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Influence of Moisture Diffusion on the Mechanical Properties of JUCO/Carbon Epoxy Composites: An Experimental and FEM Evaluation

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Abstract

In this research, JUCO fabric was hybridized with carbon fabric to develop five types of lightweight, durable, and rigid composites using hand lay-up and cold press methods. The JUCO fabric was chemically treated with a 5% NaOH aqueous solution before the fabrication of the composites. To investigate and compare the mechanical properties of the fabricated composites, tensile, flexural, impact, and hardness tests were carried out. Specimens were also submerged in distilled water (pH 7) for 150 days to evaluate the influence of moisture diffusion on the mechanical properties of the composites. The tensile and flexural characteristics were also analyzed by the finite element method (FEM). Results obtained from this study showed hybridization with carbon fibers significantly improved the mechanical characteristics of the natural fiber-reinforced composites e.g. the tensile (332.15 MPa), flexural (441.48 MPa), and impact (33.38 J/cm^2) strengths were found to be the highest for the CCJCC composite. However, a reduction in tensile strength, flexural strength, and hardness, and an enhancement in impact strength were observed because of the aging in distilled water. The findings of the numerical analysis also showed good alignment with the experimental results.

Keywords: Hybrid composites, JUCO/carbon fiber, moisture diffusion, finite element analysis.

1. Introduction

Composites are the integration of at least two materials having notably different chemical and physical properties. The synergistic contribution of the constituent materials produces a composite that has superior characteristics compared to the constituents. In recent years, natural plant-based fibers have gained tremendous attention as reinforcements for various composites. Because of the current environmental legislations and consumer demand for recyclable, biodegradable, and eco-friendly materials, natural fibers are being used more often in place of synthetic fibers that are damaging to the environment, non-biodegradable, and not recyclable [1]. Natural fiber-reinforced composites (*NFRCs*) have been getting a lot of consideration in the past few years as environmentally benign and sustainable materials because of their superior mechanical properties, biodegradability, lightweight, and affordability [2]. Synthetic fiber-based composites can be replaced by utilizing natural fibers together with synthetic fibers without much loss in strength. Natural and synthetic fibers are mixed during the hybridization process to lower the cost of the hybrids and achieve improved mechanical, thermal, and moisture-absorbing properties [3]. Applications for natural fiber-reinforced hybrid composites include furniture, sporting goods, interior and exterior parts of automobiles, various parts of airplanes, and lightweight load-bearing structures [4]. Numerous investigations have been conducted on composite materials including various polymer matrices, such as epoxy resin, polyester, polyethylene, and polypropylene. Due to its superior adhesive strength, high mechanical strength, low shrinkage, and strong resistance to corrosion, epoxy resin is the most popular polymer matrix [5]. The excellent characteristics of carbon fibers including high durability and rigidity, low density, hydrophobicity, and corrosion resistance make them ideal for use as reinforcing material in composites for many applications i.e. automobiles, aerospace, marine, and construction. However, carbon fibers are expensive and not eco-friendly [6].

Carbon fiber-reinforced composites (*CFRCs*) can be made less expensive while retaining their strength by substituting some amount of carbon fibers with ductile natural fibers. For this reason, JUCO fabric was hybridized with carbon fabric in this research work. JUCO, shown in Figure 1(a), is an industrially produced fabric where all the jute yarns are weaved as weft (aligned in the transverse direction) and all the cotton yarns are weaved as warp (aligned in the longitudinal direction) in a 1:1 weight ratio. Not many researchers have mentioned the use of JUCO fabric in composite fabrication [2, 5, 7]. Natural fibers tend to absorb moisture from the surroundings due to their hydrophilic nature. Previous studies have found that moisture diffusion deteriorates the strength of *NFRCs* because of the degradation of natural fibers [2-6]. Nonetheless, the effects of aging in distilled water on the mechanical characteristics of JUCO/carbon epoxy composites have not been explored yet. Therefore, the influence of aging in distilled water on the sustainability and durability of *NFRCs* has also been addressed in the current research project. Researchers have discovered that natural fibers can be chemically treated to strengthen their resistance to absorbing moisture. Using sodium hydroxide (NaOH) for treating natural fibers' surfaces is one of the most popular chemical treatment techniques. It is proven that the optimal alkaline treatment for the majority of natural fibers is 5% (w/v) NaOH [8]. For this reason, a 5% NaOH aqueous solution was used in this experiment to treat the JUCO fabric before its use in composite fabrication. Many researchers have studied hybrid composites made up of various natural and synthetic fibers, such as banana, jute, cotton, hemp, kenaf, sisal, coir, glass, Kevlar, and carbon [4]. However, plain JUCO fabric was hybridized with unidirectional woven carbon fabric in this study to fabricate five different types of lightweight, durable, and rigid composites using hand lay-up and cold press methods. Uniaxial tensile, flexural, impact, and hardness tests were conducted to evaluate and compare the mechanical characteristics of the fabricated composites. To investigate the influence of moisture diffusion on the mechanical characteristics of the composites, specimens were aged in distilled water for 150 days. Results obtained from the tensile and flexural tests were also validated by the finite element method.

2. Materials and methods

In this research, Lapox B-11 epoxy resin and Lapox K-6 hardener were used as matrix, and plain JUCO fabric (450 *GSM*) and unidirectional woven carbon fabric (300 *GSM*) were used as reinforcements. The epoxy resin and hardener, JUCO fabric, and carbon fabric were collected from M/S Chadpur Traders, Dhaka, Bangladesh, Mony Jute Goods and Handicrafts Ind., Dhaka, Bangladesh, and Hangzhou Impact New Materials Co. Ltd., Zhejiang, China, respectively. The JUCO and carbon fabrics had a density of 1.294 g/cm^3 and 1.822 g/cm^3, respectively. Materials used in this study for the fabrication of the composites can be seen in Figure 1. Before the fabrication of the composites, chemical treatment of the JUCO fabric was done with a 5% (w/v) NaOH aqueous solution for 24 hours. Later, the treated fabric was properly dried under sunlight after being cleaned with distilled water. Five types of composites, each having five fabric layers, were tailored using hand lay-up and cold press methods. Stacking sequences of the fabricated composites are illustrated in Figure 2. Unidirectional carbon fibers were placed along the direction of the jute fibers within the JUCO fabric during the fabrication of the composite plates.

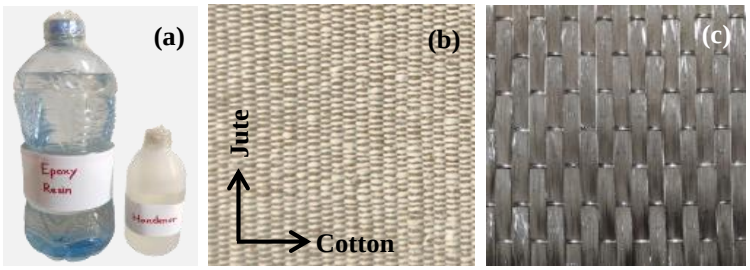


Fig. 1. Materials used: (a) epoxy resin and epoxy hardener; (b) JUCO fabric; (c) carbon fabric

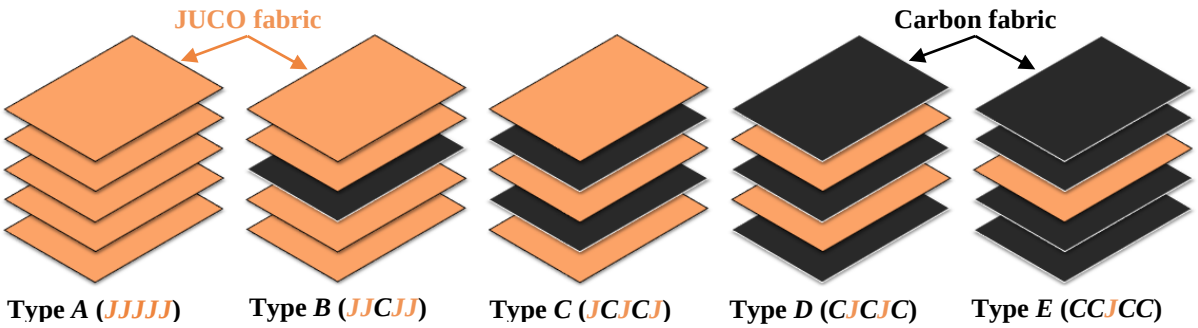


Fig. 2. Schematic stacking sequences of the fabricated composites

Epoxy resin and hardener were applied at a ratio of 11:1 by weight [2-7]. Each composite plate was cold pressed within the surface plates for 48 hours to ensure proper curing. Important mechanical tests, i.e. tensile, flexural, Charpy impact, and Shore-D hardness, were conducted to determine and compare the mechanical characteristics of the fabricated composites. Distilled water was used for the aging of the composites. Specimens were again tested after being aged for 150 days to evaluate the influence of moisture diffusion on the mechanical properties of the composites. Fabrication and all the experiments in this research work were done at room temperature. Using the Abaqus CAE software (version 6.14-2), the tensile and flexural properties obtained from the conducted experiments were validated by the finite element method.

3. Results and discussion

3.1 Uniaxial tensile test

ASTM D638-01 was used to perform the uniaxial tensile test. An Instron Testometric M500-100CT universal testing machine with a 100 kN load cell was used to conduct the tests. Pretension and cross-head speed were set to 0.001 N and 10 mm/min, respectively. All the necessary tensile properties were automatically obtained with the help of the winTest^{TM} software provided by the machine manufacturer. At least three specimens of each type of composite were tested both before and after the aging process to ensure the accuracy of the results found. Specimens that were not aged in distilled water were considered control specimens and specimens that were aged in distilled water were considered water specimens in this research work. Results obtained from the tensile tests were also validated by *FEM*. Figures 3 and 4 demonstrate the effects of moisture diffusion on the tensile properties of the fabricated composites and their validation by the finite element method. The tensile strengths obtained for the control specimens of the *A*, *B*, *C*, *D*, and *E*-type composites were 64.30 MPa, 147.84 MPa, 243.59 MPa, 299.27 MPa, and 332.15 MPa, respectively. Since carbon fibers are more durable and rigid than JUCO fibers, the tensile strength of the fabricated composites exhibited an upward trend with the increasing proportion of carbon fibers. Ahmed et al. reported the tensile strength of the JUCO composite as 68.52 MPa [5]. Khalid et al. found the tensile strengths of *CJJJC*, *CJCJC*, and *CCJCC* were 108.30 MPa, 172.80 MPa, and 257.50 MPa, respectively, in an experiment where plain woven twill-type jute fabric was hybridized with unidirectional woven carbon fabric [9]. The tensile strengths of the *A*, *B*, *C*, *D*, and *E*-type composites were reduced to 60.08 MPa, 126.21 MPa, 221.67 MPa, 266.25 MPa, and 298.15 MPa, respectively, after being aged in distilled water. The reduction in tensile strength is associated with the degradation of natural fibers. Whenever *NFRCs* are exposed to an aqueous medium, the natural fibers degrade because of their organic nature and higher moisture absorption tendencies. Ahmed et al. found the tensile strength of the JUCO composite to be 55.81 MPa after aging in distilled water [5]. Mesh convergence analysis revealed that the optimal mesh size for the numerical modeling of the tensile test was 2.26. The perfect imposition of the experimental and numerical tensile stress-strain curves and position of fracture validate the accuracy of the experimental results.

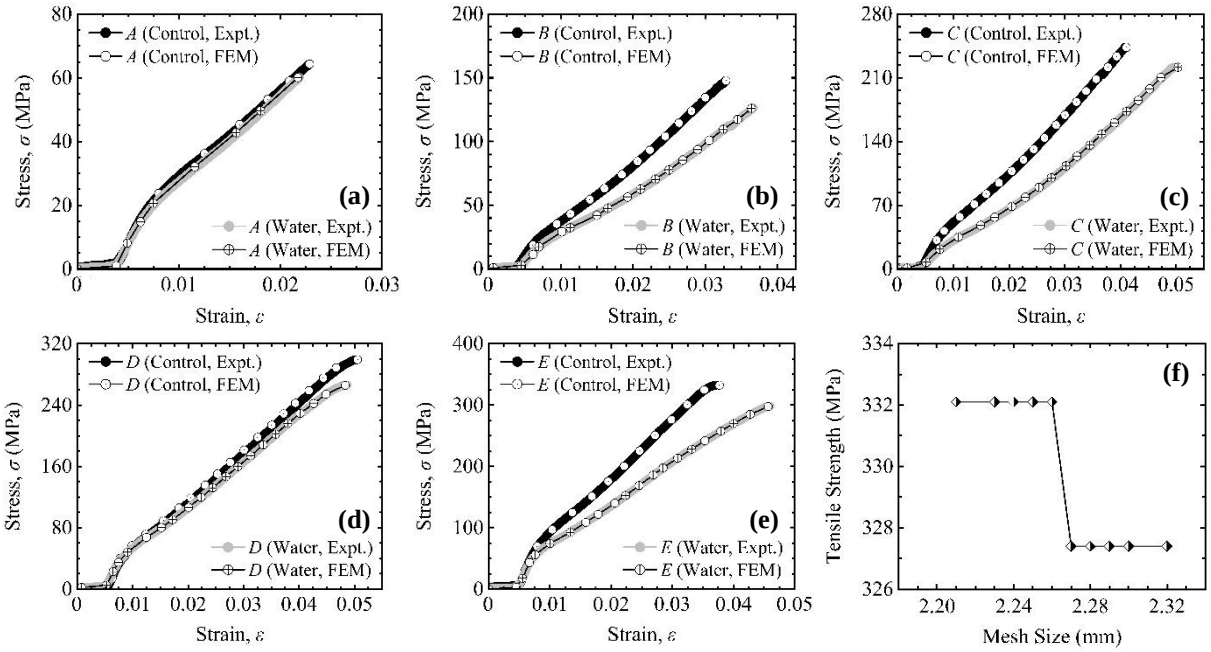


Fig. 3. Validation of tensile test results by *FEM*: (a)-(e) comparison between experimental and numerical tensile stress-strain curves; (f) mesh convergence analysis for the numerical tensile test

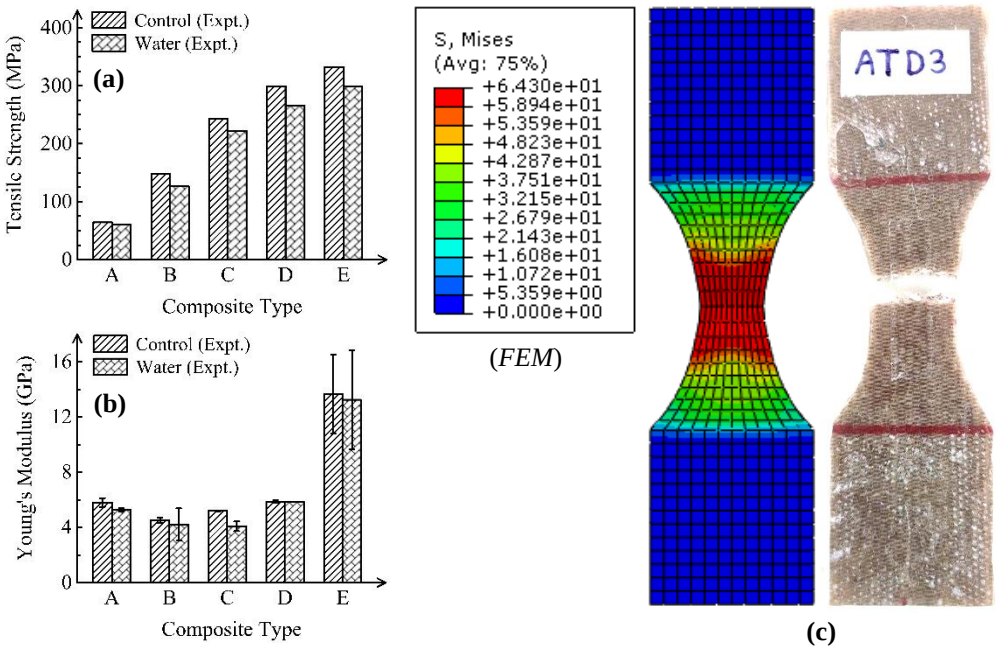


Fig. 4. Findings of experimental and numerical tensile tests: (a) tensile strength; (b) Young's modulus; (c) contour plot of von-Mises tensile stress and fractured specimen (expt.) of *A*-type (control) composite

3.2 Flexural test

The three-point bending test was conducted according to the ASTM D790 for both the control and aged specimens. The tests were performed on a Tinius Olsen 25ST *UTM* with a 25 kN load cell. The span length, cross-head speed, pre-load, and maximum allowed deflection were set to 60 mm, 10 mm/min, 5 N, and 35 mm, respectively. All the important flexural properties were obtained automatically with the help of the Horizon software provided by the machine manufacturer. At least three specimens of each type of composite were tested to find the actual results. Results obtained from the flexural tests were also validated by *FEM*. The impacts of moisture diffusion on the flexural properties of the fabricated composites and their validation by the finite element method are illustrated in Figures 5 and 6. The flexural strengths found for the control specimens of the *A*, *B*, *C*, *D*, and *E*-type composites were 91.70 MPa, 102.30 MPa, 212.83 MPa, 398.41 MPa, and 441.48 MPa, respectively.

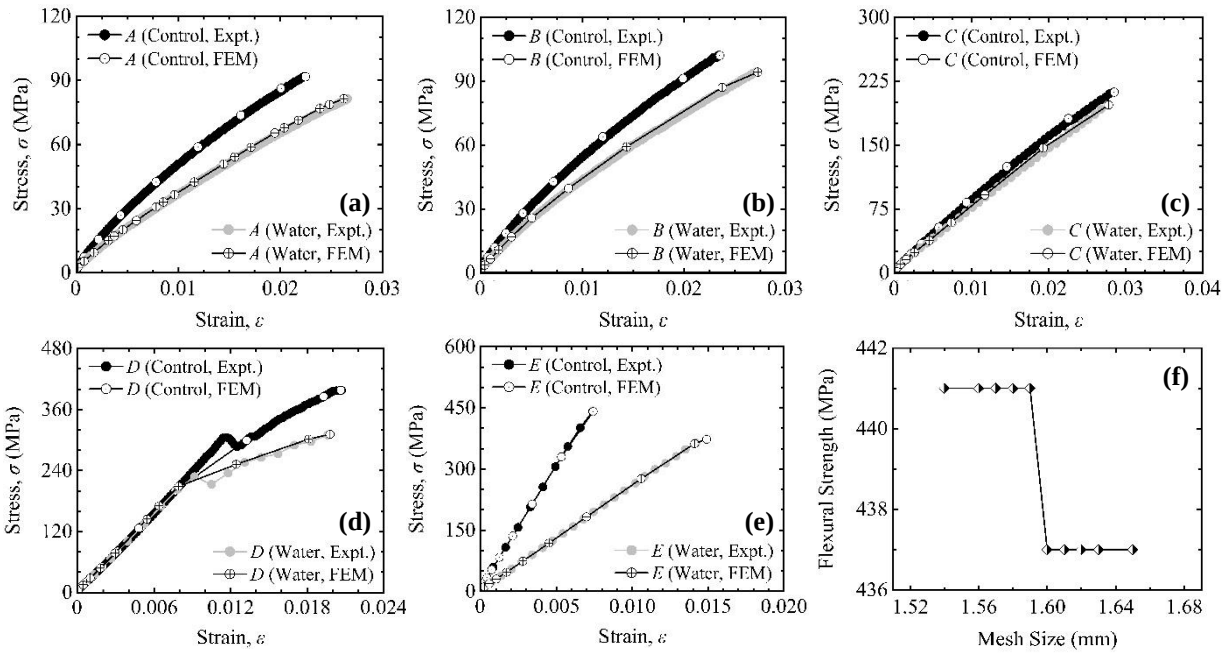


Fig. 5. Validation of flexural test results by *FEM*: (a)-(e) comparison of experimental and numerical flexural stress-strain curves; (f) mesh convergence analysis for the numerical flexural test

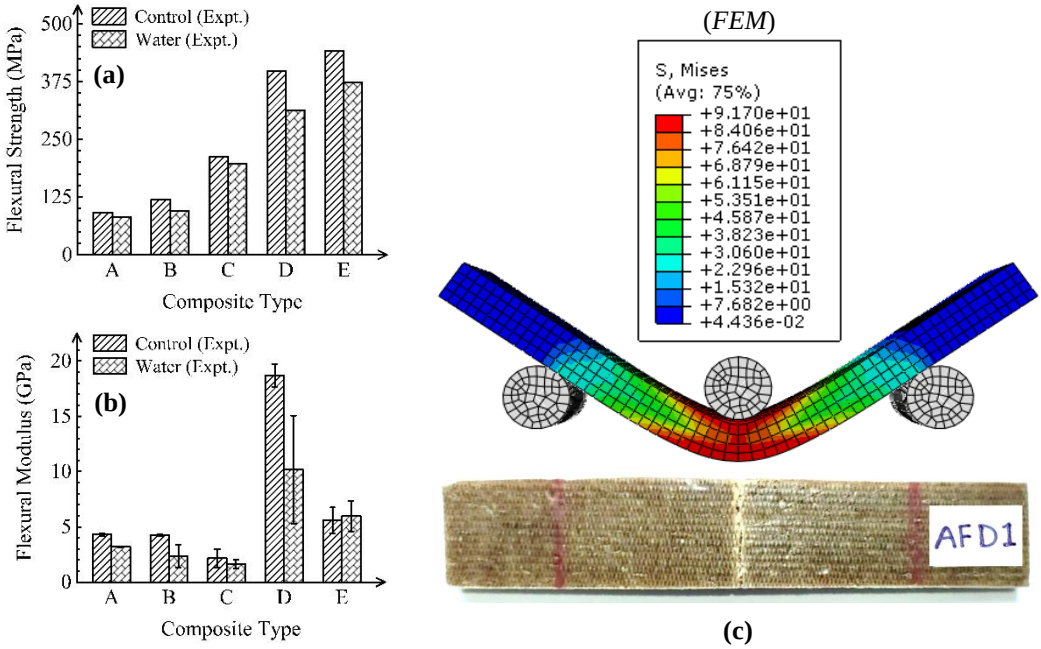


Fig. 6. Findings of experimental and numerical flexural tests: (a) flexural strength; (b) flexural modulus; (c) contour plot of von-Mises flexural stress and fractured specimen (expt.) of *A*-type (control) composite

Failure in the bending test occurs due to compression, tension, and shear. Since carbon fibers can bear a very high amount of load compared to JUCO fibers, a similar trend analogous to the tensile test was observed. The flexural strength of the JUCO composite was found to be 96.11 MPa by Ahmed et al. [5]. Ali et al. reported that the flexural strengths of *CJJJC*, *CJCJC*, and *CCJCC* were about 175 MPa, 245 MPa, and 390 MPa, respectively, when twill-type jute and unidirectional carbon fabrics were used [10]. After the aging process, the flexural strengths of the *A*, *B*, *C*, *D*, and *E*-type composites decreased to 81.45 MPa, 94.26 MPa, 197.51 MPa, 313.29 MPa, and 373.13 MPa, respectively. Degradation of natural fibers within the *NFRCs* is responsible for the reduction in flexural strength. Ahmed et al. reported the flexural strength of the JUCO composite as 84.05 MPa after being aged in distilled water [5]. The optimal mesh size for the numerical modeling of the flexural test was found to be 1.59 by the mesh convergence analysis. The perfect imposition of the experimental and numerical flexural stress-strain curves justifies the correctness of the results found experimentally. Failure of the specimens during testing also occurred at the same position predicted by the finite element analysis.

3.3 Impact and hardness tests

The Charpy impact test was executed following the ASTM D6110. The test was performed using a JB-300B dial display impact testing machine. At least three specimens of each type of composite were tested both before and after the aging process. The effect of moisture diffusion on the impact strength of the fabricated composites is presented in Figure 7(a). The impact strengths obtained for the control specimens of the *A*, *B*, *C*, *D*, and *E*-type composites were 12.38 J/cm^2, 22.27 J/cm^2, 26.22 J/cm^2, 32.95 J/cm^2, and 33.38 J/cm^2, respectively. Impact strength is the ability of a material to sustain forces applied at a high speed. The impact strength of the composites increased with the increasing amount of carbon fibers because carbon fibers can absorb a higher amount of impact force than JUCO fibers. Ahmed et al. found the impact strength of the JUCO composite to be 13.36 J/cm^2 [5].

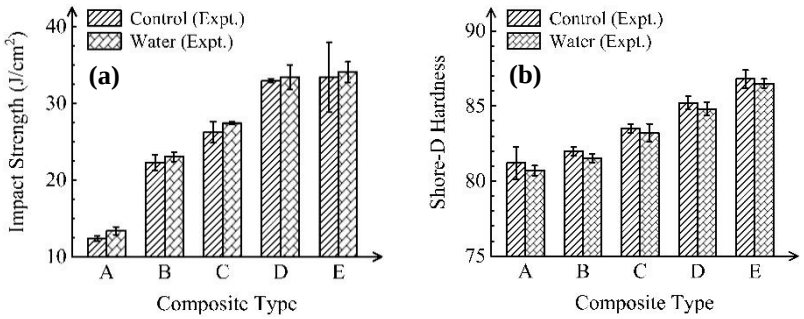


Fig. 7. Influence of moisture diffusion: (a) impact strength and (b) hardness of the fabricated composites

The impact strengths of the *A*, *B*, *C*, *D*, and *E*-type composites increased to 13.38 J/cm^2, 23.05 J/cm^2, 27.44 J/cm^2, 33.43 J/cm^2, and 34.08 J/cm^2, respectively, after the aging process. Improvement in impact strength is associated with the increased ductility of *NFRCs* due to the degradation of natural fibers. Ahmed et al. reported the impact strength of the JUCO composite as 14.25 J/cm^2 after being aged in distilled water [5]. ASTM D2240 was followed to perform the hardness test utilizing an Insize Shore-D Durometer. At least three readings were taken for each control and water-aged specimen at a distance of 5 mm apart from one another to ensure the accuracy of the obtained results. The influence of moisture diffusion on the hardness of the fabricated composites can be seen in Figure 7(b). The Shore-D hardness found for the control specimens of the *A*, *B*, *C*, *D*, and *E*-type composites were 81.2, 82.0, 83.5, 85.2, and 86.8, respectively. Due to the hard and brittle nature of carbon fibers, the hardness of the composites increased with an increasing proportion of carbon fibers. Ahmed et al. reported the Shore-D hardness of the JUCO composite as 82 [5]. The Shore-D hardness of the *A*, *B*, *C*, *D*, and *E*-type composites decreased to 80.7, 81.5, 83.2, 84.8, and 86.5, respectively, after being aged in distilled water. The increment in ductility of *NFRCs* because of the degradation of natural fibers is the reason behind the reduction of hardness. Ahmed et al. found the Shore-D hardness of the JUCO composite to be 77.8 after aging in distilled water [5].

4. Conclusion

Conclusions made from this experimental and numerical research work are as follows;

- The mechanical characteristics of the *NFRCs* were enhanced substantially by the hybridization process due to the rigid and durable nature of carbon fibers.
- Because of the organic and hydrophilic nature of natural fibers, moisture diffusion has an immense influence on the mechanical characteristics of the *NFRCs*.
- The tensile strength, flexural strength, and hardness of the composites decreased after aging in distilled water because of the degradation of JUCO fibers.
- Improvement in ductility of the *NFRCs* due to the degradation of JUCO fibers increased the impact strength of the fabricated composites.
- Results obtained from the finite element analysis showed good alignment with the experimental findings of the tensile and flexural tests.

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