Effect of glass, carbon, and kevlar fibers on mechanical properties for polymeric composite tubes produced by a unidirectional winding method

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Abstract
One of the applications of composites is in the manufacturing tubes, which are widely used in industries such as petroleum, petrochemical, and aerospace. Composite tubes are made of thermoset resin base material and reinforced by fibers, having a solid, lightweight, and corrosion-resistant structure, which is a great replacement for metal and concrete tubes. In this research, composite tubes with various resin base material, Swancor901, Epiran-1012, and Epiran-06FL reinforced by different fibers glass, carbon, and kevlar fibers, according to the compatible role, with the angle of 45° and unidirectional and same size, thickness, and diameter, were produced by the winding method. To study the mechanical properties of produced composite tubes, tensile, compressive, and three-point flexural strength tests were performed. The results showed that the highest ultimate tensile strength was obtained for carbon fibers reinforced tube (CFR) equal to 139MPa, which was 136% and 26% higher than kevlar fibers reinforced tube (KFR) and glass fibers reinforced tube (GFR), respectively. The highest flexural strength was also obtained for GFR equal to 91.08MPa, which is 132% and 13% higher than the flexural strength of CFR and KFR, respectively. Also, according to the results of the compression test, the highest compressive strength was observed in the samples reinforced with glass, kevlar, and carbon fibers, respectively. SEM imaging results from the cross-sections show that the best bonding between the base material and the fibers was observed for CFR.

1. Introduction

In recent years, with significant advances in the field of manufacturing engineering, more attention has been paid to environmental issues, and the staggering acceleration of the global consumerism phenomenon, selection of materials used in the manufacture of products has received more attention and has brought important achievements in various industrial sectors. The material selection, as well as the selection of manufacturing methods and techniques, are the major determinants of the cost, production time, and environmental impacts associated with production [1]. For this reason, in the last two decades, the tendency for innovative designing of new materials and methods has expanded. One of the most important materials, which had the largest portion of researches focused on their design and development in recent years, is the composite materials reinforced with fibers. These materials have been developed to leverage the capabilities of multiple materials together to address the weaknesses of each of them when used separately [2, 3]. The composites are divided into three groups of ceramic, polymeric, and metallic composites according to the type of base material [4]. Polymeric composites contain a polymeric base material that is divided into two groups: thermosets and thermoplastics [5].
Reinforcing fibers are also used in short, long, and continuous forms, whose main task is to withstand the forces when applying pressure to the material and causes force transfer from one fiber to another [6]. Two prominent features of fiber-reinforced composites are their high strength to weight ratio and their anisotropic properties. The high strength of these composites has enabled them to compete with other materials, including metals. The heterogeneous feature of the properties allows the designer to achieve the desired properties in the desired locations without increasing weight. These properties, along with their durability, excellent environmental resistance, and good resistance to fatigue forces, have attracted the attention of artisans and the increasing use of these materials [7]. Depending on their application, different types of composite tubes are made of reinforced glass fibers with polyester resin, vinyl ester, or epoxy. Polyesters are often used to produce tubes for water and sewage transport. Epoxy and vinyl esters are mainly used in the oil and gas industry due to their higher corrosion resistance [8]. Glass fibers are the most widely used as a reinforcement in the composites industry, and several types of them are commercially available, their chemical compounds are different, and each one is suitable for a particular application. Glass fibers have good strength and hardness, but their elastic modulus is relatively low. Also, carbon fibers are lightweight and have high strength and stiffness. On the other hand, Kevlar fibers, due to low density and high tensile strength, form a tough, impact-resistant structure with about half the strength of carbon fibers [3, 9]. As a result of sudden changes in fluid velocity within the tubes, internal shocks known as water hammer is applied to them leads to collapse. Due to their low modulus of elasticity, composite tubes have a high ability, about 50% more than metal tubes, to repel and absorb these shocks, which prolong the life of the tube [10]. Eksi et al [11] investigated the mechanical properties of polymer composites reinforced with glass, carbon, and kevlar fibers in a unilateral winding. The results of the tensile shear test showed that the samples reinforced with carbon fibers had more strength than glass fibers. Also, winding fibers with an angle of 0° gave better properties than winding fibers with an angle of 90°. In a similar study, Nasevai et al [12] investigated the tensile strength of GFR. The fibers were winded at different angles around the mandrel, and the results showed greater tensile strength was achieved compared to 0°. The results have been validated by taking SEM images from rupture locations of tensile test specimens. Faria [13] investigated the effect of composite tube manufacturing parameters with the winding method, including the winding speed of fibers, angle, resin material, temperature, and geometrical shape of the used mandrel, on their mechanical properties. Amid et al [14] manufactured composite tubes with polyester fibers. The produced tube was winded only one layer around the mandrel and underwent a tensile test and a hydrostatic test. Experimental results of the tests were studied analytically, and the results were in good agreement. The specific burst strength of the produced tubes was better than those of cast iron with the same dimensions and thickness. Stefanovska et al [15] investigated the flexural strength properties of composite tubes manufactured with glass fibers experimentally and theoretically. The fibers were winded at different angles around the mandrel, and the results showed that the flexural strength of the tube increased as the winding angle decreased.

The purpose of this study was to develop high-strength composite tubes for use in petrochemical industries; And for this purpose, polymeric composites tubes are made of resin polymer and reinforced with different fibers with a weight fraction of 50% resins and fibers. polymer composite tubes with resin base-material and reinforced with glass, carbon, and kevlar fibers were produced by the winding method. All fibers were winded unilaterally at a 45° angle with a velocity of 15 m min⁻¹ around the mandrel axis and all tubes were produced in the same size and diameter. Also, another predominant aim of this study is that using different resins that are more compatible with fibers. To determine their mechanical properties and their strengths, tensile, three-point flexural, and compressive tests were performed on them. To validate the results, SEM images of the behavior of the fibers from their fracture cross-sectional area were taken.
2. Experimental part

2.1. Preparing tubes

Given that the base material of the tubes is resin, and glass, carbon, and kevlar fibers are the reinforcing material; To produce composite tubes, different and special resins are used for the production of each tube based on used fibers. The resins were mixed with the additives in the agitator for 60 min. It should be noted that the Cobalt actuates solution with DMA126 technical specification with the amount of 1.5% weight and Peroxide acid solution with MEKP101 technical specification with the amount of 15% weight were added to the intended resins to obtain the best resin and to aid the curing and drying process [9]. The used resin for the production of GFR is Swancor901 type to overcome the brittle structure of glass fibers, and for the CFR and KFR are

| Sample | Inner Layer | Outer Layer | Middle Layer |
|--------|-------------|-------------|--------------|
|        | Mark | Material | Mark | Material | Mark | Material |
| GFR    | Mat225 | Glass Fiber | Mat225 | Glass Fiber | Women600 | Glass Fiber |
| CFR    | Re300  | Fabric    | Re300  | Fabric    | 300   | Carbon Fiber |
| KFR    | Re300  | Fabric    | Re300  | Fabric    | 49    | Kevlar Fiber |

**Figure 2.** The SEM images of used fibers.

**Figure 3.** The mandrel for producing composite tubes.

**Figure 4.** The winding device (a), The produced tubes (b).

**Table 1.** The feature and layers of fibers for production tubes.
Epiran-1012 and Epiran-06FL type resins, respectively [9]. The SEM image and photo of the used fibers and their arrangement can be seen in figures 1 and 2 and table 1. The Re300 fabric is also used to improve the connecting and bonding structure of the carbon and kevlar fibers with the resin base material.

2.2. Composite tube production

After preparing the resins, the reinforcing fibers are cut and placed in the resin solution for 20 min (Gel time) and are ready to be wound around the mandrel to make the tube. For the production of composite tubes, a mandrel with a 26.7mm diameter was prepared according to figure 3.

The mandrel surface is cleaned and polished to ensure the smooth interior surface of the composite tubes before being tucked into the winding device. Then, a very thin layer of resin called gel coat is sprayed on the mandrel with a 0.7mm thick gel coat spraying device to make the fibers attach to the mandrel more easily and to be separated. Figure 4(a) shows the used device to wind the fibers around the mandrel to produce tubes. The winding of fibers was performed at a speed of 15 m min⁻¹ and an angle of 45° around the mandrel. When the work is done and the fibers are wrapped, the specimens are kept at room temperature for 2h to allow the initial curing of the resin (figure 4(b)). The composite tubes are then separated from the mandrel for final curing and are heated in the furnace at 70 °C for 2h. Table 2 shows the geometrical specifications of the produced composite tubes. The pipes were produced according to the industrial standard with the aim of commercial production and the proportion and weight percentage of the resin and fibers is equal and is 50%. Also, to investigate the resin and fiber layers, SEM images were taken from the cross-section of the samples, which can be seen in figure 5.

According to the cross-sectional image of the specimens, the mixing of the fibers and resin is well performed.

| Sample | Thickness (mm) | Diameter (mm) | Weight per 20cm (gr) |
|--------|----------------|---------------|---------------------|
| GFR    | 3.34           | 33.40         | 79.00               |
| CFR    | 3.34           | 33.40         | 75.00               |
| KFR    | 3.34           | 33.40         | 78.00               |

Figure 5. The SEM image of the cross-section of produced tubes.

Figure 6. The specimen of the tensile test and its dimension according to (mm).

Table 2. The specification of produced tubes.
2.3. The determining mechanical properties tests

The following tests were performed to investigate the effect of the used fibers on the mechanical properties of the composite tubes produced by the winding method.

2.3.1. Tensile test

For the tensile test at ambient temperature to determine the tensile strength of the produced tubes, specimens were cut from the surface of the tubes according to ASTM D638 standard, and the test was performed with
50 mm gauge length, 5 mm min\(^{-1}\) applying force speed, and 0.001 s\(^{-1}\) strain rate\(^{[16]}\). Figure 6 shows the dimensions and specifications of the produced sample of the composite tube and figure 7 shows the prepared composite sample under tensile testing.

### Table 4. The dimensions of produced tubes for the compressive test.

| Sample       | Length (mm) | Thickness (mm) | Diameter (mm) |
|--------------|-------------|----------------|---------------|
| All Samples  | 120.00      | 3.30           | 33.40         |

2.3.2. The three-point flexural strength test

To determine the maximum fracture force and flexural strength of the produced tubes, the three-point flexural test was performed according to the ASTM D790 standard\(^{[17]}\). Applying the force with the speed of 5 mm min\(^{-1}\) continued until the outer surface of the specimens was ruptured. Also, the moment of flexural failure is considered when the force-displacement curve is reached to the maximum value. The specifications of produced specimens for the three-point flexural test are shown in table 3. Figure 8 shows the tubes during the three-point flexural test. It should be noted that the flexural strength was also calculated based on maximum force and the relations (1) and (2)\(^{[18]}\).
2.3.3. The compressive test

To test the compressive strength of the produced tubes, a compressive test was performed on them. The compressive test was performed at a constant speed of 5mm/min under the ASTM D695 standard at ambient temperature, as shown in figure 9 [19]. The dimensional characteristics of the used tubes for compressive testing are shown in table 4.

3. Results and discussion

3.1. Tensile strength test

In figure 10 the obtained engineering stress-strain curves are visible for composite tubes reinforced with different fibers. To see the results, the graph of the mean ultimate tensile strength is plotted in figure 11, where the maximum ultimate tensile strength for CFR is 139MPa, which is 26% and 136% higher than GFR and KFR, respectively. This is due to the high strength of the carbon fibers, which strengthens the resin base material. The layered structure of this fiber, which is wound around each other, also increases its strength. The resin base material directs the force to the fibers and causes more force to be needed to break the specimens. KFR also has the lowest strength among composite tubes because of the lower strength of kevlar fibers compared to other reinforcement fibers. On the other hand, the remarkable increase in tensile strength of the CFR indicates its compatibility and proper bonding with the base material; So that, only in this case, can the composite be considered successful from the perspective of increasing tensile strength [20]. In addition to these results, the rapid decrease in stress at the rupture point in all three types of specimens with different fibers indicates a simultaneous failure of the base material and the reinforcing fibers. Besides, the fiber content on the tensile strength of composites has significance for many researchers [21]. This can be attributed to many factors such as incompatibility between matrix and fibers, improper manufacturing processes, fiber degradation, and others [22]. The tensile test results of the produced composite tubes as well as the standard deviation of ultimate

\[
\sigma = \frac{M \times y}{I_x}
\]  

(1)

\[
I_x = \frac{(D_h^4 - D_o^4)\pi}{64}
\]  

(2)

Figure 11. The graph of the mean ultimate tensile strength of specimens.

Table 5. The result of the tensile test.

| Sample | Test No. | Max. of Tensile Force (N) | Ultimate Tensile strength (MPa) | Elongation (%) | Standard Deviation of UTS (MPa) |
|--------|---------|---------------------------|-------------------------------|---------------|-------------------------------|
| GFR    | 1       | 5030.82                   | 106.12                        | 3.00          | 4.89                          |
|        | 2       | 5479.12                   | 113.25                        | 2.00          |                               |
| CFR    | 1       | 5311.97                   | 144.45                        | 3.00          | 7.10                          |
|        | 2       | 4869.23                   | 134.07                        | 3.00          |                               |
| KFR    | 1       | 2716.36                   | 67.32                         | 3.00          | 12.12                         |
|        | 2       | 2220.97                   | 50.26                         | 4.00          |                               |

In figure 11 the obtained engineering stress-strain curves are visible for composite tubes reinforced with different fibers. To see the results, the graph of the mean ultimate tensile strength is plotted in figure 11, where the maximum ultimate tensile strength for CFR is 139MPa, which is 26% and 136% higher than GFR and KFR, respectively. This is due to the high strength of the carbon fibers, which strengthens the resin base material. The layered structure of this fiber, which is wound around each other, also increases its strength. The resin base material directs the force to the fibers and causes more force to be needed to break the specimens. KFR also has the lowest strength among composite tubes because of the lower strength of kevlar fibers compared to other reinforcement fibers. On the other hand, the remarkable increase in tensile strength of the CFR indicates its compatibility and proper bonding with the base material; So that, only in this case, can the composite be considered successful from the perspective of increasing tensile strength [20]. In addition to these results, the rapid decrease in stress at the rupture point in all three types of specimens with different fibers indicates a simultaneous failure of the base material and the reinforcing fibers. Besides, the fiber content on the tensile strength of composites has significance for many researchers [21]. This can be attributed to many factors such as incompatibility between matrix and fibers, improper manufacturing processes, fiber degradation, and others [22]. The tensile test results of the produced composite tubes as well as the standard deviation of ultimate tensile strength are shown in table 4.
strength are shown in table 5. The lowest percent elongation of pure fibers belongs to carbon fibers, but the CFR has a higher elongation than GFR, and the elongation value is close to the KFR. It can be concluded that there is a good bond between the base material and the carbon fibers and that no separation is established until the final stress is applied to the specimen [23].

All the failures of specimens have occurred at 45° angle in the middle of specimens that show the brittle property of polymeric specimens reinforced by fibers, and no separation between the composite layers was
observed after rupture (figure 12). According to the SEM image in figure 13, which shows the fracture cross-section of the tensile test specimen reinforced with carbon fibers, there has been little separation between the fibers and the resin until the rupture point. Also, considering the fracture level, it is found that the length variation of the base and the carbon fibers were approximately equal at the moment of fracture. But in GFR, the fibers are separated and come out of the base at the rupture point (figure 12). In the case of KFR, due to the lack of proper bonding between the fibers and the base, the failure occurred before the separation between the two. In the GFR, the glass fibers with resin have good strength, and despite being stretched during testing, the bonding between fibers and the resin is maintained, and the fibers become elongated and eventually ruptured.

### 3.2. The flexural strength test

The three-point flexural test was performed on all produced composite tubes, the output of which is illustrated in figure 14 as a force-displacement diagram. As the curves show, the highest flexural strength was obtained for the GFR equal to 91.08 MPa, which is 132% and 13% higher than the flexural strength of the CFR and KFR, respectively. Similar to the tensile test results, the highest displacement was obtained for the KFR. Increased flexural strength in GFR is due to its chain-like arrangement and greater flexural strength of glass fibers (GFR) compared to other fibers. In the flexural test, the outer layer is under compressive force, and the inner layer is under tension force and this phenomenon, and the distribution of force, cause delamination in the composite tubes. The applied force causes shear between layers, which is deflected by the fiber layers, causing the stress and strain to be distributed in the composite tubes. Three parts can be considered in the obtained diagrams. The first part is the rapid growth of the force without any change in length, which is related to the first ply failure (FPF) phase. In the second part, the force growth takes place at a slower rate, but in return, there is a considerable amount of length variation in the specimens; Which indicates that the tubes and fibers are damaged but still resist the applied force. In the final part, where the force has a decreasing trend, there is no longer longitudinal change, which means that the composite has suffered a failure [15].

Table 6 shows the results of the three-point flexural test as well as the standard deviation of strength. Also shown in figure 15 is the average flexural strength of composite tubes.

![Figure 15. The mean flexural strength of tubes.](image)

| Sample | Test No. | Max. of Bending Force (N) | Flexural Strength (MPa) | Displacement (mm) | Standard Deviation of Strength (MPa) |
|--------|----------|---------------------------|------------------------|------------------|----------------------------------|
| GFR    | 1        | 3667.82                   | 84.34                  | 13.82            | 9.53                             |
|        | 2        | 4253.46                   | 97.82                  | 14.10            |                                   |
| CFR    | 1        | 1982.08                   | 45.58                  | 16.92            | 9.02                             |
|        | 2        | 1426.77                   | 32.81                  | 15.81            |                                   |
| KFR    | 1        | 3151.57                   | 72.48                  | 19.23            | 10.92                            |
|        | 2        | 3823.29                   | 87.93                  | 19.74            |                                   |

To investigate the results and to better express, the type of rupture of the fibers, SEM images of the rupture location and damage of the tubes were obtained, as can be seen in figure 16. As can be seen from the figures, the damage location of the composite pipes is from inside and outside. Also, the images show that the crack starts from the outer surface of the pipe, and due to the layered structure of the fibers, the crack is unable to grow and...
expand. The outer surface images of the tubes show the least damage is related to the GFR, and the greatest damage is related to the CFR. Also, the inner surface images of the composite tubes show that in the GFR, the inner layers are more damaged than the other composite tubes; Which is also due to its layered structure that is more resistant to external forces.

Figure 16. The photo and SEM image of damage area of (a) GFR, (b) CFR, and (c) KFR.

Figure 17. The Strength-Strain graph of specimens.
3.3. The compressive test

The static compressive stress-strain diagram is shown in figure 17. As can be seen, by changing the reinforcing fibers from kevlar to glass, the ultimate compressive strength also increases. In a way that the greatest strength is related to the GFR that the compressive strength of the GFR was obtained 213.83 MPa, which is 7.8% and 68% more than the compressive strength of the CFR and KFR, respectively. Table 7 and figure 18 show the comparison of the effect of different reinforcement fibers on the final and mean compressive strength of the specimens as well as the standard deviation of strength.

SEM imaging was also performed from damage and wrinkle sites of the tubes to evaluate and validate the results, which are presented next to the cross-sectional area images, which are visible in figure 19. According to the cross-sectional images of the specimens after the compression test, it can be concluded that during the test, the lowest separation between the resin base material and glass fibers (GFR) occurred in the GFR and therefore had the highest compressive strength. Various manuscripts reported the winding angle of fibers plays a vital role in the compressive strength, modulus in which when winding angle increased, the compressive strength decreased [24]. Besides, some researchers approved that in the GFR, CFRP, and KFR material types, GFR material has more durability against the crushing behavior compared to other materials with the same structural [25, 26]. The obtained results for maximum compressive strength at a determined winding angle for GFR agree with previous research [27]. Oppositely, by examining the KFR images, it is observed that most of the damage and separation occurred for this specimen, which resulted in having the least compressive strength. On the other hand, the behavior of specimens reinforced with carbon fibers is similar to that of glass fibers, but due to their lower compressive strength, it results in the compressive strength of the reinforced sample.

4. Conclusion

In this research, the strength properties of composite tubes with resin base material and reinforced with glass, carbon, and kevlar fibers were investigated. Fiber-reinforced composite tubes were produced by a winding method of identical dimensions, and fibers were winded unilaterally around the mandrel. The specimens were subjected to tensile, flexural, and compression tests, and the results were as follows.

![Figure 18. The graph of the mean result of compressive strength.](image-url)
1. The highest ultimate tensile strength for the CFR was obtained equal to 139MPa, which is 26% and 136% higher than the GFR and KFR, respectively. On the other hand, the most average change in strain was for KFR which was 3.5%.

2. The highest flexural strength was for the GFR equal to 91.08MPa, which was 132% and 13% higher than the flexural strength of the CFR and KFR, respectively. And cross-sectional images and SEM images revealed that the best bonding between the fibers and the base material belonged to the GFR, which resulted in the highest flexural strength.

3. The highest compressive strength was for the GFR, equal to 213.83MPa, which was 7.8% and 68% higher than the CFR and KFR, respectively. KFR had the lowest strength against compressive force, which was confirmed by SEM images.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).
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