Tensile Modulus Prediction of Glass Fiber/Stainless Steel Wire Mesh-Reinforced Hybrid Composites via Rule of Hybrid Mixtures

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Abstract: Hybrid composites have been considered emerging materials that have garnered the attention of researchers around the globe. Combining two kinds of reinforcement may balance their merits and demerits in hybrid composites. In this work, glass fiber/wire mesh-reinforced epoxy composites were prepared via vacuum infusion to minimize void formation. Non-hybrid wire mesh and glass fiber-reinforced composites were also fabricated for comparison purposes. The thicknesses of all the composite laminates were fixed at 4 mm. Tensile tests were performed at a cross-head displacement rate of 2 mm/min with reference to ASTM D3039 to obtain the modulus of composite laminates. Subsequently, the tensile modulus of each composite laminate was predicted using the Rule of Hybrid Mixtures (RoHM). A comparison was made between the modulus of the composite laminates obtained from the tensile tests and prediction using RoHM. In accordance with the results obtained, it was found that the incorporation of glass fiber increased the modulus of the hybrid composites but did not significantly improve their tensile strength. The highest modulus (22.6 GPa) was obtained in non-hybrid glass fiber-reinforced composites, which is 107.71 % greater than non-hybrid wire mesh-reinforced composites. When comparing the experimental and predicted tensile modulus of the glass fiber/wire mesh composite laminates, both results matched well, demonstrating a linear increase in the tensile modulus with an increase in glass fiber content. Overall, the percentage error of the prediction was in the range of 3 – 6 %, indicating a high accuracy of the RoHM.

Keywords: Hybrid Composites, Synthetic fiber, Metal, Tensile Properties, Prediction Model.

INTRODUCTION

Composite materials, a characteristic of modern engineering, blend distinctive materials to obtain higher performance. Due to their virtues, such as high mechanical properties and lightweight, they are continuously evolving toward high-performance and economical products [1]. Composite materials are developed to replace metallic alloys in various engineering applications to reduce the overall weight of a structure [2]. They offer flexibility in designing material properties that meet the minimum requirements for certain applications [3]. Today, they are broadly used in various realms, including automotive, aerospace, marine and sporting goods [4,5]. Fiber-reinforced composites, a subset of these materials, involve embedding high-strength fibers within a matrix. Such composites exhibit remarkable properties such as enhanced strength, stiffness, and resistance to corrosion. Applications span diverse industries, with aerospace, automotive, and construction relying on composites for their high mechanical properties and lightweight characteristics [6]. Recent advancements in composite technology have propelled these materials to the forefront of engineering solutions. The utilization of fiber composites has become integral to the design of lightweight, high-performance structures, offering a compelling alternative to traditional materials in various applications. Glass fiber is one of the promising reinforcement for composite materials. Glass fiber-reinforced composites offer a number of advantages such as lightweight, high specific properties, excellent corrosion resistance, superior mechanical properties and economically feasible [7]. These composites have been primarily employed in the construction, aerospace, automotive and wind turbine industries [8]. In many sectors, lightweight and high-specific properties are particularly critical as they can enhance energy efficiency without compromising the material performance [9].

Researchers have explored diverse strategies to enhance the tensile properties of fiber composites. One prevalent approach involves the incorporation of reinforcing particles within the matrix material. Kord [10] demonstrated that the addition of nano particles to the matrix can significantly improve tensile strength and toughness. Furthermore, the utilization of high-performance fibers has garnered attention due to their superior mechanical properties. Another research work conducted by Wang *et al*. [11] highlighted the

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improvement in tensile modulus achieved through utilizing high-performance fiber into epoxy matrices instead of using traditional fiber such as glass fiber. Hybridization, involving the combination of different fiber types, stands out as a multifaceted strategy. It is noted that the disadvantages of one fiber can be compensated by another fiber when incorporating multiple types of fiber in hybrid composites [12]. Fuad *et al*. [13] investigated the synergistic effects resulting from hybridizing glass fiber with carbon fiber, showcasing improvements in overall tensile properties. Such methods play a pivotal role in tailoring composites to meet specific performance requirements. Elumalai *et al*. [14] studied the effect of steel wire mesh on the mechanical properties of asna fiber-reinforced epoxy composites. The findings showed that the tensile strength was decreased by 18.2 % after adding steel wire mesh to the composites. Sadoun *et al*. [15] obtained similar results where adding aluminum wire mesh into glass fiber-reinforced epoxy composites reduced their tensile strength and modulus.

In the context of glass fiber composites, hybridization commonly involves combining glass fibers with other materials to achieve a balance of properties. Rui *et al*. [16] highlighted the successful integration of carbon fibers with glass fibers, resulting in composites with enhanced mechanical properties. The combination of different fibers allows for the exploitation of their individual strengths, creating a composite material with a tailored performance profile. In the pursuit of further augmenting the properties of glass fiber composites, metals emerge as promising hybridization candidates. Their ductile properties, characterized by the ability to deform under stress, present an opportunity to enhance the overall toughness of composites. Instead of employing full metal plates, the introduction of wire mesh is proposed as a lightweight alternative. This approach aims to harness the structural advantages of metals while mitigating the associated weight increase. Notably, previous research has demonstrated the success of metal and wire mesh hybridization in enhancing the mechanical properties of composite materials [17-22].

Although glass fibers provide excellent strength to the composites, they also endow their composite materials with high brittleness [23-25]. The brittle characteristics of glass fiber-reinforced composites result in poor impact resistance and toughness of the materials. Combining glass fiber with wire mesh in hybrid composites is paramount to improve their mechanical performance. When characterizing material properties, modulus is one of the crucial properties that need to be investigated as it may affect structural integrity. However, experimental investigations are often time-consuming and may incur additional costs. Therefore, using prediction models to obtain the predicted tensile modulus is regarded as an effective yet accurate way when compared to experimental techniques. To date, the prediction of the tensile modulus of glass fiber/wire mesh-reinforced hybrid composites using the Rule of Hybrid Mixtures (RoHM) remains unexplored. Therefore, this work intends to reveal the feasibility of using RoHM to predict the tensile modulus of the composites. A validation was done to ensure the accuracy and reliability of the predicted tensile modulus.

MATERIALS AND METHOD

Materials

Plain weave E-glass fiber with an areal density of 600 g/m^2, the epoxy resin and hardener were provided by SN Chemical Sdn. Bhd. Stainless steel 304 wire mesh with a diameter of 0.1 mm and mesh count of 100 per inch was supplied by SQC Wire Mesh Sdn. Bhd.

Composite Preparation

A vacuum infusion technique was used to prepare non-hybrid and hybrid glass fiber/wire mesh composites. Figure **1** shows the process of preparing glass fiber/wire mesh-reinforced composite via vacuum infusion. The selection of this technique was to minimize the void content. Before the fabrication process, the glass surface for the vacuum infusion was cleaned with acetone to remove any impurities. A releasing agent was then applied to the glass surface. Glass fiber and wire mesh with a dimension of 300 mm X 200 mm were laid on the working area. A peel ply was positioned over the fibers, and the infusion mesh was placed on the peel ply to facilitate the resin flow. Sealant tape was attached to the boundary of the working area to fix the vacuum bag film. The connection tubes for the resin inlet and outlet were then fixed parallel to each other. Finally, the setup was covered by vacuum bag plastic film, forming a closed system for vacuum infusion. The epoxy resin and hardener were then mixed at a ratio of 10 : 6 by weight. Subsequently, the vacuum pressure was on to infiltrate epoxy resin into the composite laminates. After the vacuum infusion process, the composite laminates were cured at room temperature for three days.

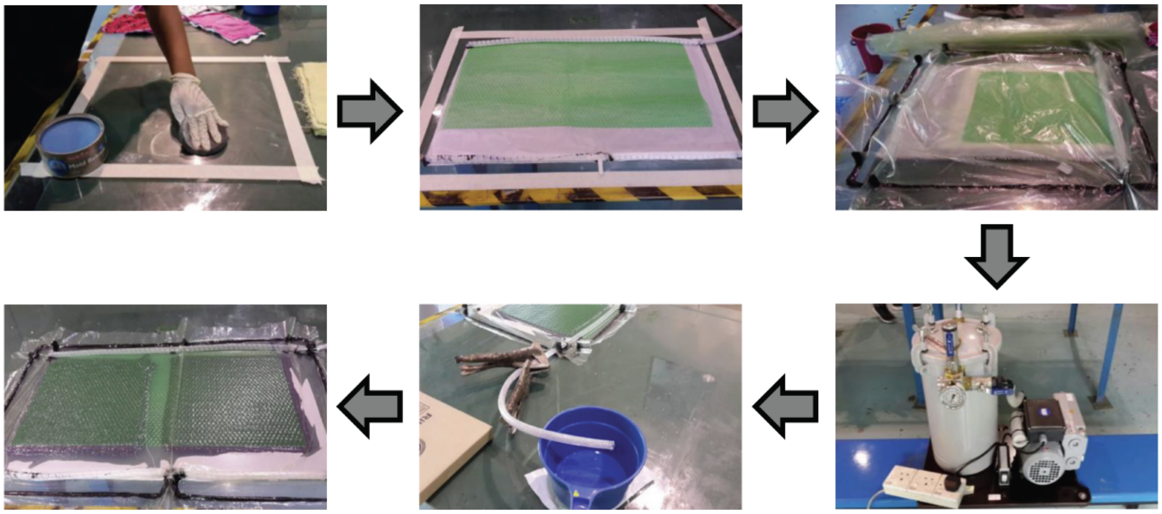

Figure 1: The process of preparing glass fiber/wire mesh-reinforced composite via vacuum infusion technique.

In order to fix the composite thickness at 4 mm, all the composite laminates consisted of different numbers of reinforcing layers as the thicknesses of glass fiber and wire mesh differed. Figure **2** shows the stacking sequences of glass fiber and wire mesh in the composite laminates. Non-hybrid glass fiber and wire mesh composite laminates are denoted as GF and WM, respectively. Hybrid composite laminates consisting of five layers, three layers and two layers of glass fibers are referred to as 5GF/6WM, 3GF/12WM and 2GF/15WM, respectively. The fiber volume fractions of each composite laminate are summarized in Table **1**.

Rule of Hybrid Mixtures

RoHM refers to the Rule of Mixtures for hybrid composites, which is used to estimate the material properties of hybrid composites. However, it is worth noting that several key assumptions are made when using this prediction model, including (a) fibers are evenly distributed in the matrix; (b) perfect fiber-matrix adhesion (c) no void content (d) Fibers are oriented either parallel or perpendicular to the loading direction (e) no residual stresses (f) fibers and matrix behave linearly elastic until failure. The approach involves considering the hybrid composite as two individual systems, assuming no interaction between the components. Applying the iso-strain condition to each system enables the derivation of the modulus of the hybrid composite using the RoHM equation [26]. The iso-strain condition of the two systems can be represented by equation (1).

$$\varepsilon_{hc} = \varepsilon_{gf} = \varepsilon_{wm} \tag{1}$$

Where ε_{hc} is the strain of the hybrid composite, ε_{gf} is the strain in the glass fiber and ε_{wm} is the strain in the wire mesh.

Then, the modulus of the hybrid composite can be evaluated from the ROHM equation, as shown in equation (2), by neglecting the interaction between the two systems.

$$E_{hc} = E_{c1}V_{c1} + E_{c2}V_{c2} \tag{2}$$

Where E_{hc}, E_{c1} and E_{c2} are the elastic modulus of hybrid composites, non-hybrid glass fiber composites and non-hybrid wire mesh composites, respectively, whereas V_{c1} and V_{c2} are the relative fiber volume fractions of the first and second systems.

The expressions, as shown in Equations (3), (4), (5) and (6), are considered valid for the prediction systems.

$$V_{c1} + V_{c2} = 1 \tag{3}$$

$$V_{c1} = V_{f1} / V_t \tag{4}$$

$$V_{c2} = V_{f2} / V_t \tag{5}$$

$$V_t = V_{f1} + V_{f2} \tag{6}$$

Where V_{f1} and V_{f2} are the fiber volume fraction of the individual first and second fiber, and V_t is the total fiber volume fraction.

Experimental Methods

The tensile tests were performed at room temperature with reference to ASTM D3039 using an Instron 5982 universal testing machine. The cross-

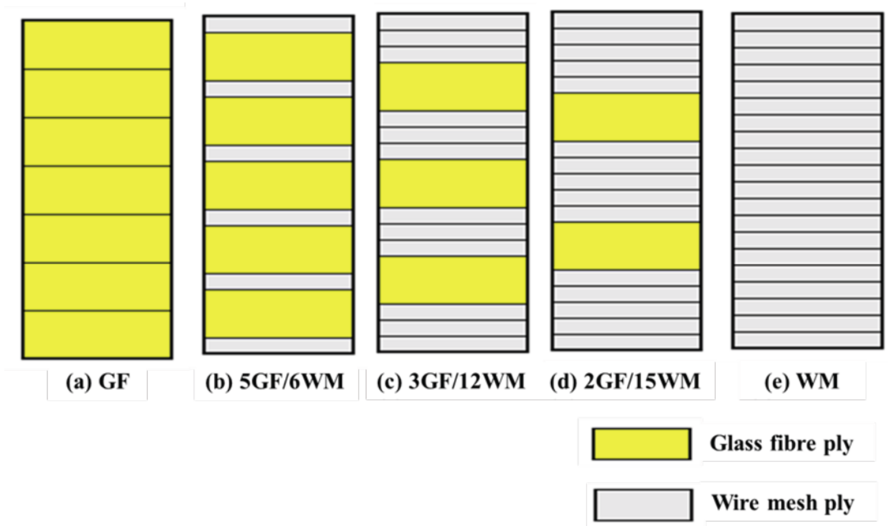

Figure 2: Stacking sequences of glass fiber/wire mesh-reinforced composites.

Table 1: Number of Fiber Layers and Volume Fractions of Composite Laminates

Sample	Number of layers		Fiber volume fraction (%)		
	Glass fiber	Wire mesh	Glass fiber	Wire mesh	Total
GF	7	0	32.88	0	32.88
5GF/6WM	5	6	29.14	8.96	38.10
3GF/12WM	3	12	18.86	18.51	37.37
2GF/15WM	2	15	12.27	23.00	35.27
WM	0	20	0	38.48	38.48

head displacement rate was fixed at 2 mm/min. The tensile properties of the composite laminates after testing were recorded. A comparison was made between the actual and predicted tensile moduli of the composite laminates for validation purposes.

RESULTS AND DISCUSSIONS

The tensile tests were conducted with three repetitions for each type of specimen to ensure reliability and accuracy. The tensile strength and modulus were subsequently computed from these curves. The load-displacement behavior for both types of composites is consistent across the three repetitions, exhibiting acceptable standard deviations in stiffness, peak load, and overall trend. The tensile properties of the glass fiber/wire mesh-reinforced composites are summarized in Table **2**.

Based on Table **2**, the average tensile modulus and strength of GF composites were found to be 22.62GPa and 209.42 MPa, respectively. As for the WM composites, the average tensile modulus and strength were 10.89 GPa and 131.29 MPa, respectively. The tensile modulus and strength of GF composites are 107.71 % and 59.51 % higher than those of WM composites. These results indicate that GF composites have a significantly higher tensile modulus and strength than WM composites. Figure **3** shows the force-displacement curves of non-hybrid glass fiber and wire mesh-reinforced composites. All the tensile tests were repeated three times for each sample. As can be seen in Figure **3**, the load-displacement curves of GF and WM composites show different behavior. The curves of GF composites show an increase in the force up to the maximum point, and the force drops sharply after reaching the peak. In contrast, WM composites manifest an apparent yield point, after which plastic deformation and damage occur. It is interesting to note that WM composites exhibited significantly higher elongation than GF composites, indicating that the ductility of WM composites was much better than GF composites.

The tensile properties of glass fiber/wire mesh-reinforced hybrid composites were also investigated to identify the hybridization effect. The tensile modulus and strength of the hybrid composites are also

Table 2: Tensile Properties of Glass Fiber/Wire Mesh-Reinforced Composites

Sample	Tensile strength (MPa)	Tensile modulus (GPa)
GF	209.42 ± 1.63	22.62 ± 2.37
5GF/6WM	91.83 ± 5.49	18.76 ± 2.72
3GF/12WM	86.11 ± 3.89	17.24 ± 1.24
2GF/15WM	93.50 ± 1.17	13.89 ± 2.27
WM	131.29 ± 1.50	10.89 ± 0.98

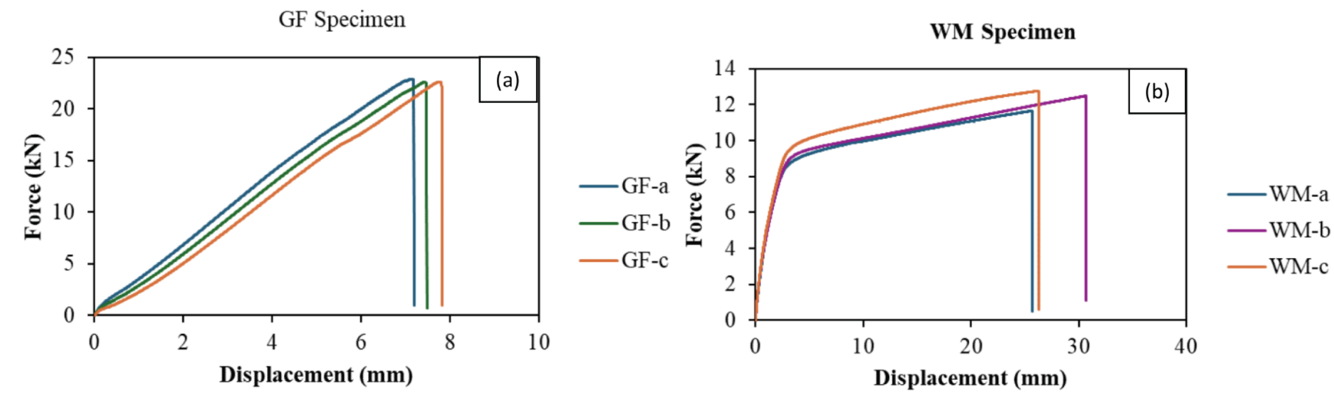

Figure 3: Force-displacement curves (**a**) Glass fiber-reinforced composites (**b**) Wire mesh-reinforced composites*a, b and c denote specimen 1, specimen 2 and specimen 3, respectively.

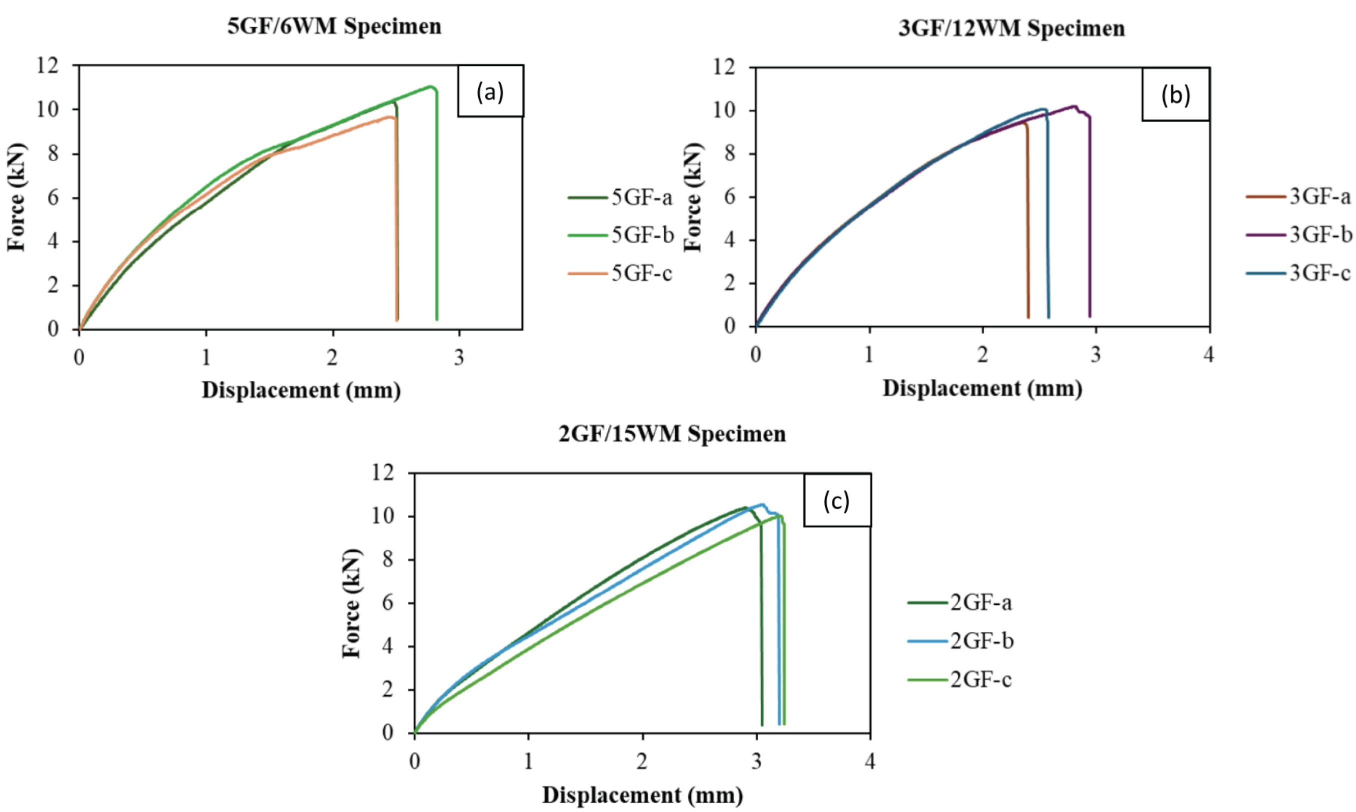

Figure 4: Force-displacement curves of glass fiber/wire mesh-reinforced hybrid composites (a) 5GF/6WM (b) 3GF/12WM (c) 2GF/15WM*a, b and c denote specimen 1, specimen 2 and specimen 3, respectively.

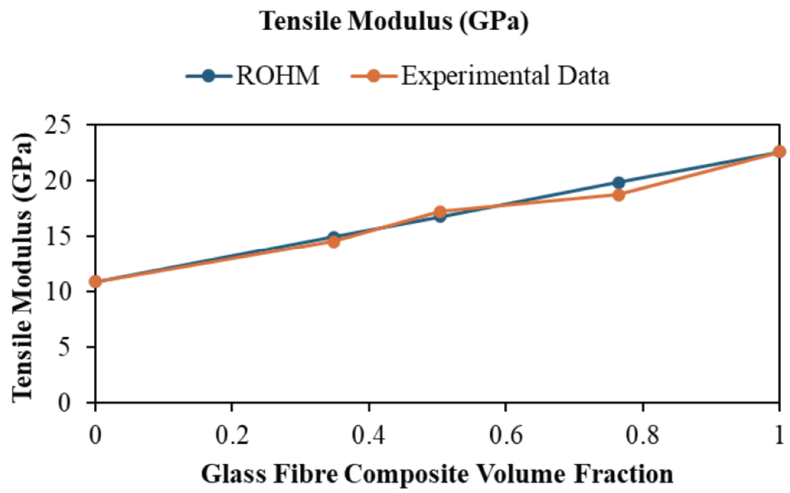

Figure 5: A comparison between the actual and predicted tensile modulus of glass fiber/wire mesh-reinforced composites.

Table 3: The Predicted Modulus, Actual Modulus and Percentage Error of Glass Fiber/Wire Mesh-Reinforced Composites

Sample	Predicted modulus (GPa)	Actual modulus (GPa)	Percentage error (%)
GF	22.62	22.62	-
5GF/6WM	19.86	18.76	5.86
3GF/12WM	16.81	17.24	- 2.46
2GF/15WM	14.97	14.54	2.99
WM	10.89	10.89	-

recorded in Table **2**. Surprisingly, it can be observed that the tensile strengths of the hybrid composites were all lower than those of both non-hybrid GF and WM composites. Interestingly, the hybrid composites showed a comparable tensile strength regardless of the relative glass fiber/wire mesh ratio. This phenomenon could be due to the incompatibility of glass fiber and wire mesh, leading to premature failure. On the other hand, the tensile modulus showed a different trend in which increasing glass fiber content improved the tensile modulus. Since the tensile modulus depends more on fiber properties than compatibility, increasing glass fiber content has increased the tensile modulus. Figure **4** shows the force-displacement curves of glass fiber/wire mesh-reinforced hybrid composites. The tensile tests were repeated three times for each sample. Apparently, the tensile behaviors of the hybrid composites were dominated by the glass fiber. The curves of the hybrid composites are similar to those of the non-hybrid GF composites.

By using the material properties of the non-hybrid composites, the predicted tensile modulus and strength were calculated using equation (2). A comparison between the actual tensile modulus and the predicted values is shown in Figure **5**. When referring to Figure 5, a linear increase in tensile modulus with increasing glass fiber content in hybrid composites is noticed. In addition, the predicted tensile moduli were in good agreement with the actual tensile moduli obtained from the experimental investigation, indicating the high accuracy and reliability of RoHM in predicting the tensile modulus of glass fiber/wire mesh-reinforced hybrid composites. The predicted and actual moduli, together with their percentage error, are summarized in Table **3**. The percentage errors of the predicted moduli were within 6 %, implying that the tensile moduli of the hybrid composites were successfully predicted.

CONCLUSION

The tensile properties of the glass fiber/wire mesh-reinforced composites with different relative fiber content were identified in this research study. Based on the findings obtained from the experimental investigations, non-hybrid glass fiber-reinforced composites exhibited greater tensile modulus and strength than non-hybrid wire mesh-reinforced composites. The tensile modulus and strength of GF composites are 107.71 % and 59.51 % higher than those of WM composites. However, the ductility of WM composites was better than GF composites, mainly due to the ability of the wire mesh to deform without failure. When looking at the tensile properties of hybrid composites, their tensile strengths were comparable regardless of the relative glass fiber/wire mesh ratio. This could be due to premature failure as a result of the incompatibility of glass fiber and wire mesh. However, the tensile modulus of the hybrid composites showed a different trend in which an increase in the glass fiber content led to an enhancement in the tensile modulus. Overall, the tensile behaviors of the hybrid composites were similar to those of non-hybrid GF composites. In terms of modulus prediction, the tensile moduli of the hybrid composites were in agreement with the actual tensile modulus obtained from the experimental investigation, with a percentage of error of less than 6 %. These results indicate that RoHM can be used to accurately predict the tensile moduli of glass fiber/wire mesh-reinforced composites.

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