RESEARCH ARTICLE

Effect of Nanoparticles on the Improving Mechanical Behavior of GFRP Composites in a Corrosive Environment

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ABSTRACT

Corrosive environment can significantly affect the mechanical behavior of composite structures which can be improved by using hydrophobic nanoparticles. The aim of this study is to investigate the improvement of the mechanical properties of incorporating glass fiber reinforced polymer (GFRP) composite specimens with 3 wt. % of nanoclay and nanosilica in a corrosive environment. Filled GFRP composites were fabricated using the mechanical stirrer followed by sonication method, and the hand lay-up method. After preparing the neat and incorporated GFRP according to ASTM standards, all the samples were immersed in 5% sulfuric acid solution for 0, 1, and 3 months. As the immersion time increased, the samples containing nanosilica absorbed more water than the other samples. The tensile and compressive tests were performed at different immersion times to obtain the ultimate tensile and compressive strength and tensile modulus. The results showed that by adding nanoparticles, the mechanical properties were increased, which GFRP containing nanoclay showed a better behavior in the corrosive environment. By adding 3 wt. % of nanoclay, the ultimate tensile and compressive strength and the tensile modulus decreased after one month of immersion by only 0.34%, 1.81% and 2.95%, respectively, and after three months of immersion only decreased by 0.43%, 10.88% and 6.95%, respectively. Finally, SEM images of all specimens were examined to investigate the fracture mechanisms and the corrosion behavior of fabricated nanocomposites.

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INTRODUCTION

In recent decades, fiber reinforced polymer (FRP) composites, especially GFRP composites due to their high specific strength and stiffness, superior corrosion resistance, high static and dynamic behavior and the ability to adapt its features to any required application like aerospace, military, defense, marine and chemical industries, are a good alternative to conventional materials like metallic alloys [1-5]. In recent years, a considerable amount of studies have been conducted on the effect of various corrosive environments on the mechanical properties of composites because corrosion has adverse effects on human life [6, 7]. Investigating previous literature showed reducing the mechanical properties because of corrosive environments, including the tensile strength [8-10], flexural strength [11-13], fatigue life [14, 15]. In other studies, water attack causes swelling of matrix [16], relaxation and oxidation of matrix, fiber/matrix deboning, continuous cracks and matrix plasticization [17], which degrades all the mechanical properties. The studies of previous researches, illustrated that the addition of different nanoparticles into composite materials could improve the mechanical properties, significantly [18-24]. Therefore, the idea of improving the corrosion resistance of composite materials by adding nanoparticles, especially nanoclay due

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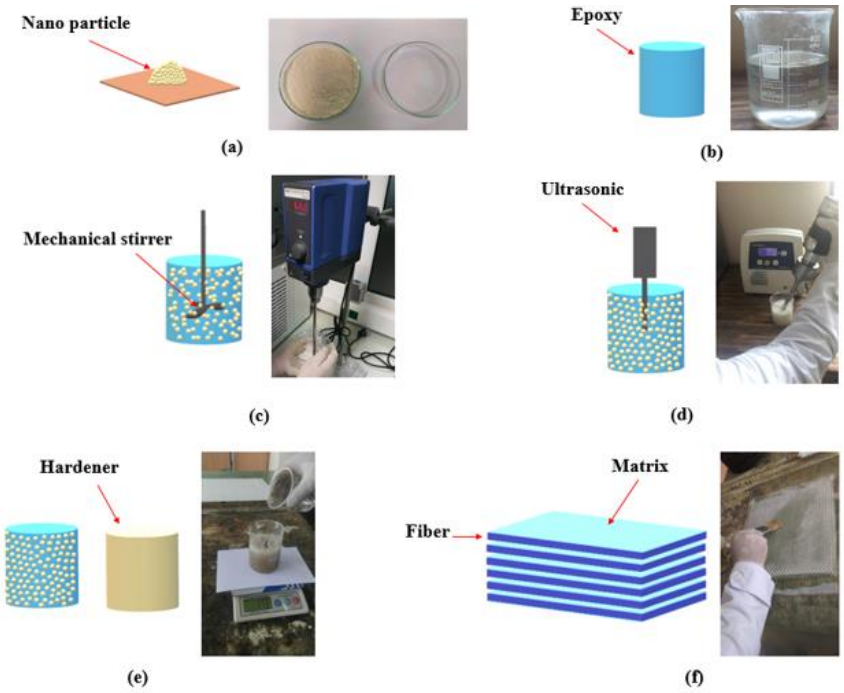

Fig. 1. A schematic of the fabrication process of nanocomposite specimens including (a) weighing nanoparticle and (b) weighing epoxy resin (c) distribution with mechanical stirrer (d) dispersion via sonication (e) adding hardener (f) fabrication of composite laminates using hand layup method.

to their high aspect ratio [25, 26], attracted researchers.

Among those investigations, Eesaee and Shojaei [27] investigated the mechanical properties of glass/epoxy composite reinforced with 0.5, 1.5 and 2.5 wt. % of natural clay (Cloisite Na^+) and organically modified clay (Cloisite30B) in different corrosion solutions. They found that the elastic modulus of filled GFRP with 2.5 wt. % of CN and CB has increased by 38% and 43 wt. % respectively, and flexural modulus of both of them has increased by 15%. Also, their observations showed that the hydrophilic nature of nanoclays has absorbed water, so the tensile and flexural strength have reduced due to interface debonding and matrix degradation. Mahesh et al. [28] studied the effect of various additions of clay, including 0 to 8 wt. %, in the vinylester/glass composites immersed in alkaline solutions for a maximum of 100 days. Their results showed a reduction in flexural strength, ILSS and impact strength in the corrosion environments. But, samples with different amounts of clay have better mechanical behavior than pure specimens because of the hydrophobic nature of the clay, which prevents the water penetration into the composites. Gao et al. [29] investigated the mechanical properties of a nanostructured coating by adding 0.2 wt. % surface-functionalized MWCNTs and 1% nanoclay in alkaline solution. They showed that coated samples with clay due to the sheet structure of clay, which represents its highest water barrier and anti-corrosion property, would not find a significant strength reduction, while in specimens containing MWCNTs strength was significantly reduced. Rafiq and Merah [30] examined flexural properties of glass fiber/epoxy reinforced with I.30E clay contents ranging between 0 and 5 wt.%, in the water at two temperatures, 23°C and 80°C. They showed that the water uptake could decrease the flexural strength and modulus. Also, their results indicated that the reduction in flexural strength at room temperature is between 6 and 10%, proportionate to the amount of clay. Pure samples lost the most strength (10%) in the presence of water and loss of strength for the neat samples and GFRE-nc hybrid composite immersed in water at 80°C is about 40% and on the average 36%, respectively. Generally, the study of previous researches showed that the addition of different amounts of clay has a positive effect on strength and stiffness of composites in a corrosive environment.

Han et al. [31] studied the effect of incorporating 2 wt.% nanosilica on improving the tensile behavior and fracture toughness of epoxy for

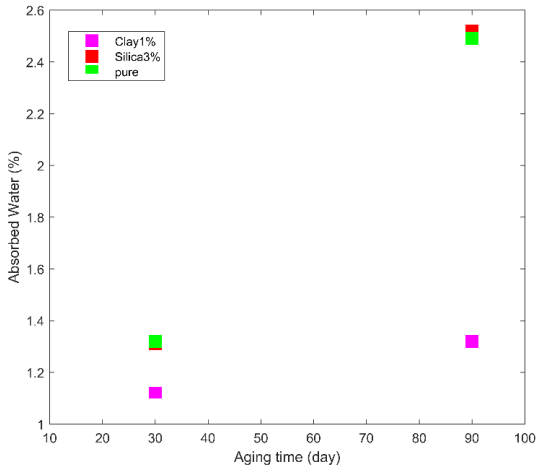

Fig. 2. Moisture absorption percentage by specimens after 30 and 90 days.

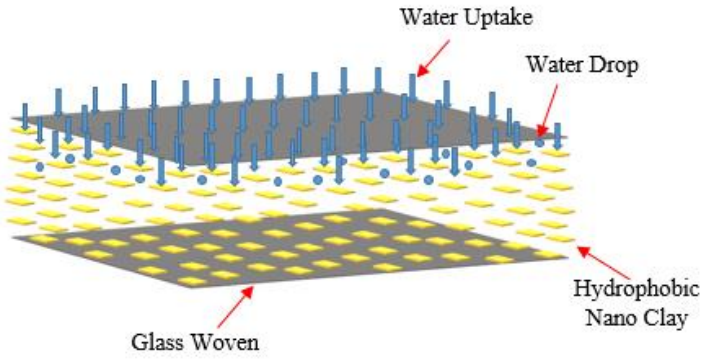

Fig. 3. Penetration of water and acid into clay nanocomposite.

different periods (0, 7, 30 days) immersion in the seawater. As their results presented, after 7 and 30 days of seawater immersion, there was no decrease in the tensile properties for both neat epoxy and nanocomposite. Also, their results showed that immersion in the seawater decreased the maximum load and the fracture toughness of both neat epoxy and nanocomposite specimens compared with the samples without salt water immersion. After 7 days of immersion, the KIC values of the neat epoxy and the nanocomposite decreased by about 18.5% and 16.8%, respectively. After 30 days of immersion, the KIC decreased only 1% more than 7 days of immersion. However, they claimed that the enhancement of fracture toughness due to the addition of nanosilica was able to offset the loss due to the salt water immersion and epoxy reinforced with silica could be useful for the marine industry compared to pure epoxy. Kamal and Kadhim [32] investigated the effect of nanosilica particles (3 wt.%) on hardness, tensile properties and impact strength of the reinforced (glass/Kevlar) fabrics, polyester hybrid composite in both alkaline and acid solutions. They observed that the tensile properties and impact strength of all samples decreased when immersed in these solutions and this decline increase with increasing immersion time. Also, they claimed that the hybrid composite reinforced with nanosilica presents more resistance to these chemical solutions by enhancing the surface hardness of the polyester matrix.

Chang et al. [33] studied the effects of adding 0-2 wt.% of SiO_2 on the chemical resistance, glass transition temperature (Tg) and dynamic mechanical properties of glass fiber/epoxy composite in acetone. They observed that the storage modulus for 0, 1, and 2 wt. % silica were 10510MPa, 11998MPa and 13444MPa, respectively. The storage modulus for neat samples and samples with 2 wt. % nanosilica after being immersed in acetone has decreased by 11.76% and 0.84% respectively, indicating the chemical resistance of

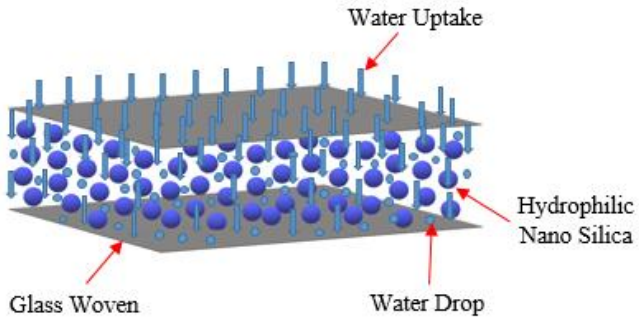

Fig. 4. Penetration of water and acid into silica nanocomposite.

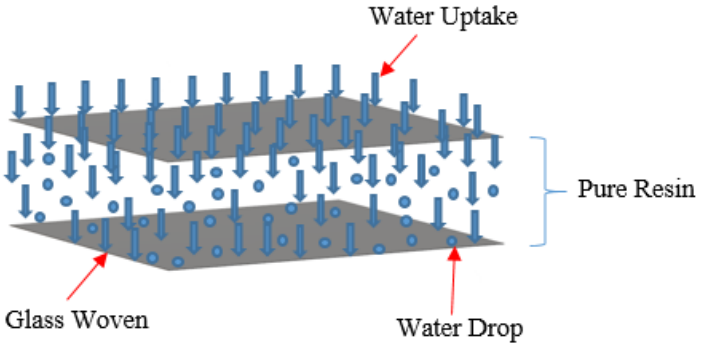

Fig. 5. Penetration of water and acid into pure nanocomposite.

the specimens containing nanosilica.

The study of previous researches showed that there is no specific study comparing the effect of adding nanosilica and nanoclay into GFRP composites with the same fabrication condition on improving the mechanical properties of GFRP immersed in a corrosive environments, which is very harmful because the corrosive environments can reduce the mechanical properties and change the behavior of the materials[31, 34]. Hence, this study intends to investigate and compare the effect of incorporating 3 wt. % of nanoclay and nanosilica on the tensile and compressive responses of GFRP immersed in 5% sulfuric acid for different times compared to neat GFRP composites. Also, the improvement mechanisms and corrosion behavior were studied using scanning electron microscopy (SEM) examination.

EXPERIMENTAL PROCEDURES

Materials

C-glass woven fabric, Epon 828 epoxy resin and two types of nanoparticles, including nanoclay and nanosilica were used to fabricate fibrous nanocomposites. The plain weave C-glass fabric with the areal weight of 600 g/m2 purchased from Mytex Turkey. The composite matrix was composed of Epon 828 epoxy resin, which was an undiluted clear difunctional bisphenol-A and supplied by Kumho P&B Chemicals and the hardener with a ratio of 100:10 by weight was Deithvlenetriamine (DETA) which was provided by Kumho P&B Chemicals as well. The spherical silica nanoparticles with average particle size of 20–30 nm, density 2.2 g/cc and SSA (specific surface area) 180–270 m2/g and without surface modification were supplied by Tecnan nano-materials Co., Spain. Montmorillonite clay Cloisite 15A nanoparticles with a diameter of the plate 24.2 and density of 1.77 supplied by Merck, Germany. The environmental solution contained H_2SO_4 (98%) and deionized water.

Manufacture of incorporated GFRP with nanoparticles

Fig. 1 shows the process of nanocomposite fabrication. Before layering the nanocomposite laminates, the resin containing the nanoparticles must be prepared. First, the epoxy resin was preheated for a few minutes to better distribute the particles inside the matrix. Then, 3 wt. % of nanoclay and nanosilica were added to the epoxy resin and mix using a mechanical mixer. Then, the

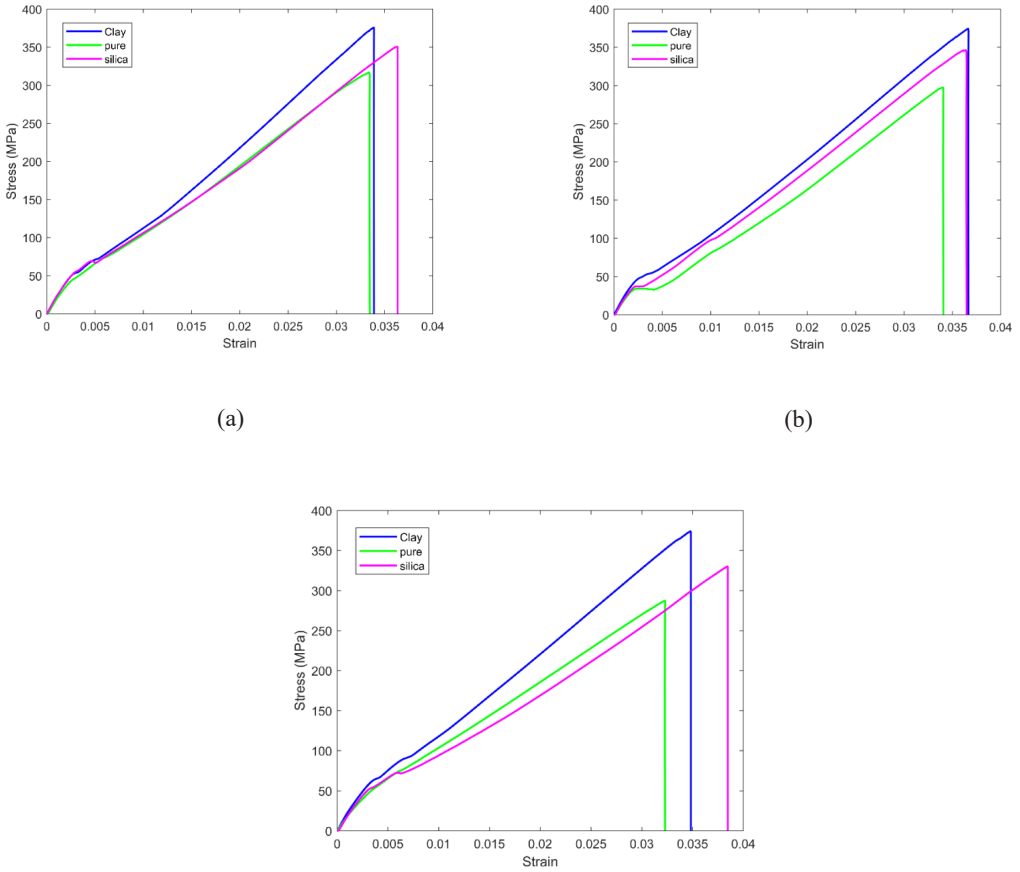

Fig. 6. Stress-strain diagram of immersed samples at (a) 0 month (b) 1 month (c) 3 months.

particles were well separated from each other and dispersed in the epoxy resin using the ultrasonic method which, both of these methods were used for 35 minutes. In this study, Bandelin Sonopuls Ultrasonic Homogenizer, made in Germany, was used to homogenize the mixture, properly. The clear color of mixture of the epoxy resin and nanoparticles showed a good distribution of nanoparticles in the epoxy resin. The voids caused by the ultrasonic and the mechanical stirrer must be eliminated, so the mixture was degassed for 20 min using a vacuum oven. After degassing process, the mixture was cooled at room temperature, and finally hardener was added to the mixture.

After preparing the nanocomposite matrix, the composite laminates should be constructed. So, by using the hand layup (HLU) method, six plies with overall dimensions of 300*300 mm^2 were prepared on a steel mold plate. The composite laminates were cured at room temperature under a pressure of 10 KPa for 24 hours. Finally, in the HLU method, the nanocomposite laminates with a nominal thickness of 3 mm were fabricated.

Aging conditions

To prepare sulfuric acid, first in a volume of one liter, the amount of 5% acid is calculated from the following formula.

$$\frac{5}{96} * 1000\,\text{ml} = 52\,\text{ml} \quad (1)$$

Where 96 is liquid acidity. After this calculation, the required amount of distilled water is added to 52 ml of sulfuric acid to reach a volume of 1 liter liquid.

Both conventional and nanophase specimens were cut by a water jet method according to the ASTM standards and were immersed in the solution

Table 1. Tensile Strength (MPa) values of samples in different immersion months.

	pure	Silica 3%	Clay 3%
0 month	316.59	364.36	375.71
1 month	297.39	350.63	374.41
3 month	287.19	330.24	374.08

for 0, 1 and 3 months at room temperature. After the immersion time, the specimens were dried with a kleenex and immediately were weighted. The amount of the absorbed water by the immersed specimens was calculated using the following equation:

$$\%\ \text{wt. gain} = \frac{M_f - M_i}{M_i} \times 100 \qquad (2)$$

M_i and M_f are the initial and the final weight of specimens, respectively.

Measurements of the mechanical properties

The tensile and compressive tests were performed to obtain the mechanical properties of composite specimens, including the ultimate tensile and the compressive strength and the tensile elastic modulus. The tensile and compressive tests of the specimens were performed according to the ASTM D3039 and ASTM D3410 standards, respectively, using a universal SANTAM testing machine (STM-50), at room temperature.

RESULTS AND DISCUSSIONS

Percentage of weight gain due to moisture absorption

Fig. 2 shows the percentage of weight gain of the specimens due to water and acid absorption during different immersion times. The OH groups in the hydrophilic polymers structure known as the polar hydroxyl group, which absorbs water [35]. According to Sharma et al. [17], these materials are very prone to bonding with the water molecules due to the large amounts of the OH groups, which can increase the adsorption of polar molecules. Since there are not many hydroxyl groups in the structure of the epoxy Epon 828, this polymer is not very dependent on water apart from other polymers. On the other hand, water can penetrate into the composites through the voids and micro-cracks in the matrix and voids along with the fibers matrix interface. Water absorption can cause the swelling and the hydrolysis in the epoxy and it also separates fiber and matrix interface and create more micro-cracks, which can lead to more water penetration [17, 36].

Nanoparticles have a large surface area and surface energy, which attract each other and absorb polar molecules in their surroundings [37]. For this reason, particles are known as hydrophilic particles. One way to reduce the amount of polar groups and hydrophilicity of nanoparticles is to modify their surface [38, 39]. Sharma et al. [17] used silane coupling agents to modify the surface of nanoclay, and they observed that by modifying the surface, polar groups and hydrogen bonds on the surface of nanoparticles can be eliminated and turned into hydrophobic particles [17]. With the hydrophobicity of the particles, the repulse of moisture and water can increase and also the corrosion of the specimens can decrease. In this research, the clay nanoparticles have been modified using the modifying group, but silica nanoparticles have been used without surface modification, which the obtained results showed a better behavior for GFRP containing nanoclay.

The decrease in water absorption is related to the improvement of the matrix in water resistance due to the presence of hydrophobic clay sheets [17, 40]. Intercalated and exfoliated clay located parallel to the layers [41] and increases the water penetration path, prevents water attack and reduces penetration rate [42], as shown in fig. 3.

On the other hand, unmodified silica have many hydroxyl groups on their surface due to place in the environment. Besides, the structure of silica has -Si-O-Si- bonds, which have a series of broken bonds in their structure and absorb hydroxyl groups of the fibers and the environment. Also, silica nanoparticles have a porous structure [43, 44], which helps more acid and water to penetrate into the specimens. The absorption of water into blue nanosilica is shown in Fig. 4. Therefore, silica nanoparticles not only prevent the penetration of acid, but they also promote the absorption of acid.

Table 2. Elastic modulus (GPa) values of samples in different immersion months.

	pure	Silica 3%	Clay 3%
0 month	10.612	13.461	14.064
1 month	9.976	11.279	13.649
3 month	8.327	10.036	13.086

Table 3. Compressive Strength (MPa) values of samples in different immersion months.

	Pure	Silica 3%	Clay 3%
0 month	121.874	125.813	127.605
1 month	120.278	120.7453	125.291
3 month	108.669	109.577	113.715

Hence, silica nanocomposites were expected to absorb more water than other specimens.

Pure specimens and silica nanocomposites have more corrosion than clay nanocomposite in sulfuric acid medium. In silica, due to the presence of oxygen in its structure, corrosion in sulfuric acid increases sharply, which leads to a considerable reduction in the mechanical properties, which the same trend was reported by [45]. On the other hand, because of the presence of distilled water in sulfuric acid 5%, distilled water can provide the conditions for oxidation and sufficient moisture. Therefore, due to the presence of water in sulfuric acid 5%, the clay nanocomposites also corrode, but this corrosion was much less than other specimens. The voids in the pure specimen can increase the penetration path and the resin corrosion, which reinforcing particles try to prevent corrosion as shown in fig. 5.

With adding 3 wt. % of nanoclay, the water absorption has decreased after one and three months of immersion compared to other specimens. However, the reinforced GFRP composites with nanosilica had more water absorption. In the specimens containing 3 wt. % of nanosilica, the water absorption was increased after one and three months because, these particles did not adequately cover the voids and bubbles in the matrix. On the other hand, the porous and hydrophilic silica particles had a strong tendency to bond with water and acid molecules. Therefore, a good condition was provided for more water and acid penetration. As shown in fig. 4, the highest amount of adsorbed water was observed in the nanocomposite with 3 wt. % of nanosilica. So, the addition of nanosilica did not have a beneficial effect on moisture dissipation. Despite the corrosion-resistance and hydrophobicity of the fibers and matrix in the pure specimen, water and acid have penetrated the specimen through voids in the matrix and micro cracks with increasing immersion time [46, 47]. As the immersion time increased, the water uptake increased slightly. This phenomenon can be due to the removing of damaged fibers and matrices from the nanocomposites, which can increase the porosity and voids [48].

Mechanical properties

Fig. 6 illustrates a comparison of the stress-strain curves of the pure and nanocomposite specimens in different immersion periods. As the results of Table 1 illustrate, the mechanical properties of the specimens without immersion were enhanced by the addition of nanoparticles. The tensile strength with the addition of 3 wt. % of clay and 3 wt. % of silica has increased by 18.67% and 10.75% compared to the pure specimen, respectively. The tensile modulus by adding 3 wt. % of clay and silica has increased by 32.5292% and 26.847% compared to the pure specimen, respectively. The addition of nanoparticles also increased the compressive strength of the specimens. So that, the addition of 3 wt. % nanoclay has increased the compressive strength by 4.7% and the addition of 3 wt. %

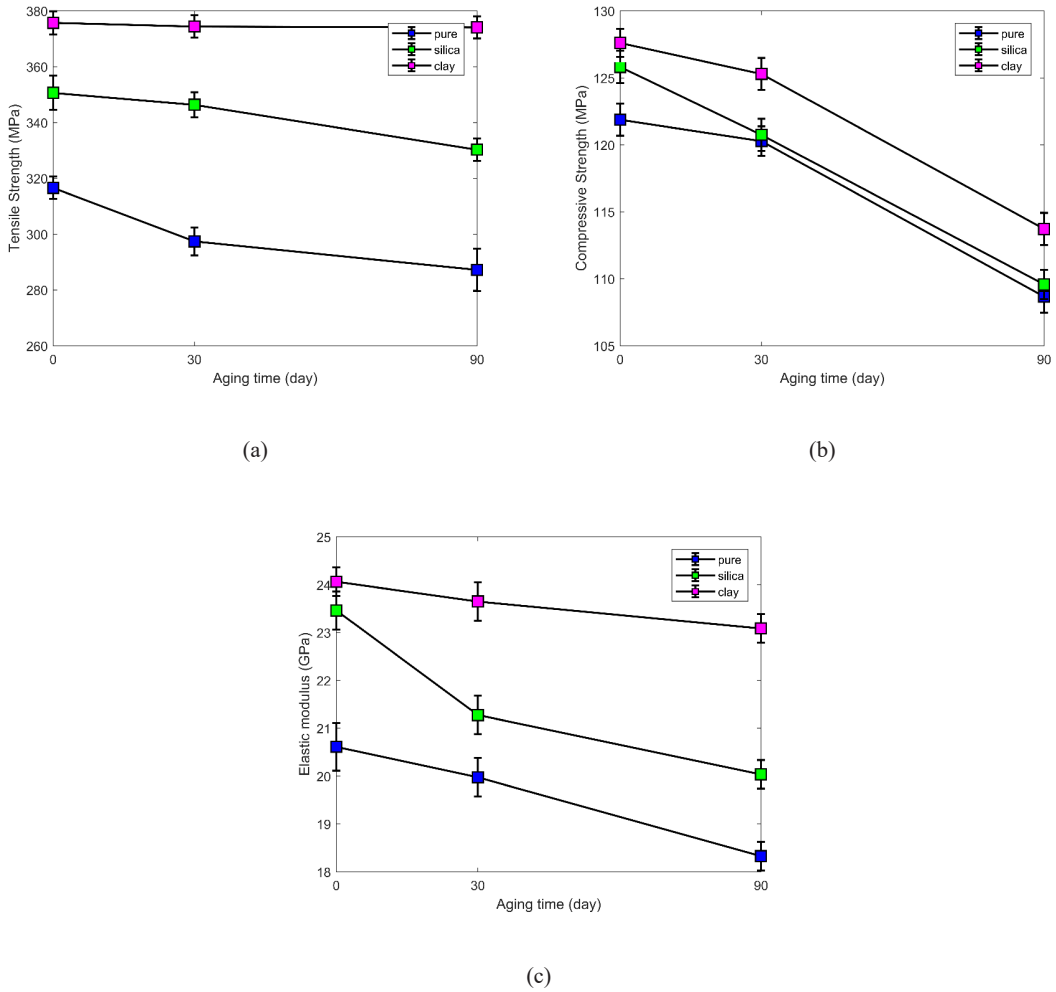

Fig 7. Comparison of (a) Tensile Strength (b) Compressive Strength (c) Elastic modulus of specimens in different immersion time.

nanosilica has increased it by 3.23 % compared to the pure specimens. These results are consistent with the results of previous studies. According to chen et al. [49] as well as alsaadi et al. [50] the addition of clay and silica to the polymer-based nanocomposites can increase the mechanical properties of the nanocomposites. Increasing the surface area to the volume is the main factor of increasing the mechanical properties [51]. This factor has strengthened the bond between the fibers and the matrix, which can improve the mechanical properties [51].

A uniform increase in the bonding network results in a better stress transfer and an increase in the tensile strength. Adding nanoparticles like a bridge has reduced defects such as voids and delayed the onset of cracking, which can increase the mechanical properties [52]. The clay has further improved the tensile strength and tensile modulus than the silica. According to jahangiri et al. [45], the clay has smaller dimensions than the silica. The size of the empty space in the specimens containing clay is less than other specimens. Nanoclay and nanosilica increase the surface bond between the fibers and the matrix and act as a barrier to crack propagation by increasing its length [50, 53], that both of them can increase the toughness. The toughness can be considered as the ability of samples to absorb energy before its failure [54]. Also, the silica nanoparticles harden the propagation of crack by blocking its growth path, which increases the toughness [55].

After one and three months of immersion, the mechanical properties of all specimens decreased. After one month of immersion, the tensile strength of the clay nanocomposite, the silica nanocomposite,

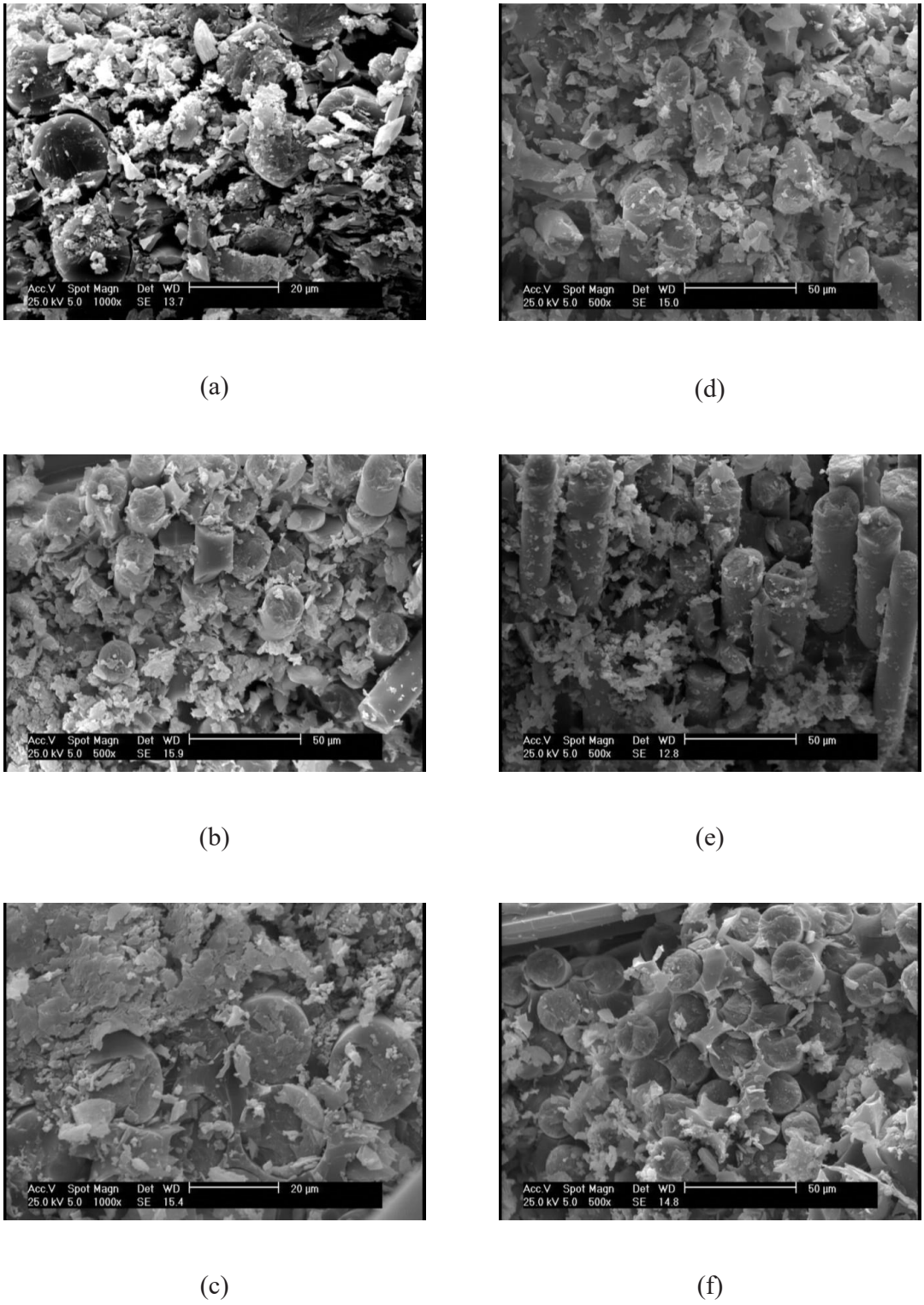

Fig. 8. The SEM images related to corrosion of (a) pure sample and samples containing (b) 3 wi. % of nanosilica, (c) 3 wt. % of nanoclay, after 1 month (d) pure sample (e) 3 wt. % of nanosilica, (f) 3 wt. % of nanoclay after 3 months.

and the pure specimen decreased by 0.34%, 1.2% and 6.06%, respectively. Also after three months of immersion the tensile strength decreased by 0.43 wt. %, 5.81% and 9.28%, respectively compared to the nanoclay, nanosilica and the pure specimens without corrosion. The clay nanocomposite did not have a significant decrease in the tensile strength with increasing immersion time, because nanoclay sheets act as a barrier against moisture penetration and also the empty space and voids in these specimens can be negligible [25]. Besides, hydrophobic particles of clay did not tend to absorb water. Therefore, the bond strength between the matrix and the fibers has been preserved. Also due to less water penetration, corrosion of the matrix and the creation of voids and also crack propagation can be neglected. By increasing immersion time, specimen containing nanosilica despite absorbed more water, it had a smaller reduction in the tensile strength than the pure samples which can be due to the dominance of the bond strength between the fibers and the matrix and the prevention of crack propagation over corrosion [31].

As fig. 7 illustrates, after one month of immersion, the elastic modulus of specimens containing nanoclay, nanosilica and the pure specimens has decreased by 2.9508%, 16.98% and 5.932%, respectively, and also after three months of immersion, the elastic modulus has decreased by 6.9539%, 25.4439 and 21.532%, respectively compared to the clay and silica nanocomposite and the pure specimen without immersion. The specimens containing nanoclay did not show much reduction in tensile modulus despite immersion. The nanocomposite containing nanosilica, due to water absorption and be softer, reduced their tensile modulus more than the nanoclay and pure specimens. Table 2 shows the values of the elastic modulus in different immersion months.

Although this specimen absorbed more water, it still has a better tensile modulus than the pure specimen. The same trend was observed for tensile strength which has indicated the dominance of the increase in tensile modulus due to the addition of nanoparticles over corrosion. As can be seen in table 3 the same trend was observed for the compressive properties as well as tensile strength and modulus. The compressive strength of the specimens containing nanoclay, nanosilica and the pure specimen decreased after one month of immersion by 1.81%, 4.02% and 1.3 wt. %, respectively and after three months of immersion decreased by 10.88%, 12.9% and 10.83 wt. % respectively compared to clay and silica nanocomposite and pure specimen without immersion. Specimen containing nanoclay despite the tensile strength and modulus had more reduction in compressive strength after one and three months of immersion.

Morphological studies by SEM

In order to investigate the effect of incorporating nanosilica and nanoclay into GFRP on failure mechanism and corrosion behavior of fabricated nanocomposites, the fracture surface of all specimens was examined using scanning electron microscopy (SEM). Uniform distribution of particles is an important issue. Because the agglomeration of nanoparticles increases the volume percentage of voids relative to nanoparticles. Nanoparticles prevent the fibers from getting wet during fabrication by forming lumps, which create bubbles in the composite structure. Fig. 8 shows SEM images of the specimens containing different percentages of nanoparticles and a pure sample which was immersed for three months. These images illustrate the interface between fiber and matrix and determine that how the voids were created in the matrix. Also, all specimens were fabricated using the hand layup method, which practically could cause the presence of voids and micro cracks into the matrix of fabricated nanocomposite specimens. It is important to notice that the presence of voids and micro cracks is a convenient area for penetrating water and acid into the samples.

As the SEM images illustrate, the pure sample has little tendency to absorb water due to the hydrophobicity of the matrix and fibers, but the presence of micro-cracks and voids can be an appropriate area for penetration of water and acid. The images of the sample containing 3 wt. % of nanosilica show that this specimen after 1 month has less water absorption and thus corrosion than the pure sample. Also in these images, the resistance of the matrix containing nanoparticles against corrosion can be clearly seen. In these samples, there are not enough gaps and empty spaces to absorb more water despite the hydrophilicity of the particles. After three months of immersion the corrosion rate of samples containing 3 wt. % of silica increased compared to the pure sample which can be due to the increasing of absorption water.

Sample containing nanoclay behaved better than other samples in a corrosive environment.

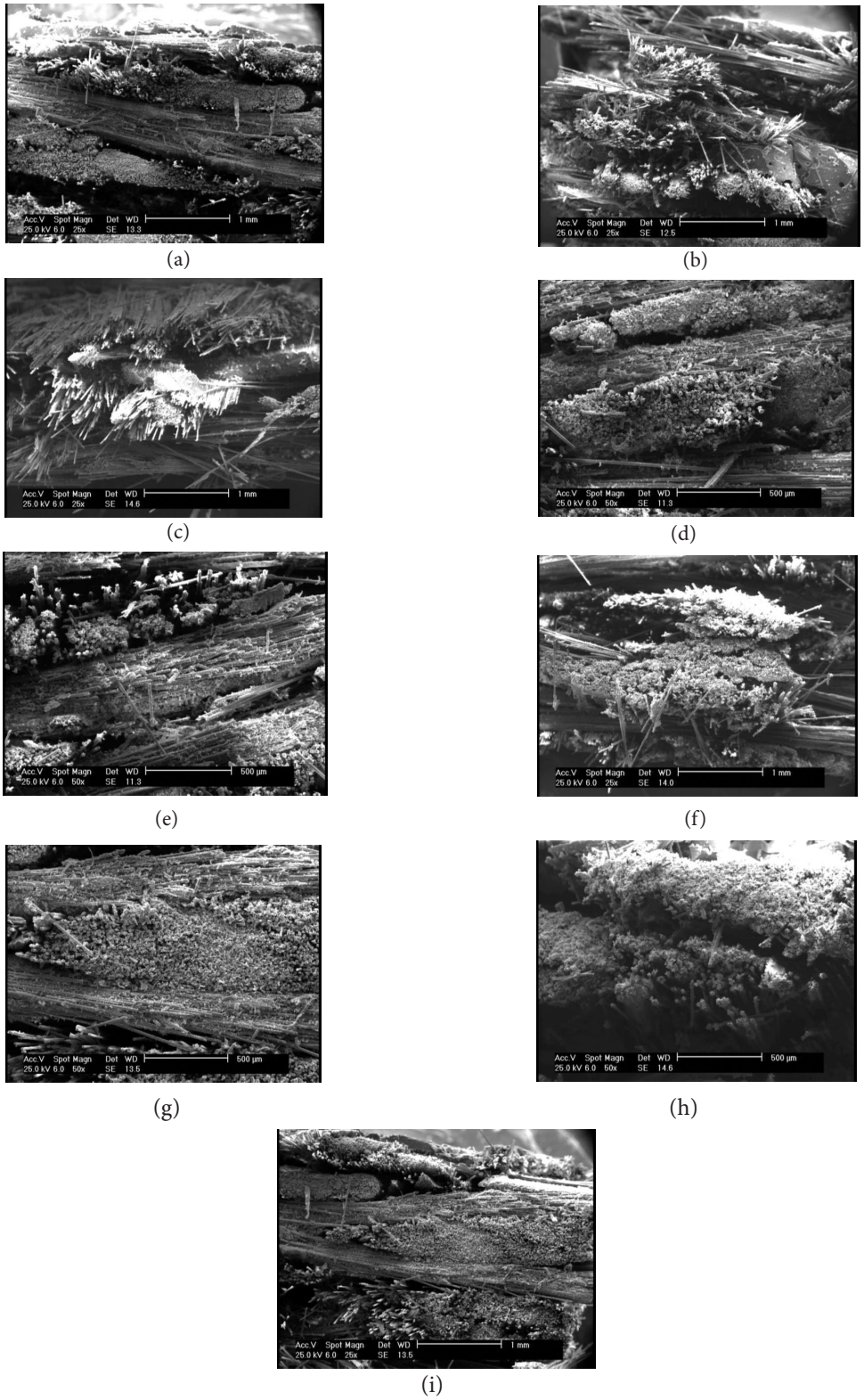

Fig. 9. SEM images related to the fracture surface of pure sample (a) without immersion, (b) after one month of immersion, (c) after three months of immersion and samples containing 3 wt. % of nanosilica (d) without immersion (e) after one month of immersion, (f) after three months of immersion and specimens containing 3 wt. % of nanoclay, (g) without immersion, (h) after one month of immersion and (i) after three months of immersion.

As can be seen from the images of specimens containing nanoclay after several months of immersion, the sheet shape of nanoclay prevented the penetration of water and acid into the structure of nanocomposite specimens and resulted in less damage of matrix in comparison with pure and incorporated composites with nanosilica. Specimen containing 3 wt. % of nanoclay had suffered some corrosion due to the presence of water in a corrosive solution. Due to the proper dispersion of particles in the specimen containing nanoclay, a good bond was formed between the matrix and the fibers, which could prevent the formation of micro cracks. Therefore, the specimen containing nanoclay has shown excellent resistance to environmental attack in a corrosive environment.

Also, uneven scattering of particles within the matrix results in reduction of the mechanical properties. Voids formation decreases with the uniform distribution of particles within the matrix, which increases the mechanical properties. The fracture cross section of samples containing nanoparticles is more uniformed than specimens without nanoparticles. In specimens without nanoparticles, the fiber has more fracture cross section, delamination and fiber separation than specimens containing nanoparticles. The addition of nanoparticles can reduce the separation and extrusion of fibers. The comparison of failure modes also shows that the addition of nanoparticles into the GFRP composites can increase the fracture toughness.

Fig. 9 shows how the submerged specimens failed in different immersion months under tensile force. The pure specimen without immersion illustrates a more uniform fracture cross section than the pure sample with immersion. However, images of wet specimens show non-uniform failure cross section due to matrix corrosion and separation of matrix and fibers. The predominant mode of failure in these specimens is fiber protrusion. In samples containing 3 wt. % of nanosilica without immersion, the failure cross section is uniform and no protrusions of the fibers are observed.

Despite corrosion and separation of fibers and matrix in immersed specimens containing nanosilica for three months, but also have a more uniform failure cross section than the pure samples, which can be due to the dominance of nanoparticle strength in tensile tests. As can be seen in the images related to the specimens containing 3 wt. % of nanoclay in different immersion months, these samples have shown a good resistance against corrosion, so that the breaking surface is uniform and there is no fiber protrusion.

CONCLUSION

In order to examine the effect of incorporating nanoclay and nanosilica on the mechanical behavior of GFRP composites in a corrosion environment, three types of nanocomposites were fabricated using the hand layup method and immersed in sulfuric acid 5% for 0, 1 and 3 months. The mechanical behavior of specimens containing nanoparticle and the pure samples was completely different in various immersion months. According to this study, the following results are concluded:

- In non-immersion samples, the addition of nanoparticles has increased the mechanical properties. In fact, by adding 3 wt. % of nanoclay, tensile and compressive strength and tensile modulus increased by 18.67, 4.7 and 32.52%, respectively, and by adding 3 wt. % of nanosilica increased by 10.75, 3.23 and 26.87%, respectively.

- Specimens containing nanosilica had higher water and acid absorption than other samples due to their hydrophilic and porous nature of nanosilica. Therefore, more corrosion has been observed in these samples.

- After one and three months of immersion, the mechanical properties of all specimens were reduced due to the absorption of water and acid. The tensile strength of specimens containing nanoclay and nanosilica and pure sample decreased after one month of immersion by 0.34%, 1.2% and 6.06% and after three months of immersion by 0.43%, 5.81% and 9.28%, respectively, in comparison with the samples without immersion.

- The tensile modulus of specimens containing nanoclay and nanosilica and the pure sample decreased by 2.95 %, 16.20%, and 5.99%, respectively, after one month of immersion and after three months of immersion decreased by 6.95%, 25.44, and 21.53, respectively, compared to non-immersion samples.

- The compressive strength of specimens containing nanoclay and nanosilica and the pure sample decreased by 1.0%, 4.02% and 1.3 wt. %, respectively, after one month of immersion and after three months of immersion decreased by 10.88%, 12.9% and10.83%, respectively, compared to samples containing nanoclay and nanosilica and pure sample without immersion. Hence, the obtained results illustrated that the addition of

nanoclay into GFRP composites showed a better benefit in a corrosive environment.

- The fracture surfaces of all specimens were examined and the improvement mechanisms and also the corrosion behavior were discussed.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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