens Fabrication*

Colan™ E-glass plain weave fabric and Sigmatex™ carbon 2/2 twill weave fabric (T300, 3 K Tow, 199 GSM) were employed as reinforcement materials for Sikador 52 LP, which was cured using a Sikador hardener. The fabrication process involved wet lay-up to create laminates as show in Figure 1 using five distinct lay-up configurations: $[C]_6$, $[CGC]_s$, $[GCG]_s$, and $[G]_6$, where 'C' and 'G' represent carbon and glass fibers, respectively. Also, Figure 1(a) and (b) illustrate the used glass and carbon fabrics. The composite laminates underwent a 48-hour ambient temperature curing process before being cut into specimens for mechanical testing. The overall fiber weight fraction in the composites was approximately 45%, and the thickness of the cured composite laminates ranged between 2.5 mm and 3 mm.



a)

b)

c)

Figure 1. Architecture of the hybrid composite laminate a) Stacking of the fabrics, b) Carbon fiber, and c) Glass fiber

To simulate seawater aging condition, specimens were placed in a laboratory-prepared artificial seawater solution, following the guidelines outlined in ASTM D 1141. This water was maintained at room temperature, it has a salinity of approximately 2.9% and contains $NaHCO_3$, NaCl, Na_2CO_3, and $MgCl_2$ at percentages of 0.16, 29.2, 0.021, and 11.2, respectively. The synthetic seawater was regularly replaced with fresh batches, and the samples were periodically removed from the solution and weighed to measure the amount of water absorption.

1.2. *Properties characterization*

1.2.1. *Tensile and bending tests*

Tensile and bending tests were performed at room temperature following the ASTM D3039-76 and to ASTM D 790 standards, respectively Figure 2 shows the tensile and bending tests' specimens. The tests were performed using a universal Instron 8800 tensile test machine.

Loading rate of 1.1 mm/m and 2.5 mm/m were used for the tensile and bending tests, respectively. The tensile samples had dimensions of 250 mm in length and 25 mm in width, while the flexural test samples were sized at 100 mm in length and 25 mm in width.

a) Tensile specimens

b) Bending specimens

Figure 2 (a) Tensile and (b) bending test specimens

1.2.2. *Impact test*

Motorized pendulum impact Charpy tester was employed to perform the impact test. The tester pendulum assembly has effective mass of 54.4 kg and length of 762 mm, which produce 5.28 m/s impact velocity and 750 J impact energy. Figure 3 shows the impact test specimens. Investigated samples have uniform dimensions of 60 mm in length and 10 mm in width. Apart from the specimen dimension, which were selected based on both machine capacity and recommended size in literature, the methodology closely followed the guidelines outlined in ASTM-D6110-10. For each test, three separate specimens were used and average values were determined.

Figure 3. The impact test specimens

1.2.3. *Hardness test*

Digital Shore D hardness tester was used to determine the hardness of the samples. It has measurement range of 0 –100 HD, resolution of 0.5 HD, indenter depth of 0–2.5 mm, and test pressure range of 0–45.5 N. Before initiating the test, the specimens were positioned on a stable and immovable surface. The indenter needle was applied vertically onto the test specimen, and the displayed measurement was recorded within 0.5 second after the pressure foot's base made full contact with the specimen surface. Each specimen was tested three times for accuracy.

2. Results and discussions

2.1. *Aging*

Seawater permeates the composites, leading to the formation of microcracks which results in increased weight gain and subsequently deterioration in mechanical properties due weakening of the matrix/fiber interface. Figure 4 depicts the samples weight increase due to immersion in seawater. The weight consistently rises with immersion duration and reaches its peak after 32 weeks. The [G]6 specimen shows the most substantial increase in weight, while the [C]6 sample shows the lowest weight gain. The remaining two samples demonstrate weight gain percentages falling in between where a strong relationship can be recognized between the glass fiber content the water gain percentage.

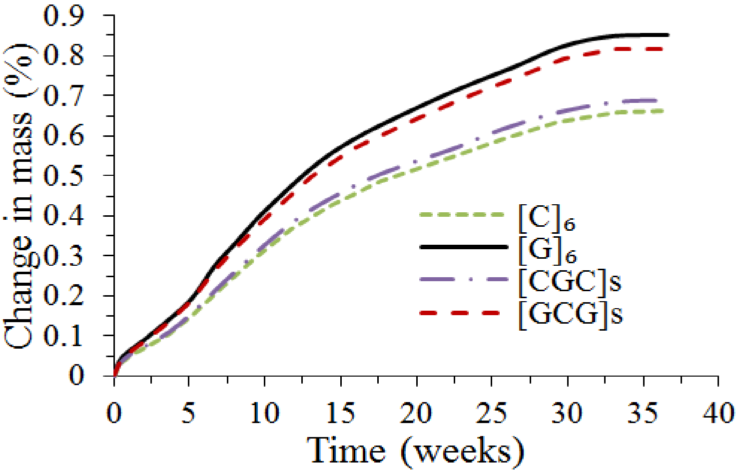


Figure 4. Immersion period effect on the $[C]_6$, $[G]_6$, $[CGC]_s$, and $[GCG]_s$ sample water uptake

2.2. *Tensile Properties*

Two groups of samples were used for the tensile test; the first is called dry samples which are tested before the sweater immersion. The second is called wet samples which are experienced 32 weeks of seawater immersion. This provides good determination for the effects of the hybridization and aging process. Figure 5 and Figure 6 show the stress-strain relationships of the dry and wet samples, respectively. Figure 5 shows that the $[C]_6$ sample has the highest strength and lowest failure strain compared to other samples. $[G]_6$ sample, on the other hand, exhibits the lowest strength and highest failure strain. This behavior is which is attributed to the higher mechanical properties and lower ductility of the carbon fiber relative to the glass fiber. However, $[C]_3[G]_3$ composite displayed intermediate strength and strain values. As for the [CGC]s and [GCG]s samples the results show that the tensile characteristics were proportional to the volume fraction of each of the constituent fibers.

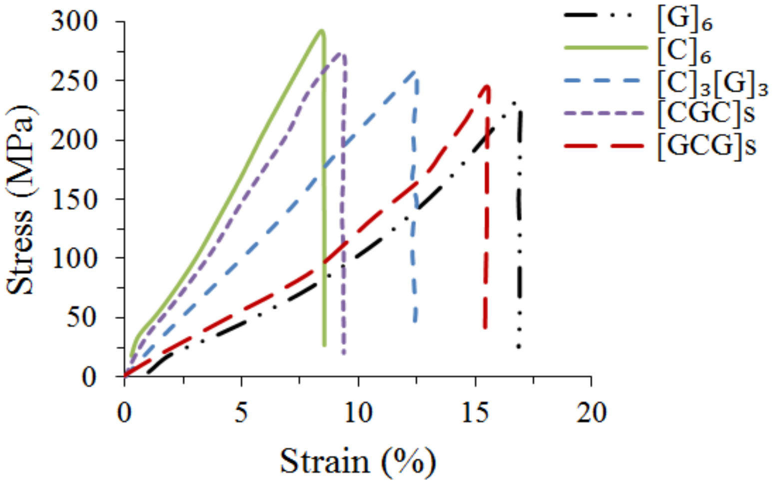


Figure 5. Tensile stress-strain relationships of the dry composite samples

Figure 6 illustrates the tensile test results for the wet samples. Overall, the findings indicate a decrease in strength and a slight increase in failure strain of all aged samples compared to the dry samples. Strength reduction of 20%, 21%, 25%, 27%, and 30% is recognized in the $[C]_6$, $[CGC]_s$, $[C]_3[G]_3$, $[GCG]_s$, and $[G]_6$ samples, respectively. This reduction is attributed to the matrix-fiber interface debonding which happens due to the seawater intrusion. The strength reduction is found to be proportional to the number of glass fiber layers in the composite which is due to higher water uptake of the glass.

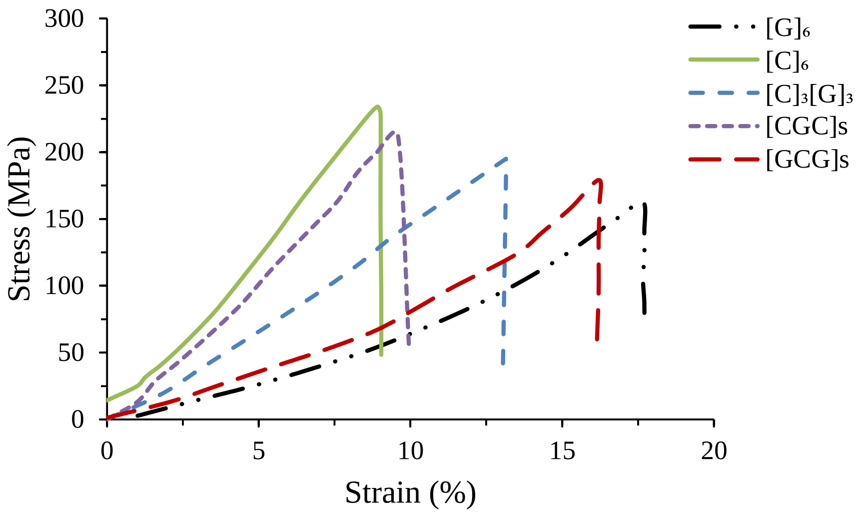


Figure 6. Tensile stress-strain relationships of the aged composite samples

2.3. *Flexural Properties*

Figure 7 and Figure 8 depict the flexural stress-strain relations of the dry and moist specimens, respectively. In Figure 7, it is evident that the $[C]_6$ sample boasts the highest flexural, the $[G]_6$ sample demonstrates the lowest strength. The $[CGC]_s$ sample shows the second highest strength which is due to the higher carbon fiber fraction and because of the existence of the carbon layer in the upper and lower layer of the bending sample. The $[C]_3[G]_3$ sample contains three carbon layers therefore is shows higher strength than the [GCG]s sample and lower than the [CGC]s sample. Exhibits intermediary values for both strength and strain.

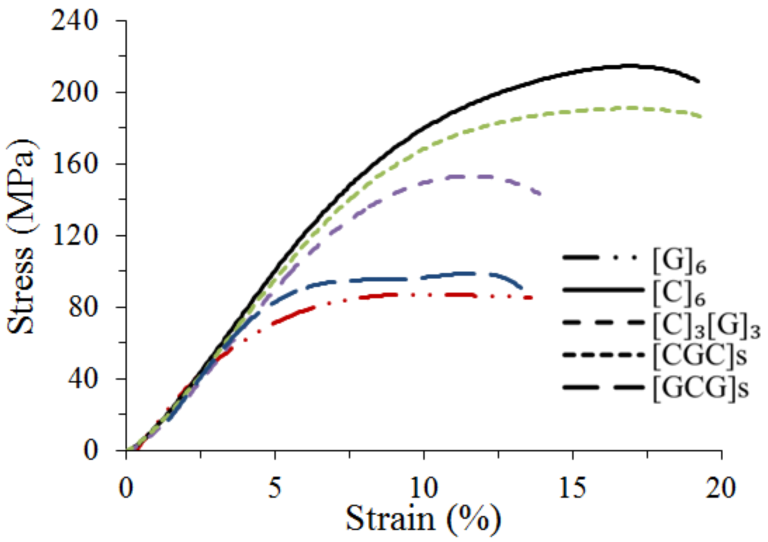


Figure 7. Flexural test stress-strain relationships of the dry composite samples

Figure 8 illustrates the outcomes of the flexural tests conducted on the wet samples. In general, the results reveal a decline in strength compared to the dry samples. A strength reduction of 10.2%, 11%, 11.6%, 12%, and 12.5% is recognized in the [C]6, [CGC]s, [C]3[G]3, [GCG]s, and [G]6 samples, respectively, due to the ageing. This may be due to the plasticization and swelling degradation of the polymer matrix which increase in the polymer's ductility. Additionally, the absorption of water has the potential to induce hydrolysis within the polymer matrix, leading to the degradation of the fiber/matrix interface.

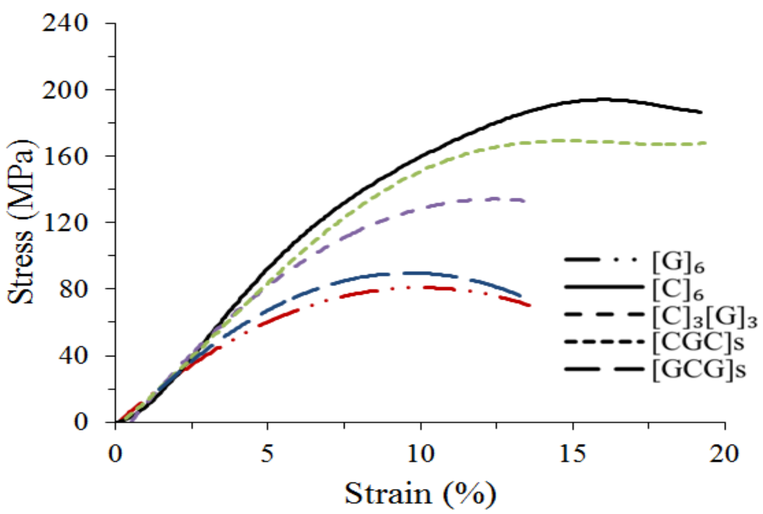


Figure 8. Flexural test stress-strain relationships of the wet composite samples

2.4. *Impact Properties*

The assessment of impact strength was conducted on both dry and seawater-aged composite materials. Figure 9 presents a comparative analysis of the impact strength among the glass fiber reinforced composite ($[G]_6$), the carbon fiber reinforced composite ($[C]_6$), and the hybrid composites ($[CGC]_s$, $[GCG]_s$, and $[C]_3[G]_3$).

In dry condition, it was observed that the plain $[G]_6$ composite exhibited the highest impact strength at 132 kJ/m^2, while the plain $[C]_6$ composite had the lowest at 32 kJ/m^2. Among the dry hybrid composites, $[GCG]_s$ displayed the highest impact strength at 69 kJ/m^2 when compared to the others. This increased impact strength in the $[GCG]_s$ hybrid composite can be attributed to the higher ductility of the glass fibers.

Following exposure to seawater aging, the impact strength of the $[G]_6$ composite exhibited the highest value, at 111 kJ/m^2, while the $[C]_6$ composite showed the lowest value, at 22.8 kJ/m^2. Markedly, the impact strength of the plain $[G]_6$ and $[C]_6$ composites decreased by 16% and 29%, respectively, due to seawater aging. In contrast, the impact strength of seawater-aged hybrid composites of $[CGC]_s$, $[C]_3[G]_3$, and $[GCG]_s$ types decreased by 25%, 21%, and 18%, respectively. It is evident that the reduction in impact strength is higher in composites that contain more carbon layers.

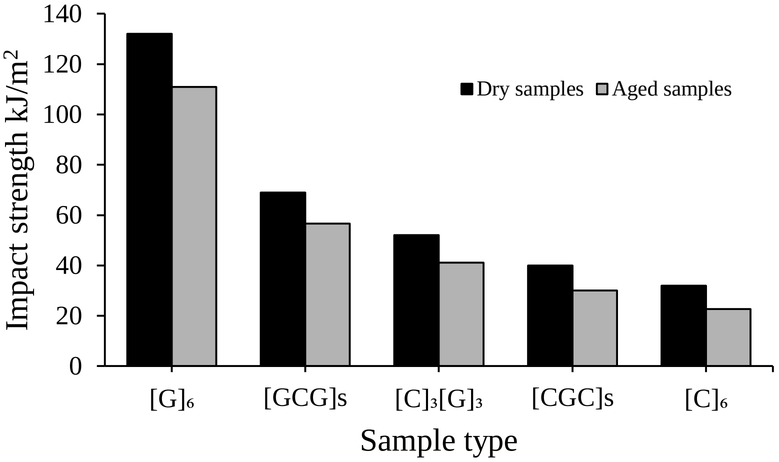


Figure 9. Impact strength of the different composite samples before and after the sea water ageing

2.5. *Hardness*

Hardness is the material's ability to resist surface indentation. This could be due to the higher mechanical properties of the carbon fiber; also it could be attributed to the better bonding between the fiber and the matrix. Moreover, it's obvious that the micro hardness values for the [G]$_3$[C]$_3$, [GCG]s, and [G] samples are quite similar. One possible explanation for this behavior is the layup arrangement, wherein the glass fiber is at the external layer where the indentation is applied.

Regarding the aged samples, the results indicate a decline in micro hardness due to the seawater aging. The [C]$_6$ sample experiences the least reduction at 5%, whereas the [G]$_6$ sample exhibits the highest reduction, with a percentage decrease of 39%. The reason behind can be attributed to the higher absorbency of the glass fiber, which leads to swelling within the composite and subsequently weakens the fiber-matrix interface region. In the case of the hybrid samples, it is noteworthy that the degradation percentages appear to correlate with the glass fiber content. Specifically, for the [CGC]s, [G]$_3$[C]$_3$, and [GCG]s samples, the degradation percentages are 10%, 16%, and 18.5%, respectively.

Figure 10 illustrates the variations in micro hardness observed in the composite samples as a result of altering the reinforcing fibers and the subjecting to aging effect. Specifically, the [C]$_6$ sample demonstrates the greatest micro hardness compared to the other composites. For the dry samples, the results demonstrate that the [C]$_6$ sample exhibits micro hardness values that are 17%, 28%, 30%, and 35% higher than those of the [CGC]$_s$, [G]$_3$[C]$_3$, [GCG]$_s$, and [G]$_6$ samples, respectively.

This could be due to the higher mechanical properties of the carbon fiber; also it could be attributed to the better bonding between the fiber and the matrix. Moreover, it's obvious that the micro hardness values for the [G]3[C]3, [GCG]s, and [G] samples are quite similar. One possible explanation for this behavior is the layup arrangement, wherein the glass fiber is at the external layer where the indentation is applied.

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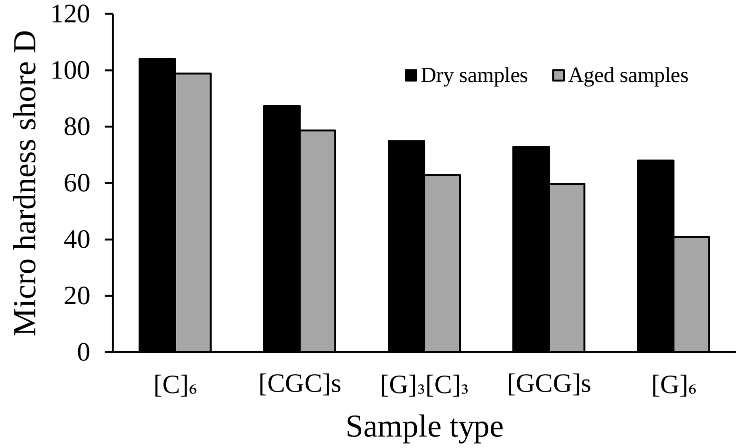

Figure 10. Shore D micro hardness of the composites before and after sea water ageing

3. Conclusions

Study findings revealed properties degradation due to ageing, and the degree of degradation is found to be affected by the hybridization. The $[G]_6$ sample demonstrated highest degradation in tensile strength, due to ageing, with a value of 30% compared to 20% for the [C]6. Other hybrid samples showed a degradation percentages falling between these two extremes. A similar behavior is observed in the flexural test, though the extremes values were smaller, 10.2%, and 12.5%. The impact test showed an inverse relationship between the glass fiber content and impact strength degradation due to aging, while hardness investigation exhibited a linear correlation between the glass fiber content and the hardness degradation.

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