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## Effect of Environmental Exposure on The Notch Sensitivity of GFRP Composites Used in Construction

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THE present research investigated the effect of different environmental conditions including moisture, saline and alkaline conditions on the notch sensitivity of short and 2D plain woven glass fibers reinforced epoxy matrix composites fabricated by the hand lay-up technique with fiber volume content of 23.5 and 38.6 vol.%, respectively. The test was carried out through open hole tension test at constant ratio of (D/W = 0.2) and the notch sensitivity of these composites under different environmental conditions was evaluated by comparing the notched tensile strength and the characteristic distance (do) of these composites applying Whitney-Nuismer mathematical model. The obtained results indicated that the environmental exposure has a pronounced negative effect on the notched tensile strength of all composites compared to the unconditioned state (virgin state). Moreover, the fracture zone of the composites under the alkaline environment is smooth and shows much less fiber pull out validated by SEM micrographs which distinguishes brittle failure.

**Keywords:** Environmental conditions; Notch sensitivity of glass composites; Whitney-Nuismer model.

## Introduction

Nowadays, construction and civil sector has become one of the world's largest consumers of polymer composites and recently fiber reinforced polymer (FRP) composites especially glass fiber reinforced polymer (GFRP) have gained a great worldwide interest in civil, construction and other applications due to their advantages including lightness, high mechanical performance, possibility of fabrication in any shape, ease of installation. The mechanical properties of polymer composites such as glass fiber reinforced polymer composites make fiber matrix attractive for structural and energy absorption applications due to low cost, low density, high stiffness and strength-to-weight ratio [1-9].

Much of research has been made on the durability of FRP composites to find the best alternatives for reinforcing concrete structures to minimize the corrosion problems of the steel bars. Singh and Majumdar et al. [10,11] found that the strength retention of glass fiber reinforced cement increases as the fiber volume increases during the five to ten-year durability results under air, and the fiber length has an important role in dry air environment.

Moreover, Aboelseoud and Myers[12] examined the durability of a commercial E-glass/ vinylester laminate used to encase the hybrid composite beam. They found that GFRP has excellent durability in relation to the expected weathering exposures in the mid-west United States. Orlowsky et al. [13,14] found that the strength of alkaline resistant glass reinforcement in textile reinforced concrete decreases in concrete caused by weathering conditions through mathematical modeling and experimental study. Zhou et al. [15] compared the durability of the bond between GFRP and steel reinforcing bars in concrete under different environment. They concluded that there is no any bond degradation

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due to the continuous immersion in tap water, alkaline and salt solutions for ninety days; however the acid+chloride solutions have more negative effect on bond strength of GFRP bars in concrete. Micelli and Aiello [16] found that alkaline exposure has a significant effect on the durability of fiber cementitious composite materials.

Peled et al. [17] investigated the effect of dimension-stabilizing admixture and blast furnace slag with and without acrylic polymer on the mechanical properties of glass fiber reinforced concrete panels. They found that the addition of dimension-stabilizing admixture and slag significantly improves the long-term durability of glass fiber reinforced concrete composites. On the other hand, the effect of curing conditions on the behavior of the alkali-resistant glass fibers used in different cement matrices was reported by Nourredine [18]. He found that the nature of the cement has a large influence on the protection of the fibers and meanwhile, the mechanical strength of the glass fiber reinforced cement was enhanced by the substitutions of a part of cement by silica fume.

FRP composites especially GFRP composites are primarily used in civil applications to increase flexural capacities, shear capacity and the ductility of concrete load bearing members. Glass fiber reinforced polymer composites are possibly used in civil and construction applications as mechanical fastening joints to join different structural members however, a source of stress concentration around the hole may results and thereby the tensile strength of the composite structures decreases as reported in [19-21]. The stress distribution due to the presence of a circular hole in a composite plate has been simulated by mathematical modeling as reported in [22-25]. According to the point stress criterion in Whitney-Nuismer mathematical model [26], the characteristic distance is the distance which the failure occurs when the stress over some distance away from the discontinuity is equal to or greater than the strength of the unnotched material. Eriksson and Aronsson [27] have reported that a damage zone is assumed to be found in the maximum stress region of carbon fiber-epoxy laminates when the tensile stress reaches the tensile strength of the unnotched composite laminate. The projected damage zone length was also close in value to the characteristic distance of the point stress criterion of Whitney-Nuismer model.

Moreover, when GFRP composites are used as fastening joints in different environmental conditions like water, alkaline and chloride solutions and other environments, they are prone to degrade and therefore the tensile strength of notched GFRP composites decreases. Much of the research has been focused on the effect of environmental conditions on the mechanical properties of the polymer matrix as was reported in [28] and on the mechanical properties of FRP composites [29-33]. Epoxy resins are the most common matrices for high performance advanced polymer composites as reported in [3], however, according to the point view of the authors no research works have been conducted to investigate the effect of environmental conditions on the notch sensitivity of GFRP composites applied in construction. Therefore the objectives of the present work are to investigate the effect of different environmental conditions including moisture, saline and alkaline conditions on the notch sensitivity of short and 2D plain woven glass fibers reinforced epoxy matrix composites through open hole tension test at constant ratio of (D/W = 0.2) of the specimen hole diameter (D = 4 mm) to the specimen width (W = 20 mm) as compared to the unnotched specimens. Moreover, the notch sensitivity of these composites for different environmental conditions is compared through the notched tensile strength and the calculated characteristic distance of the composites using Whitney-Nuismer mathematical model.

## Experimental

*Materials*

Plain woven glass fiber and chopped strand glass mats fiber with a density of 430 g/m$^2$ and 330 g/m$^2$ (Fig. 1 a and b) were used as reinforcement (Al Ahram Company Export and Commercial Agencies, Egypt) . Kemapoxy 150 (solvent free- non pigmented liquid epoxy resin) it was used with the hardener with ratio of 2:1 (Chemicals for Modern Building International Company - CMB International Company, Egypt). Sodium hydroxide and sodium chloride (Elnasr Pharmaceutical Chemicals Company, Egypt) and calcium hydroxide (Alpha Chemika, India) and potassium hydroxide (Badawi Chemicals Co., Egypt).

*Preparation of the composites*

Glass fiber reinforced unsaturated matrix was fabricated using traditional hand lay-up method. In this method, the polymer or epoxy resin after mixing with the hardener was poured on the mold plate. The first layer of woven glass fiber was impregnated with the resin and the second layer of resin was poured to impregnate the second layer of the glass using a roller or brush. This method achieves good through wet out of the fibers in the yarn with the resin and the details were reported in Elbadry *et al.* [34]. The fiber volume fraction of the composites was determined according to the ignition loss method according to ASTM D2548 (1968). Five layers of plain woven and short glass-epoxy composites were laminated with fiber volume content of 38.6 and 23.5 vol.%, respectively. Post curing was carried out at temperatures of 100° C for 2 hours then, left to cool in oven. Specimens for all the tests were cut out from the cured composite plates by water jet cutting. The abbreviations of the two composite systems are PWGEC and STGEC for 2D plain woven glass and short strand glass reinforced epoxy composites, respectively.

*Environmental Conditions*

The exposure environments used in the durability test are distilled water, salt water (to simulate a marine and offshore environment), and an artificial concrete pore solution (to simulate the alkaline interior of a cementitious material in reinforcing bars), and indoor natural weathering for 60 days at ambient temperature. The salt water solution was composed of NaCl solution of (3.5% by weight) in distilled water. Moreover, the concrete pore solution according to Chin *et al.* [28] was composed from a mixture of potassium hydroxide (KOH) (1.8% by weight), sodium hydroxide (NaOH) (0.68 % by weight), and calcium hydroxide ($Ca(OH)_2$) (0.5 % by weight) in a distilled water and after the immersion, the samples were dried by cloth prior to the tension test. The conditioned samples were tested through open hole tension test at constant ratio of (D/W = 0.2) of the specimen hole diameter (D = 4 mm) to the specimen width (W = 20 mm) as compared to the unnotched specimens (unconditioned).

*Mechanical characterization*

Tensile test was carried out with the unnotched sample with dimensions of 200×20×2 mm using aluminum taps of 1 mm thickness to prevent gripping damage. The measurements were done using a universal computerized tension testing machine at room temperature.

For the notched specimens, the hole diameter was 4 mm with 20 mm specimen width with (D/W=0.2) and the drilling was carried out on wooden plates to avoid delamination during the drilling.

*Surface Morphology Test*

The morphology of polymers was examined by a Scanning electron microscope (SEM) using a Joel- JSM-5400 LV -SEM at Electron microscopy unit- Assiut university. The SEM sample was prepared by putting a smooth part of polymer powder on a copper holder and then coating it with a gold-palladium alloy. SEM images were taken using a Pentax Z-50P Camera with Ilford film at an accelerating voltage of 15 kV using a low dose technique.

## Results and discussions

*Whitney-Nuismer Mathematical Model*

The tensile strength of fiber-reinforced polymer composite materials is not only influenced by the type of reinforcements or the matrix used, but also by other factors such as the stacking sequence, fiber type, fiber orientation, and the process curing system. Therefore, the tensile strength of glass fiber reinforced epoxy composites with different stacking sequences was compared in order to understand and analyze the behavior of composite materials.

The unnotched tensile strength of the composites, $\sigma_o$ can be determined from Equation 1:

$$\sigma_o = \frac{F_{max}}{W * t} \quad (1)$$

The tensile strength of notched composites, $\sigma_n$ can be determined from Equation 2:

$$\sigma_n = \frac{F_{max}}{(W - D) * t} \quad (2)$$

Where $F_{max}$ is the maximum load (*N*), *W* is the specimen width (mm), *D* is the notch diameter and *t* is the specimen thickness (mm) as shown in Fig. 2.

The characteristic distance $d_o$ is a material property represents the distance over which the material must be critically stressed in order to find a sufficient flaw size to initiate the failure. According to the point stress criterion of Whitney-Nuismer Mathematical Model [26], the characteristic distance $d_o$ is the distance at which the failure occurs when the normal stress $\sigma_y$ over some distance $d_o$ away from the discontinuity is equal to or greater than the strength of the unnotched material $\sigma_o$. The details of Whitney-

Nuismer Mathematical Model was reported by Elbadry *et al.* [34].

The experimental data obtained from tensile tests, which used for the Whitney-Nuismer Mathematical Model calculation to calculate the characteristic distance are listed in Table 1. Relatively recent studies have also proven the use of this model with a reasonable degree of confidence at similar conditions [24,35-38].

*Effect of environmental conditions on the notch sensitivity of the composites*

The tensile strength of the notched specimens ($\sigma_n$) and the unnotched strength ($\sigma_o$) of PWGEC and STGEC composites for different environmental exposure calculated from the results of the tension test is shown in Fig. 3. Generally, it was indicated that the environmental exposure has a pronounced negative effect on the notched tensile strength of all composites as compared to the unconditioned state (unnotched virgin state) and the effect was higher in STGEC composites than that of PWGEC composites. It is clear that the notched tensile strength of the composites decreases when subjected to different environmental conditions as compared to that of the virgin case as shown in Fig. 3.

Additionally, a little loss in the notched tensile strength of PWGEC specimens was observed when they are subjected to the indoor condition as shown in Fig. 3a; however a larger drop was observed in the notched strength of STGEC specimens in indoor environment as shown in Fig. 3b compared to that of the virgin case. Meanwhile, the alkaline environment (concrete pore solution) showed an equal large negative effect on the notched tensile strength of PWGEC and STGEC specimens compared to the virgin case. The notched specimens of PWGEC composites lost around 17.6%, 52%, 62%, and 71.8% of the tensile strength when subjected

(a) (b)

**Fig. 1. Types of reinforcement (a) 2D plain woven glass (b) chopped strand glass mats.**

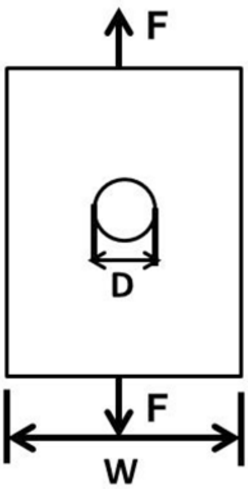



**Fig. 2: Dimension of the notched tensile specimen.**

to indoor, water, salt water, and concrete pore solution, respectively as shown in Fig. 3a. On the other hand, the notched specimens of STGEC composites lost around 46.6%, 55.7%, 63.9%, and 71.2% of the tensile strength when subjected to indoor, water, salt water, and concrete pore solution, respectively as shown in Fig. 3b.

It can be observed that, water has a high negative effect on the notched tensile strength as represented in Fig. 3. The moisture can diffuse into the polymer leading to changes in their mechanical characteristics and the absorbed moisture will cause mechanisms to be set up such as plasticization, saponification or hydrolysis and can exacerbate microscopic cracks and surface defects in the fiber and thus reduce the tensile strength of the glass fiber [3]. Moreover, it is clear from Fig. 3 that the alkali solution severely causes the degradation in notched tensile strength of PWGEC and STGEC composites as compared to other environmental conditions due to the aggressive effect of the alkaline on the matrix and the fibers which leads to degradation of the fiber, matrix and the interface between them.

Fig. 4 illustrates the stress distribution of both types of the composites around the hole applying Whitney-Nuismer mathematical model according to point stress criterion.

It is indicated that the stresses is more amplified and concentrated near the hole tip when the specimens were subjected to alkaline, salt water, water, indoor conditions, respectively and the magnitude of this localized stress diminishes

**TABLE 1. The experimental data used for the characteristic distance calculation according to Whitney-Nuismer Mathematical Model.**

| Materials Conditions | Plain woven composites | | Chopped glass composites | |
|---|---|---|---|---|
| | $\sigma_n$,MPa | $\sigma_o$, MPa | $\sigma_n$,MPa | $\sigma_o$, MPa |
| Indoor | 365.1 | | 167.6 | |
| Water | 212.2 | | 138.9 | |
| Salt Water | 168.1 | 442.9 | 113.2 | 313.6 |
| Pore soln. | 124.6 | | 90.3 | |

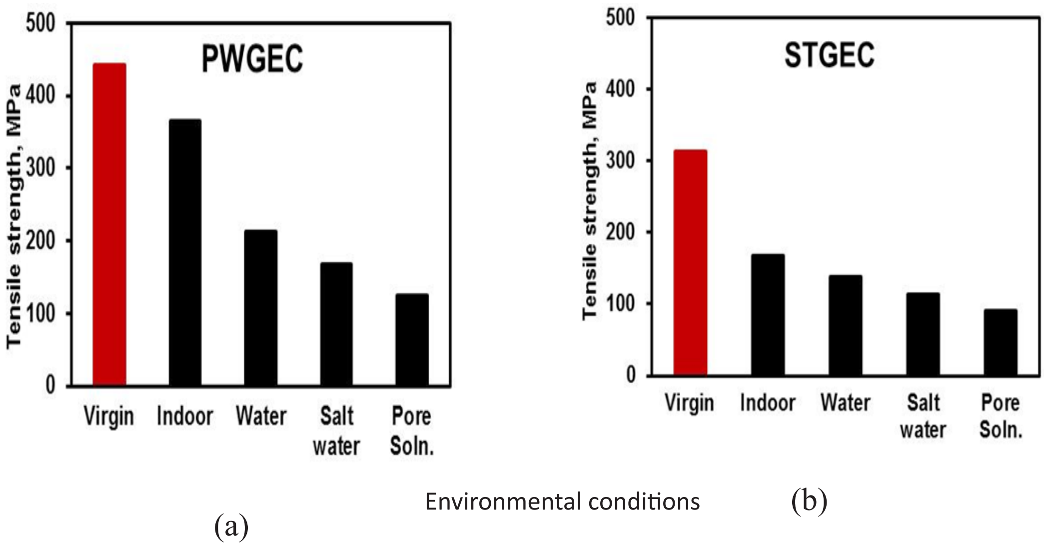
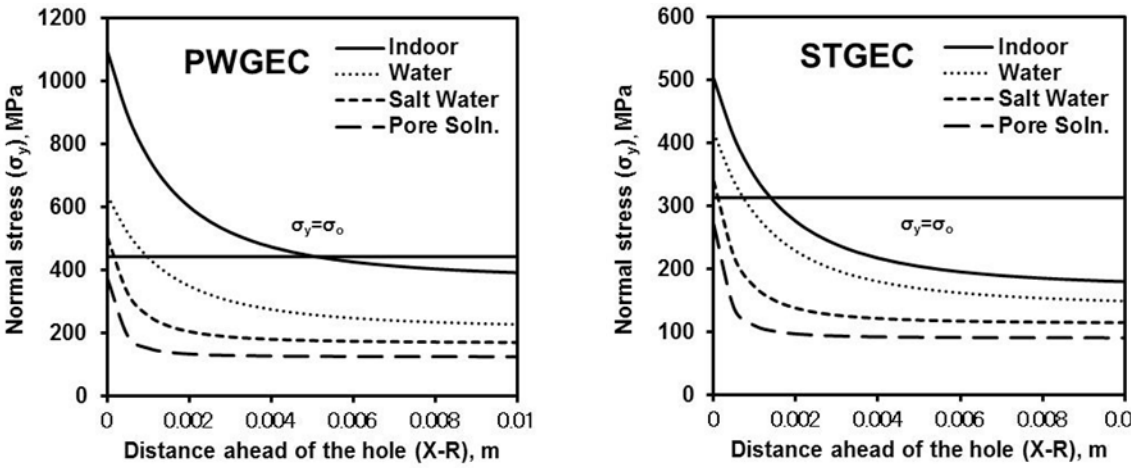



**Fig. 3: The effect of different environmental conditions on the notched tensile strength of (a) PWGEC composites (b) PWGEC composites as compared to the virgin condition.**




(a) (b)

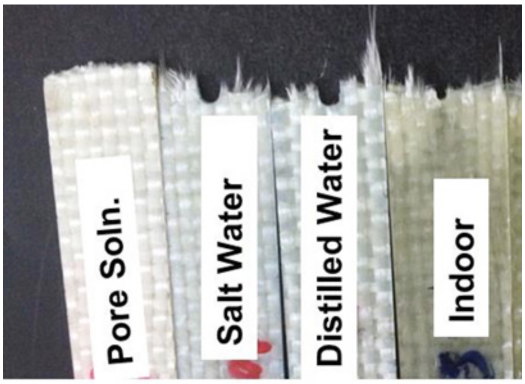
**Fig. 4: Stress distribution around the hole of (a) PWGEC composites (b) STGEC composites for different environments.**

with distance away from the hole tip as represented from Fig. 4. Therefore, it is expected that the resistance of PWGEC and STGEC specimens to the notched tensile loading is keeping lower when these composites are subjected to alkaline, salt water, water, indoor environments, respectively as shown in Fig. 4.

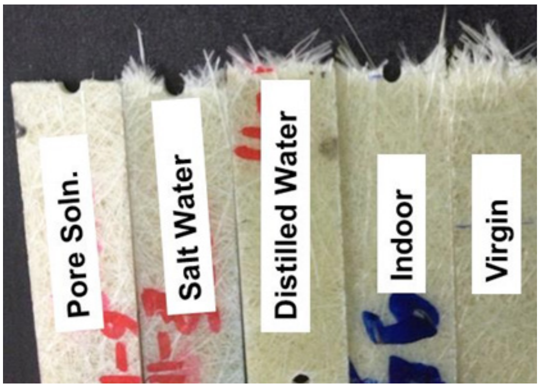
Some researchers [34, 39] have been used the characteristic distance principle to determine the notch sensitivity of the composites. It is well known that higher characteristic distance $d_o$ means lower sensitivity and vice versa as indicated in Fig. 4. The value from higher to the lower of the characteristic distance of different composites is in indoor environment, distilled water and salt water environments, respectively and therefore the sensitivity of PWGEC and STGEC composites to the hole notch was lower when they are subjected to indoor environment, distilled water and salt water environments, respectively as shown in Fig. 4.

Moreover, it is very interesting to note that the characteristic distance of PWGEC and STGEC composites is almost zero under alkaline environment according to Fig. 4. This physically means that these composites are very brittle under notched tensile loading when they are subjected to alkaline immersion (concrete pore solution) and the fracture is occurring suddenly around the notch boundary without warning. These results were validated from the visual view of failure damage of the notched specimens of PWGEC and STGEC composites under notched tensile loading for D/W=0.4 for different environments as compared to that of the virgin state. The failure mechanisms were seen to be similar to those of the received (unnotched) composites for both types of the composites of open hole specimens under different environments except that in alkaline environment as shown in Fig. 5.

It can be observed that the fracture zone of these composite laminates showed five typical failure modes fiber pull out, delamination, matrix cracking and debonding and the shape of fractured and virgin specimens was a ‘broom’ type in all composite types for different environment except in alkaline environment. However, the fracture surface of the specimens exposed to the alkaline environment for different composites was smooth and showed much less fiber pull out. This means that this alkaline environment has a decreasing effect on the elasticity of the matrix and glass fibers. Therefore, the failure suddenly occurs before fiber pull out occurs. This mode of failure distinguishes brittle failure which validates the results obtained from the results of Whitney-Nuismer mathematical model as shown in Fig. 4. This fracture spread extremely rapidly, with very little accompanying plastic deformation and the crack was unstable, it continues spontaneously as the crack propagation was started without an increase in magnitude of the applied stress as reported in [40]. Similar fracture surfaces were obtained by Kim *et al.* [41] for tension test of




(a)




(b)

**Fig.5: Fracture surface of notched specimens for composites with D/W=0.2 (a) PWGEC composites (b) STGEC composites for different environments.**

unnotched E-glass/vinylester composites with and without subjecting to different environments.

*Scanning electron microscope measurements*

The morphology of all tested samples from composites systems PWGEC and STGEC were examined by SEM. Figs. 6 and 7 (a,b,c,d, and e) illustrate SEM images for the fracture surface of PWGEC and STGEC specimens, respectively under different environmental conditions as shown in Figs.6, 7 (b, c, d, e), compared to that of the virgin (unconditioned) state as indicated in Figs. 6 (a) and 7 (a). Fig. 6 (a) reveals the presence of 'hackles' at the whole the fiber surfaces in the virgin specimen which are the matrix bonded to the fibers even after the fracture which confirms the presence of a strong bond at the interface between the fiber and the matrix. On the other hand, less 'hackles' can be seen at the fiber fracture surface for the specimens exposed to different environmental conditions as shown in Figs. 6 (b, c, d, e) as compared to Figs. 7 (b, c, d, e).

Moreover, it can also be observed that the fracture surface of the specimen exposed to alkali solution (pore solution) reveals relatively clean fiber surface from the matrix resulted from the weak fiber-matrix bonding. Meanwhile, less glass fiber pull out were observed at the fractured section for the specimen exposed to alkali solution which distinguishes brittle failure and the interface between the fiber and the matrix could hardly be identified due to the excessive degradation of the matrix by the chemical effect under pore solution environment as shown in Fig. 6 (e) as compared to Fig. 7(e). On the other hand, the effect of other environmental conditions on the interface between the fibers and the matrix was relatively little and the matrix was relatively still bonded the fibers even after the fracture as shown in Figs. 6 (b, c, d, e) as compared to Fig. 7 (b, c, d, e).

In summary, from these results it is better recommended to use PWGEC and STGEC composites as joining bolts for assembling mechanical parts in indoor environment, whereas it is not better recommended to use PWGEC and STGEC composites as joining bolts in concrete pore solution.

## Conclusions

Comparing the effect of different environments of 2D plain woven and short glass fiber reinforced epoxy matrix composites on the notch sensitivity of these composites, it can be concluded that:

1. The environmental exposure has a pronounced negative effect on the notched tensile strength of all composites as compared to that of unnotched virgin state and the effect was higher in short glass composites than that of plain woven glass composites.

2. A little loss in the notched tensile strength of plain woven glass composites was observed when they are subjected to the indoor condition, however a larger drop was observed in the notched strength of short glass composites in indoor environment.

3. The value of the characteristic distance of different types of the composites from the higher to lower is in case of indoor environment, distilled water and salt water environments,

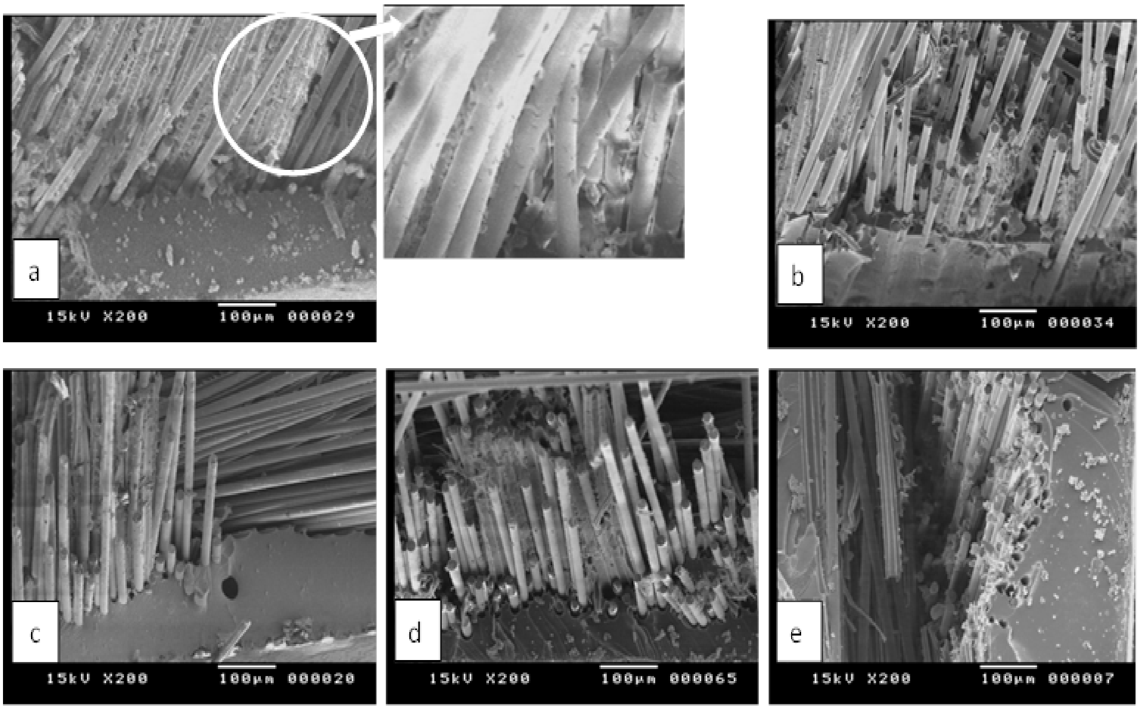



**Fig. 6: SEM micrographs for continuous fiber reinforced composites (PWGEC) at different conditions (a) virgin, (b) indoor, (c) distilled water, (d) sea water, and (e) Pore solution.**

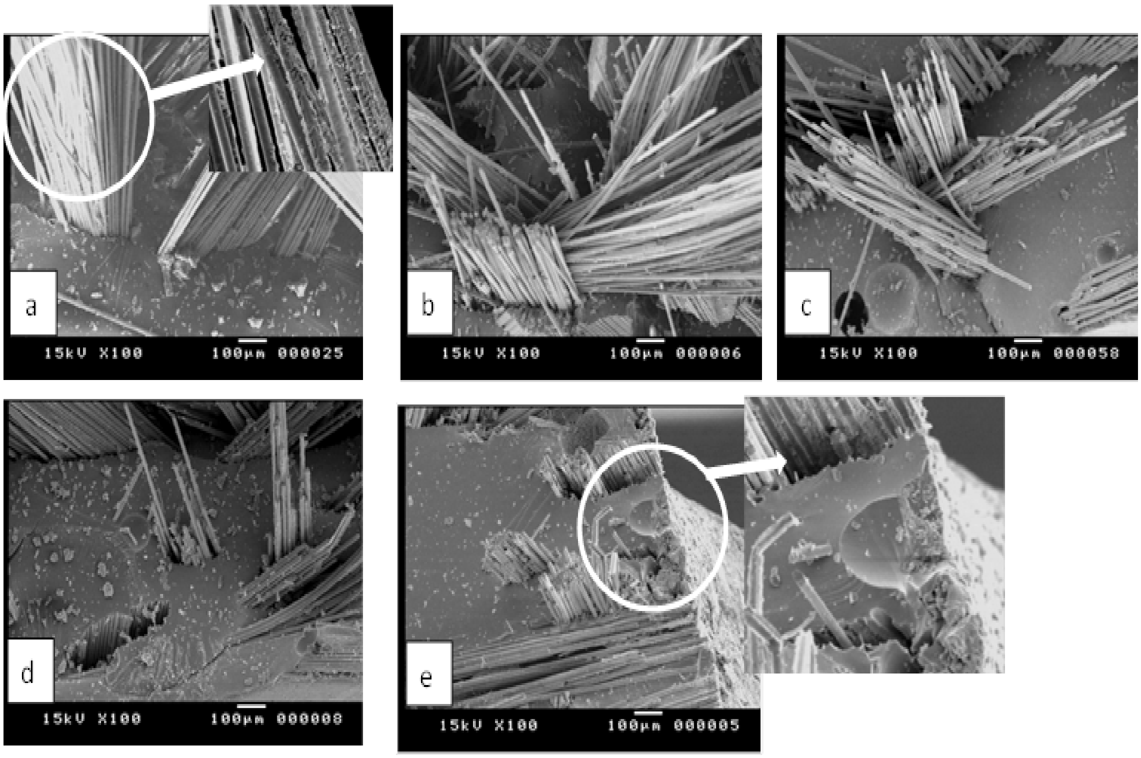



**Fig. 7: SEM micrographs for short fiber reinforced composites (STGEC) at different conditions (a) virgin, (b) indoor, (c) distilled water, (d) salt water, and (e) Pore solution.**

respectively and therefore the sensitivity these composites to the hole notch was lower when they are subjected to indoor environment, distilled water and salt water environments, respectively.

4. The characteristic distance of PWGEC and STGEC composites was almost zero under alkaline environment. This physically means that these composites are very brittle under notched tensile loading when they are subjected to alkaline immersion.

5. Similar fracture mechanisms were observed for both types of the composites for open hole specimens under distilled water, salt water and indoor environments as in virgin specimens which the fracture zone of these composite laminates showed five typical failure modes fiber pull out, delamination, matrix cracking and debonding.

6. The fracture surface of the specimens exposed to the alkaline environment is smooth and showed much less fiber pull out validated by SEM micrographs. This mode of failure distinguishes brittle failure which validates the results obtained from Whitney-Nuismer mathematical model.

7. SEM micrographs revealed the presence of 'hackles' at whole the fiber surfaces in the virgin specimen which are the matrix bonded to the fibers even after the fracture which confirms the presence of a strong bond at the interface between the fiber and the matrix. On the other hand, less 'hackles' can be seen at the fiber fracture surface for the specimens exposed to different environmental conditions.

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