



MANUFACTURING AND PROPERTIES OF HYBRID BFRP & GFRP BARS

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ABSTRACT

The durability of reinforced concrete elements is a constant challenge for engineers around the world, especially in marine environments. Under these difficult conditions faced by concrete structures in aggressive environments, concrete is more susceptible to excessive cracking that allows water or other aggressive agents to pass through it, thus causing corrosion of the reinforcing steel. This corrosion reduces the cross-sectional area of the bar, reducing its tensile strength and its resistance to bonding with the concrete. Deteriorated concrete structures require regular maintenance to extend their service life and may require expensive rehabilitation costs, which may equal the budget of building a new building. Recently, fiber-reinforced polymer (FRP) reinforcement bars, such as carbon, basalt, and glass reinforcement bars, have become widespread, and their use may be an effective solution to improve the durability of concrete structures in aggressive environments in general. Previous studies have confirmed that carbon bars have the least ductility and the highest tensile strength, while glass has the best ductility but the least tensile strength. Basalt bars have a relatively average ductility among other fiber bars and a much higher tensile strength than ordinary reinforcing steel. Therefore, this research is concerned with the manufacture of hybrid bars of basalt fibers and glass fibers in different proportions to benefit from the high tensile strength of basalt fibers and the high ductility of glass fibers and reach the optimum ratio that achieves the highest efficiency. In order to investigate the behavior of the hybrid bars, experimental work was conducted to determine the physical and mechanical properties of the BFRP and GFRP hybrid bars. The test results are presented and analyzed in detail.)

KEYWORDS: Durability; Fiber-reinforced polymer (FRP); aggressive environments; corrosion; hybrid bars

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تصنيع وخصائص قضبان هجينة من البلاستيك المقوى بألياف البازلت والبلاستيك المقوى بألياف الزجاج

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الملخص

تشكل متانة عناصر الخرسانة المسلحة تحديًا مستمرًا للمهندسين حول العالم، وخاصةً في البيئات البحرية. في ظل هذه الظروف الصعبة التي تواجهها الهياكل الخرسانية في البيئات القاسية، تكون الخرسانة أكثر عرضة للتشققات المفرط الذي يسمح بمرور الماء أو غيره من العوامل القاسية من خلاله، مما يسبب تآكل حديد التسليح. يُقلل هذا التآكل من مساحة المقطع العرضي للقضيب، مما يُقلل من مقاومته للشد ومقاومته للالتصاق بالخرسانة. تتطلب الهياكل الخرسانية المتدهورة صيانة دورية لإطالة عمرها الافتراضي، وقد تتطلب تكاليف باهظة لإعادة تأهيلها، قد تُعادل ميزانية بناء مبنى جديد. في الآونة الأخيرة، انتشرت على نطاق واسع قضبان التسليح المصنوعة من البوليمر المُسلَّح بالألياف (FRP)، مثل قضبان الكربون والبازلت والزجاج، وقد يكون استخدامها حلاً فعالاً لتحسين متانة الهياكل الخرسانية في البيئات القاسية بشكل عام. وقد أكدت دراسات سابقة أن قضبان الكربون تتمتع بأقل ليونة وأعلى مقاومة شد، بينما يتمتع الزجاج بأفضل ليونة وأقل مقاومة شد. تتميز قضبان البازلت بمتوسط ليونة نسبيًا مقارنةً بقضبان الألياف الأخرى، وقوة شد أعلى بكثير من حديد التسليح العادي. لذلك يهتم هذا البحث بتصنيع قضبان هجينة من ألياف البازلت والألياف الزجاجية بنسب مختلفة للاستفادة من قوة الشد العالية لألياف البازلت والمرونة العالية لألياف الزجاج والوصول إلى النسبة المثلى التي تحقق أعلى كفاءة. لدراسة سلوك القضبان الهجينة، أُجريت تجارب لتحديد الخصائص الفيزيائية والميكانيكية لقضبان BFRP و GFRP الهجينة. وُعرضت نتائج الاختبارات وحُللت بالتفصيل.

الكلمات المفتاحية : المتانة؛ البوليمر المقوى بالألياف (FRP)؛ البيئات العدوانية؛ التآكل؛ القضبان الهجينة.

1. INTRODUCTION

Corrosion of steel is one of the greatest threats to the longevity of concrete buildings due to the harsh environmental conditions they are exposed to, leading to the failure of reinforced concrete buildings to meet their expected performance. Corrosion reduces the service life of a concrete building if sufficient moisture and oxygen are present at the reinforcing steel level [1], a phenomenon that is particularly common in marine environments. The estimated design life is an important consideration for engineers and researchers, which has recently prompted researchers to search for alternative corrosion-resistant materials. The use of fiber-reinforced polymer (FRP) to strengthen existing concrete structures is an accepted and well-documented approach [2]. There are different types of high-tensile-strength fibers used to make reinforcing bars, including carbon, glass, aramid, and basalt. It is worth noting that FRP bars are semi-electrically non-conductive and non-corrosive [3-7]. Unlike conventional steel reinforcing bars, these bars have a lower modulus of elasticity and a linear elastic stress-strain relationship (without a yield point) [8-11].

Recently, basalt fiber reinforced polymer (BFRP) rods have become increasingly popular due to their numerous advantages. The most significant advantages of basalt rods are their lower cost than CFRP [12], their resistance to high temperatures, their ability to withstand freeze-thaw cycles, and their exceptional resistance to acids, vibration, and shock stacking. Because no specific additives are required during production, BFRP rods are less expensive and easier to manufacture than many other fiber types [13]. Compared with glass FRPs, BFRPs have better chemical stability, especially in acidic environments. Additionally, they exhibit excellent resistance to seawater corrosion [14]. Furthermore, BFRP bars have achieved significant success due to their high chemical resistance, especially in alkaline conditions, and their greater elongation at break [15-17]. Building with BFRP offers numerous financial benefits. Because the density of basalt is approximately one-third less than that of steel, lifting, shipping, and other associated construction costs are lower. Furthermore, basalt-reinforced concrete sections can be designed smaller than those reinforced with conventional steel due to the much higher tensile strength of BFRP bars. Because the hybrid bars do not corrode or absorb water under extreme conditions, concrete cover distances can also be reduced. Bridge and marine applications, which today require relatively long concrete cover distances, would particularly benefit from this, potentially resulting in significant cost savings in both construction and maintenance. According to global estimates, approximately 14 kWh/kg of energy is required to produce one kilogram of steel, but the energy required to produce basalt fiber in an electric furnace is approximately 5 kWh/kg [18].

Hybrid steel-reinforced structures appear to be the most advanced based on published information to date due to their high performance and low cost for pilot projects [19, 20]. Bridges using fixed FRP cables and hybrid columns and beams made of FRP and concrete are important examples, as are FRP bridge decks supported by steel beams [21, 22]. Hybrid bars have proven their effectiveness in concrete elements subjected to tensile stresses. This effectiveness was confirmed by a previous study on the importance of using hybrid reinforcement of glass fibers and basalt in concrete slabs, as this led to a significant and effective improvement in the overall behavior of the slab [23]. Therefore, in this study, we will focus on manufacturing hybrid bars of basalt and glass

fibers with different fiber ratios for each to achieve the optimal ratio that maximizes the high tensile strength of basalt fibers and the high flexibility of glass fibers.

2. RESEARCH SIGNIFICANCE

The feasibility of using hybrid bars was studied through a thorough study to determine their mechanical and physical properties. The optimal ratio of basalt and glass fibers was also determined to achieve the best mechanical and physical properties for the bars, allowing them to be used in structural elements subjected to tensile stresses. The most important of these properties are specific gravity, ultimate tensile strength, modulus of elasticity, and bond strength between the hybrid bars and concrete, taking into account the effect of temperature on these properties.

3. EXPERIMENTAL DETAILS

3.1. Materials

- Basalt fibers:** Basalt fibers are the most common type of reinforcement due to their favorable mechanical behavior, such as elastic modulus, tensile strength, toughness, and high temperature resistance, as the main fiber in all types of hybrid composite bars [24]. Basalt fibers are available in a variety of forms, including chopped fibers, mats, and continuous filament tows. Composites made of basalt fibers are more fragile than glass or aramid and can corrode galvanically when placed close to metal. As seen in Fig. 1, a barrier material like glass and resin is employed to stop this from happening. Table 1 displays the mechanical properties of the basalt fiber used.



Fig. 1: Basalt Fibers [24]

Table1: properties of basalt fibers

Mechanical Properties	Magnitude
Modulus of Elasticity (GPa)	120
Elongation (%)	3.1
Density (gm/cm ³)	2.8
Thickness (mm)	0.12
Tensile strength (Mpa)	4100

Glass Fibers: The fibers used are evenly textured E-glass fiber roving, which has several good properties, including easy rolling, easy chopping, and good affinity to resin. The fibers have a linear weight of roving of 2400 g/km [25]. These glass fibers are purchased in rolls weighing 16 kg. Fig. 2 shows the glass fiber rolls. Table 2 displays the mechanical properties of the glass fiber used. Glass fiber was subjected to the necessary tests at the National Housing Research Center in Cairo to ensure its compliance with quality standards.



Fig. 2: The Glass Fiber [25]

Table 2: properties of glass fibers

Mechanical Properties	Magnitude
Modulus of Elasticity (GPa)	48
Elongation (%)	4.7
Density (gm/cm ³)	2.48
Thickness (mm)	0.12
Tensile strength (Mpa)	2100

Epoxy Resin: Epoxy resins are employed in place of vinyl esters and polyesters because of their higher fatigue resistance, good strength, superior mechanical qualities, reduced shrinkage when compared to polyester resins, and good adhesion to various fibers. It is well known that epoxy resins have higher resistance to acids, alkalis, and ultraviolet radiation than vinyl esters or polyesters. Epoxy resin's tensile strength is between 50 and 100 MPa, its tensile elastic modulus is between 3 and 6 GPa, its ultimate tensile elongation is between 2 and 8%, its unit weight usually falls between 1.1 and 1.2 gm/cm³, and its heat distortion temperature is between 120 and 200 °C [26]. The performance of epoxy resin is excellent at high temperatures, as shown in Fig. 3.

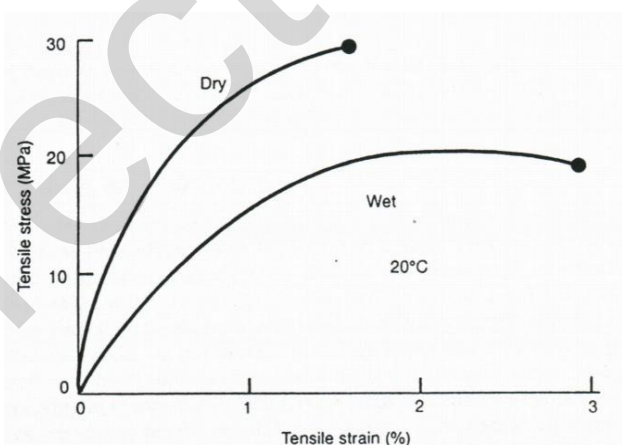


Fig. 3: Typical effects of temperature and moisture on the epoxy mechanical behavior of an unmodified cold - curing epoxy in tension [26]

3.2. The components of hybrid bars used in this study.

3.2.1. Hybrid Bar content 40% Epoxy ,60%FRB (45% Basalt & 15% Glass).

- i.e. VFB=75% Fiber, VFG=25% Fiber

Area of bar = $\pi R^2 = \pi (5)^2 = 78.54 \text{ mm}^2$, Total Volume of Hybrid Bar = Area * Length = $78.54 * 1150 = 90321 \text{ mm}^3 = 90.321 \text{ cm}^3$, The used hybrid bars are circular bars with diameter 10mm and its length 1150mm.

For basalt fiber for this bars was the volume of basalt Fiber (V_B) = $0.15 * 90.321 = 40.644 \text{ cm}^3$, Area of basalt Fiber (A_B) = $V_B / L_B = 40.644 / 115 = 0.3534 \text{ cm}^2$, Width of basalt net = $0.3534 / 0.12 = 29.5$, No. of BFRP /bar = $29.5 * 9 / 5 = 54$ line.

For glass fiber for this bars was the volume of basalt Fiber volume of glass Fiber (V_G) = $0.15 * 90.321 = 13.55 \text{ cm}^3$, Weight of glass Fiber = $\gamma_G * V_G = 13.55 * 2.48 = 33.6 \text{ gm}$, Total length of glass in Bar = $33.6 / 2.25 = 14.93 \text{ m}$, No. of GFRP /bar = $14.93 / 1.15 = 13$ line.

3.2.2. Hybrid Bar content 40% Epoxy ,60% FRB (30% Basalt Glass &30% Glass).

- **i.e. VFB=50% Fiber, VFG=50% Fiber**

For basalt fiber for this bars was the volume of basalt Fiber (V_B) = $0.15 * 90.321 = 27.096 \text{ cm}^3$, Area of basalt Fiber (A_B) = $V_B / L_B = 27.096 / 115 = 0.2356 \text{ cm}^2$, Width of basalt net = $0.2356 / 0.12 = 19.63 \text{ cm}$, No. of BFRP /bar = $19.63 * 9 / 5 = 35$ line.

For glass fiber for this bars was the volume of glass Fiber (V_G) = $0.30 * 90.321 = 27.096 \text{ cm}^3$, Weight of glass Fiber = $\gamma_G * V_G = 27.096 * 2.48 = 67.2 \text{ gm}$, Total length of glass in bar = $67.2 / 2.25 = 29.87 \text{ m}$, No. of GFRP /bar = $29.87 / 1.15 = 26$ line.

3.2.3. Hybrid Bar content 40% Epoxy ,60% FRP (15%Basalt & 45% Glass).

- **i.e. VFB=25% Fiber, VFG=75% Fiber**

For basalt fiber for this bars was the volume of basalt Fiber (V_B) = $0.15 * 90.321 = 13.55 \text{ cm}^3$, No. of yarns in Basalt mesh = 9 Yarns /5cm, thickness of Mesh net = 0.12mm , Area of basalt Fiber (A_B) = $V_B / L_B = 13.55 / 115 = 0.1178 \text{ cm}^2$, Width of basalt net = $0.1178 / 0.12 = 9.81 \text{ cm}$, No. of BFRP /bar = $9.81 * 9 / 5 = 18$ line.

For basalt fiber for this bars was the volume of glass Fiber (V_G) = $0.45 * 90.321 = 40.644 \text{ cm}^3$, weight of 1m = 2.25 gm/m, Density of Glass (γ_G) = 2.48 gm/cm^3 , Weight of Glass Fiber = $\gamma_G * V_G = 40.644 * 2.48 = 100.8 \text{ gm}$ Total Length of Glass in Bar = $100.8 / 2.25 = 44.8 \text{ m}$, No. of GFRP /bar = $44.8 / 1.15 = 39$ line.

3.2 Method of Pultrusion

Pultrusion is an automated, continuous closed-molding method that works well for producing pieces with a consistent cross-section in large quantities. Therefore, this industrialization process is utilized to produce highly reinforced plastic structural forms in the longitudinal direction rather than the transverse direction. An explanation of pultrusion from a processing perspective is the aim of this section. **Fig. 4** provides a detailed schematic illustration of the pultrusion process. It is worth noting that the pultruded products (hybrid bars) are produced at Badr Manufacturing in El-Asher Men's Ramadan.

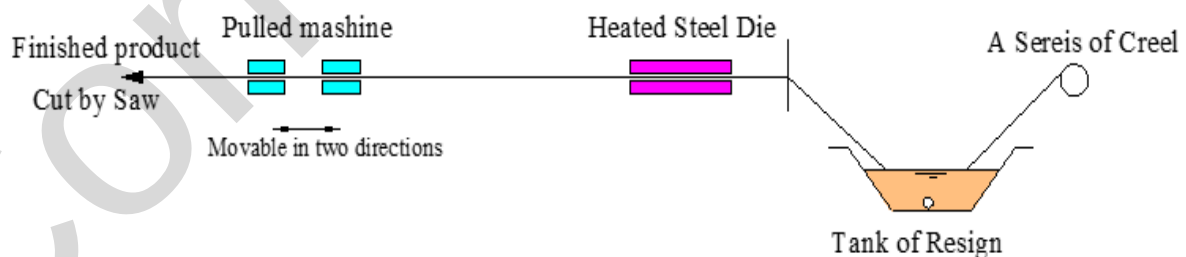


Fig. 4: A diagram illustrating the hybrid bar pultrusion process

3.2.1 Process Technology of Pultrusion

The pultrusion process can be described in detail in the following points, as shown in **Fig. 5**:

- Reinforcing fibers used in the current study are pulled from a series of creels.
- The used fibers are impregnated with resin.

- This composite material is then passed through a heated steel die. Heat initiates an exothermic reaction, thus curing the resin matrix.
- The bar is continuously pulled and exits the mold as a hot, constant cross-sectional bars.
- These bars are cooled in the surrounding air.
- An automatic cutoff saw cuts the product to the required length after it emerges from the puller mechanism.



a) General Layout of Pultrusion Machine.



b) General Layout of Pultrusion Machine.



c) Tank of Resin.



d) Heated.



e) The location of the bar's exit.



f) Refrigeration the hybrid bars in bars.

Fig. 5: The different parts of the pultrusion machine for producing hybrid bars

3.3 Roughing surface of hybrid-bars

The bond between hybrid bars and concrete is of great importance to create a structural element with high load-bearing capacity over time. There are several different methods for enhancing the bond strength between the concrete and reinforcing steel surfaces, which depend on both the

surface area of the bars and the surface roughness, resulting in increased physical or mechanical interlocking between the hybrid bars and the concrete.

- **Helical wrapping pitch of hybrid-bars**

The hybrid bars are manufactured at Badr Factory, located in 10th of Ramadan City, and have a smooth surface and a round form, which gives concrete a weak bond. The roughness process is using fiber yarn wrapped helically with pitches of 1 cm, and it is one of the important modern techniques for enhancing the bond between concrete and hybrid bars. A certain number of yarns could be used per bar. supported on a table, and the first point of the yarns supported with the bolt and rotated about itself until it became strong yarns and rounded about one hybrid bar with pitches of 1 cm. The final production of roughened hybrid bars is displayed in **Fig. 6**.



Fig.6: Final production of Roughened Hybrid-bars

4. TESTING AND RESULTS OF THE PHYSICAL AND MECHANICAL PROPERTIES OF HYBRID BARS

The qualities of the concrete and reinforcement, as well as the bond between them, determine how well a reinforced concrete structural member performs under loads. Fiber-reinforced polymer bars are anisotropic materials. Factors such as volume fiber fraction and manufacturing quality assurance are crucial to the mechanical properties, such as the reinforcement's axial tensile characteristics and how well it bonds to concrete, taking the effect of temperature into account in this property. This section includes the basic tests performed on fiber-reinforced polymer bars and their results. The tested hybrid bars program in the diagram is shown in **Fig. 7**. The testing program was carried out in HBRC (Housing, Building, and Research Center) at Cairo to determine the physical and mechanical properties.

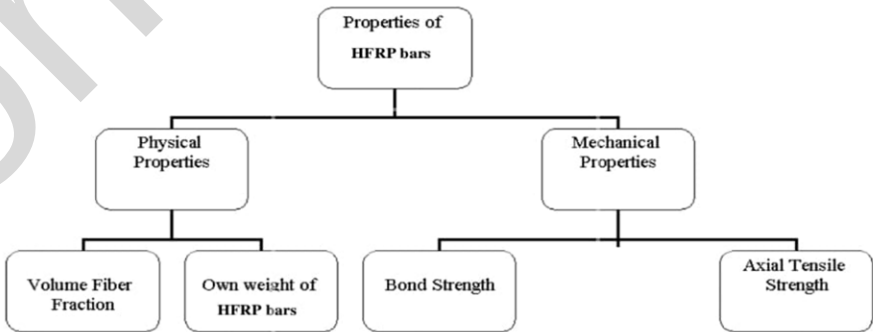


Fig.7: Flow diagram of the tested HFRP bars

4.1. Physical Properties

4.1.1. Fiber-Volume Fraction (V_f)

Fiber volume fraction indicates the ratio between the volume of the basalt fiber and the total volume of fiber in hybrid bars. This means that when the value of (V_f) increases, the tensile strength of the hybrid bar increases due to the high tensile strength of basalt fiber. This test is conducted to verify the accuracy of the manufacturing process of the hybrid bars and to also ensure the quality of the drawing process and that there is no damage or fraying of the fibers. The following procedures can be used to calculate the fiber-volume fraction:

- Cut a sample with any dimensions from the bar.
- Used the sensitive balance to determine the sampling weight, as illustrated in **Fig. 8**.
- The ceramic plate is weighted.
- Placing the sample in a ceramic plate and then in the oven for two hours with a temperature degree up to 800 °C.
- The weight of both the left fibers and the plate was determined again.
- The fiber volume fraction can now be determined by the following Equation 1:

$$V_f = \frac{1}{1 + \frac{(M_e - M_f)}{M_f} \frac{\rho_f}{\rho_m}} \quad \text{Eq. (1)}$$

Where:

V_f Fiber volume fraction.

M_e Mass of composites in gm.

M_f Mass of fiber in gm.

ρ_f Density of fibers (taken as specific 2.48 gm/cm³ glass, 2.8 gm/cm³ basalt).

Fig. 8: Sensitive Balance

➤ Experimental study of fiber-volume fraction (V_f)

The results of tests are listed in **Table 3**. From **Table 3**, it can be seen that the fiber fraction ratio differs slightly from the desired fiber volume fraction for the bars. This depends on the extrusion

process and the number of threads used in manufacturing the bars. The results confirmed a very slight, almost negligible difference, which is the biggest evidence that the pultrusion process was carried out efficiently and with high quality. The extrusion process was carried out according to the guidelines of previous researchers on important future methods proposed for extrusion with high precision [27].

Table 3: The results of Fiber-Volume Fraction of HFRP Bar

Specimen No.	No. of Basalt Fibers Yarns	No. of Glass Fibers Yarns	Average bar diameter (mm)	Weight of HFRP Bar (gm) M_e	Weight of Glass Fibers (gm) M_f	Weight of Basalt Fibers (gm) M_f	measured Density of matrix (gm/cm ³) ρ_f	Fiber- Volume Fraction of Basalt Fiber (V_{fb}) %	Fiber- Volume Fraction of Glass Fiber (V_{fg}) %
HFRP bar (1)	54	13	10	190.58	38	137.5	3.25	75.06	24.11
HFRP bar (2)	35	26	10	186	80.8	89	3.11	50.49	49.08
HFRP bar (3)	18	39	10	178.84	126.4	42.7	3	25.21	74.45

4.1.2. The unit weight of hybrid bars

To know the strength-to-weight ratio of the hybrid bars, the unit weight of the bars must be determined. In order to compare them with steel bars, for example, the hybrid bars have much less weight than steel reinforcing bars. The low unit weight facilitates the transportation of the hybrid bars and also eases the labor work with hybrid bars.

- **The unit weight can be determined by the following steps:**
- Cutting the sampling from the bar for any dimensions.
- The specimen lengths and diameters were measured by using a digital vernier, as shown in **Fig. 9**.
- The sampling weight is determined by sensitive balance as shown in **Fig. 8** mentioned previously.
- The following Equation 2 was used to calculate the hybrid bars ' unit weight according to previous studies [28, 29].

$$\gamma = \frac{4 * W}{\pi d^2 * L_s} \quad \text{Eq. (2)}$$

Where:

W Total weight in gm.

D Diameter of the GFRP bars in cm.

L_s Measured length of specimen in cm.



Fig. 9: Digital Vernier

- **Experimental study of unit weight for the hybrid bars**

The actual specific gravity values of the tested hybrid bars are shown, respectively, in **Table 4**. From **Table 4**, we observed that the unit weight of study bars is ranging between 1.98 and 2.11 gm/cm³. These results show a low unit weight for the hybrid bars compared with steel, which has a unit weight of 7.85 gm/cm³. The most prominent studies in this field have confirmed that all bars manufactured from fibers have a specific weight much lower than the specific weight of traditional reinforcing steel [30]. Indeed, bars manufactured from hybrid fibers will have a specific weight lower than reinforcing steel. These results highlight the potential of hybrid reinforcement in improving both the deflection and deformability of reinforced concrete members, making it a practical alternative to conventional steel reinforcement due to its light weight and high tensile strength.

Table 4: Unit Weigh of HFRP-Bars

Specimen No	Length (cm)	Diameter (mm)	Weight Of Bars (gm)	Unit Weight γ (gm/cm ³)
HFRP bar (1)	115	10	190.58	2.11
HFRP bar (2)	115	10	186	2.06
HFRP bar (3)	115	10	178.84	1.98

4.2. Mechanical Properties

4.2.1 Axial tensile strength and young's modulus of hybrid bars

- **Theoretical Study was conducted according to a Previous study [29].**

$$\text{Modulus of Elasticity}(E) = \frac{\text{Stress}(\sigma)}{\text{Strain}(\varepsilon)} = \frac{\frac{F}{A}}{\varepsilon} \Rightarrow P = A * E * \varepsilon$$

L : Is Constant $\rightarrow \varepsilon$ Constant

$$A_T = A_R + A_B + A_G$$

$$P_T = P_R + P_B + P_G$$

$$A_T * E_T * \varepsilon = A_G * E_G * \varepsilon + A_B * E_B * \varepsilon + A_R * E_R * \varepsilon$$

$$A_T * E_T = A_G * E_G + A_B * E_B + A_R * E_R$$

$$E_T = \frac{E_G * A_G + E_B * A_B + E_R * A_R}{\Sigma A}$$

Where : $E_C = 1200 \text{ t/cm}^2$.

, $E_G = 480 \text{ t/cm}^2$.

, $E_R = 310 \text{ t/cm}^2$.

Fig. 10 shows the components of the hybrid bar in details.

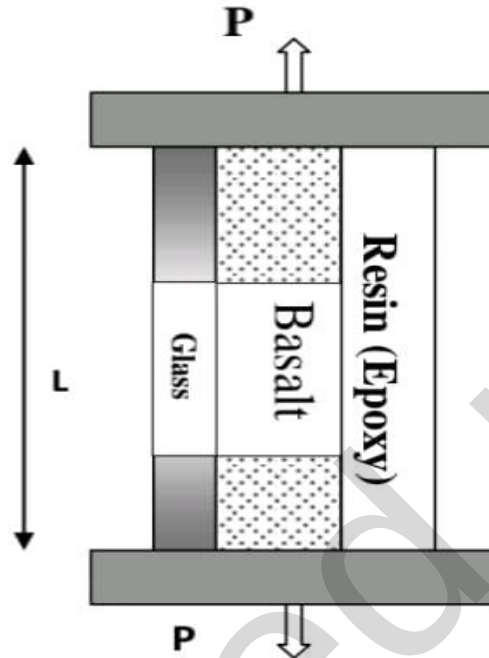


Fig. 10: A Schematic Showing Material Consisted HFRP [29]

- Determine the modulus of elasticity for bars with different fiber-volume fractions.

1- Hybrid (Basalt & Glass) bar (1)

- $A_B = 0.45 A_T$, $A_G = 0.15 A_T$, $A_R = 0.4 A_T$

$$E_T = \frac{E_B * A_B + E_G * A_G + E_R * A_R}{\Sigma A}$$

$$E_T = \frac{1200 * 0.45 A_T + 480 * 0.15 A_G + 310 * 0.4 A_T}{A_T} = 736(t / cm^2)$$

2- Hybrid (Basalt & Glass) bar (2)

- $A_B = 0.3 A_T$, $A_G = 0.3 A_T$, $A_R = 0.4 A_T$

$$E_T = \frac{E_B * A_B + E_G * A_G + E_R * A_R}{\Sigma A}$$

$$E_T = \frac{1200 * 0.3 A_T + 480 * 0.3 A_G + 310 * 0.4 A_T}{A_T} = 628(t / cm^2)$$

3- Hybrid (Basalt & Glass) bar (3)

- $A_B = 0.15 A_T$, $A_G = 0.45 A_T$, $A_R = 0.4 A_T$

$$E_T = \frac{E_B * A_B + E_G * A_G + E_R * A_R}{\Sigma A}$$

$$E_T = \frac{1200 * 0.15 A_T + 480 * 0.45 A_G + 310 * 0.4 A_T}{A_T} = 531(t / cm^2)$$

• Experimental Study (Tension Tests)

The objective of this part is to determine the strength of hybrid bars with different volume fiber fractions. The Shimadzu testing apparatus, which performs the tests and has a maximum tension capability of 1000 kN, has a constant rate of loading of 5 mm/min. The stress-strain relationship can be drawn to determine the modulus of elasticity (E_f) with a variable volume fiber fraction. The modulus of elasticity, E_f , was determined as the average value of the ratio between the difference between two successive readings of stress and the difference between the corresponding readings of strains for each two successive readings, as shown in Equation 3, according to a previous study [31].

$$E_f = \frac{(\sigma_{n+1} - \sigma_n)}{(\varepsilon_{n+1} - \varepsilon_n)} \quad \text{Eq. (3)}$$

Where:

- σ_n tensile stress at a certain loading point (n).
- ε_n tensile strain at a certain loading point (n).
- σ_{n+1} tensile stress at a certain loading point (n+1).
- ε_{n+1} tensile strain at a certain loading point (n+1).
- E_f elastic modulus of hybrid bar.

• Specimens and Test Procedure

Since high compressive stress and mechanical damage can happen due to the surface of conventional wedge-shaped grips, the hybrid bars used are not possibly tested using the same gripping techniques as used for steel. Encasing the hybrid sample's ends in an anchorage system was necessary for the investigation's experiments in order to disperse the grip stresses and prevent them from concentrating at key locations on the hybrid bar. **Fig. 11** illustrates how the gripping system's lateral compressive force would be applied to the bar's ends. The aforementioned hybrid bars were utilized for tensile tests. Each sample was cut into 1150 mm length bars and anchored with an anchor system at two ends. The anchor used in this investigation consisted of a tube of steel with an external diameter equal to 2.80 cm, an internal diameter equal to 2.0 cm, and a length equal to 36 cm filled with high-performance epoxy grout. The free length of the test samples between the two anchors was about 40 cm, which was within the range recommended from 24 cm to 43 cm by Castro and Carino [32]. An appropriate embedment length must be determined in order to guarantee that the bar won't slip from the tube when subject to the loading. Due to restrictions on the sample length, the maximum embedment length for 1150 mm ranged from 24 to 40 times the bar diameters, respectively. Depending on the size of the bar, the hybrid bars' free lengths to diameter ratios range from 24 cm to 43 cm.

Fig. 11 : Tension Tests Specimen [32]

- **Experimental results of the tension test**

In all tests, the failure was brittle and explosive in the middle third of the bars, and **Fig. 12** shows the hybrid bar during testing. The results of the tension test for the hybrid bar sample show linear behavior with no yield of the hybrid bars until failure, as shown in all figures from **Fig. 13** to **Fig. 15**. From **Fig. 13**, the modulus of elasticity for hybrid bar (1), which has a fiber-volume fraction ($V_{fR}=40\%$, $V_{fB}=45\%$, $V_{fG}=15\%$), was 765 t/cm^2 ; in **Fig. 14**, the modulus of elasticity for hybrid bar (2), which has a fiber-volume fraction ($V_{fR}=40\%$, $V_{fB}=30\%$, $V_{fG}=30\%$), was 640 t/cm^2 . From **Fig. 15**, the modulus of elasticity for the hybrid bar (3), which has a fiber-volume fraction ($V_{fR}=40\%$, $V_{fG}=45\%$, $V_{fB}=15\%$), was 531 t/cm^2 . Hybrid bar (1) is considered the optimal bar in this study, as it achieved the highest values for the elastic modulus and tensile strength. This improvement is mainly due to the higher volume fraction of basalt fibers than that of glass fibers, and basalt fibers have an ideal modulus of elasticity and tensile strength, so they improve the mechanical properties of the bar as a whole. It is worth noting that this improvement is consistent with a previous study by Gang Wu et al. [33]. This investigation into hybrid bars aptly supports the suitability of hybrid reinforcement strategies for use in concrete members subject to tensile stresses.



Fig. 12 : Tensile test for hybrid bars

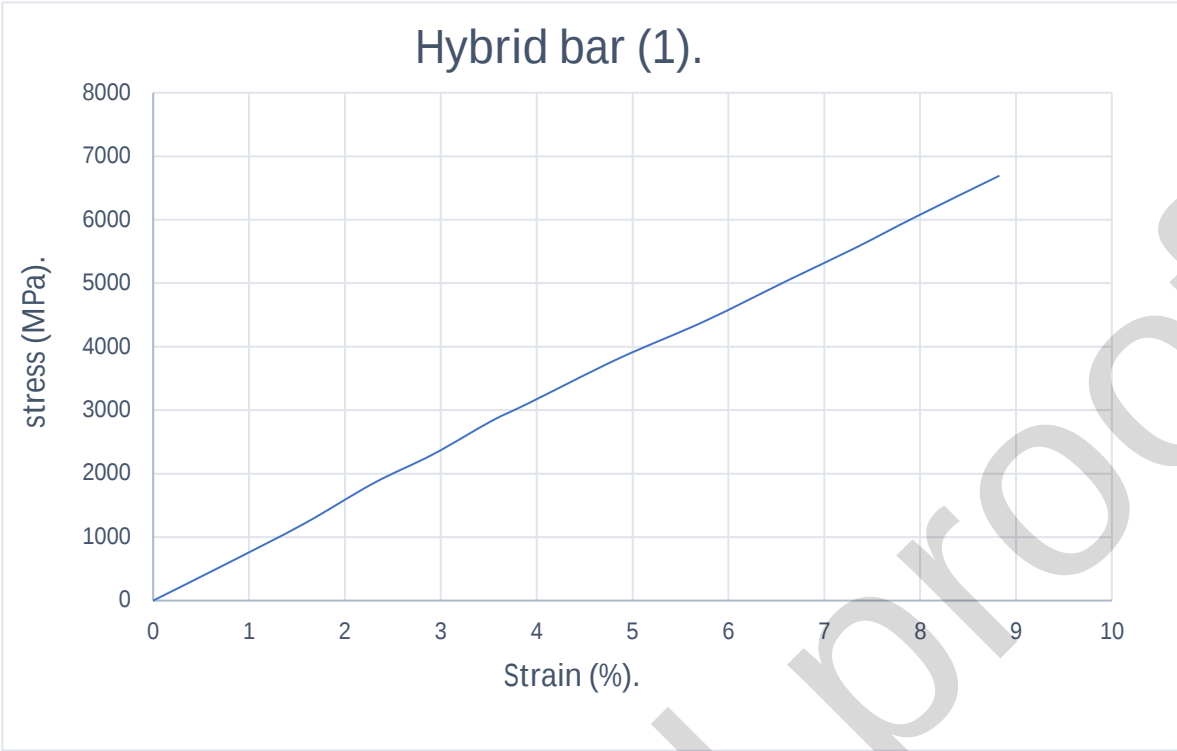


Fig. 13: Stress – Strain Relationship of HFRP-bar 1
($V_{FR}=40\%$, $V_{FB}=45\%$, $V_{FG}=15\%$)

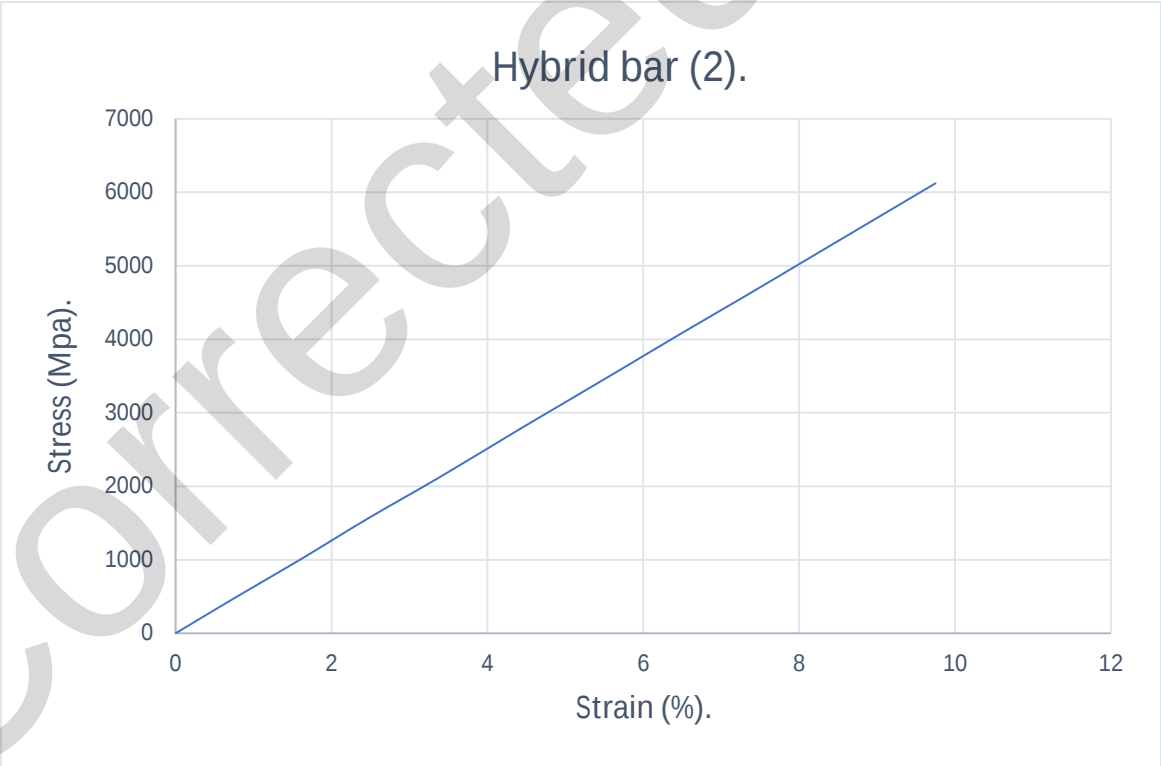


Fig. 14 : Stress – Strain Relationship of HFRP-bar 2
($V_{FR}=40\%$, $V_{FB}=30\%$, $V_{FG}=30\%$).

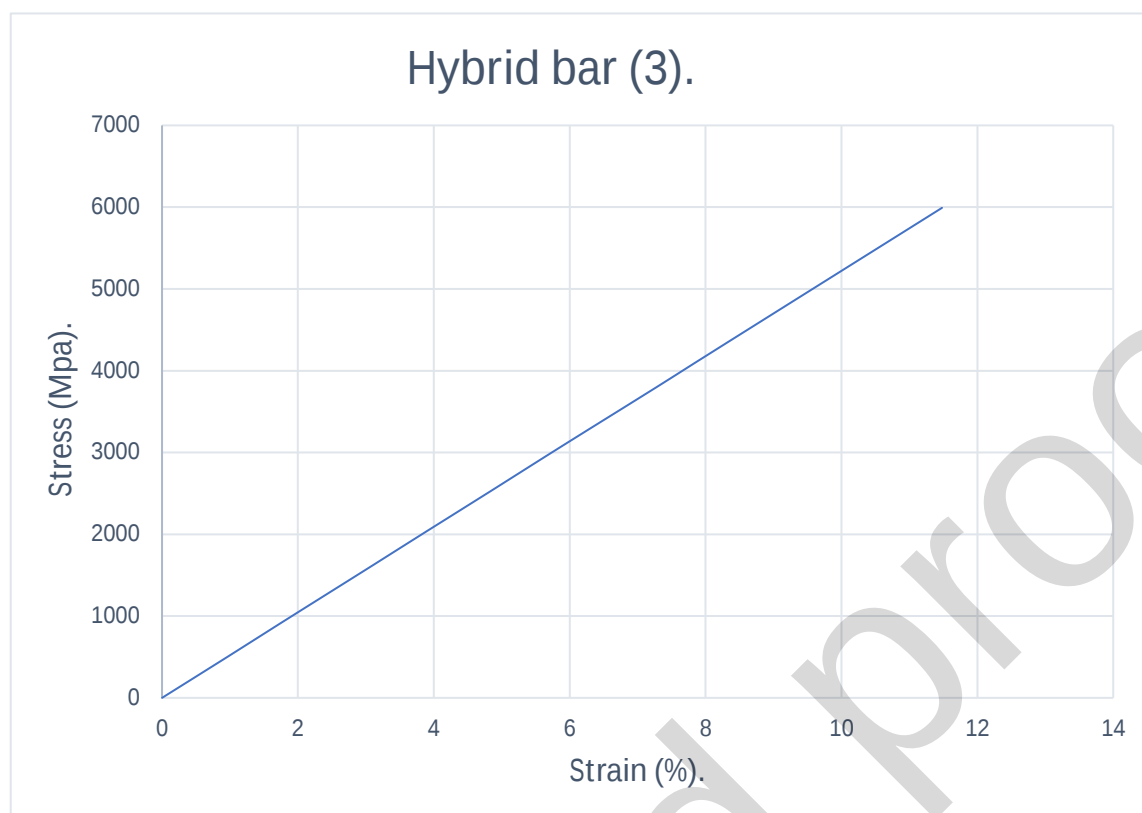


Fig. 15: Stress – Strain Relationship of HFRP-bar 3

($V_{FR}=40\%$, $V_{FB}=15\%$, $V_{FG}=45\%$).

4.2.2. Pull-out tests to assess the strength of the concrete-hybrid bar bond

The major mechanical property that needs to be considered for slabs or beams reinforced with hybrid bars is the bond between them and concrete. Because the weak bond strength between the hybrid bars and concrete parts causes the binding failure. This bond failure depends on numerous factors, including the roughness of the bar surface and the transverse coefficient of thermal expansion of the bars. When the temperature increases, the hybrid bars laterally expand; this results in internal microcracks around the bars and ultimately weakens the link between the concrete portion strengthened with hybrid bars. Sand coating is often used to roughen the surface of hybrid bars to improve bond properties.

- **Test Set-up and Procedure**

A pull-out testing frame was constructed as illustrated in **Fig. 16**. The frame consisted of two steel plates with dimensions of 300x300x25 mm connected with four 22 mm diameter bolts with a length of 600 mm. A steel bar with a 20 mm diameter and 80 mm length was welded to the upper plate to be connected to the tension grips. On the other plate, a 25 mm diameter hole was drilled in the center of the lower plate for the hybrid bar to pass through it and grip into the other end of the testing machine. The tensile testing machine used was the Shimadzu testing machine with a 1000 kN capacity and a constant rate of loading of 5 mm/min.

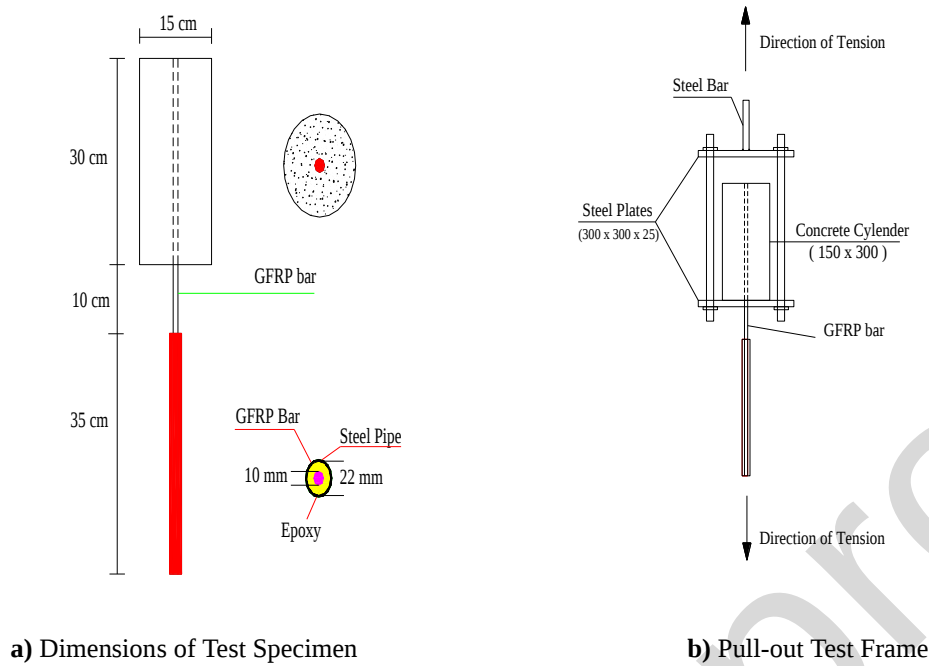


Fig. 16: Dimensions of Test Specimen and Pull-out Test Frame

• Description of test Specimens

The experimental program consists of four groups; each group consists of three cylinders, each cylinder has a diameter of 150 mm and a length of 300 mm. The samples were cast with concrete with a compressive strength of 35 MPa and were embedded with either steel or hybrid bars in their center, each bar reaching the end of the cylinder and having a free length of 300 mm. The first group consists of three samples with steel bars with a diameter of 10 mm. Three samples with hybrid bars that have a 10 mm diameter make up the second group, where the bars of this group contain 75% fibers of basalt and 25% fibers of glass. The third group consists of three samples with hybrid bars with a diameter of 10 mm, where the bars of this group contain 50% fibers of basalt and 50% fibers of glass. As for the fourth and last group, it consists of three samples with hybrid bars, which have a 10 mm diameter, where the bars of this group contain 25% fibers of basalt and 75% fibers of glass. The sample was inverted and inserted into the test machine load frame's bottom platform. During testing, both the embedding bar's slipping and the applied load are monitored. **Fig. 17** and **Fig. 18** exhibit samples of pull-out test procedures and failure shapes, respectively. After more than 28 days, all specimens were tested. The concrete cylinders with HFRP bars were heated in the oven to different temperature degrees (25°C, 100°C, 200°C, and 300°C). The concrete cylinders with steel bars are exposed to the same conditions. (Same different temperature degree and different times). The bond stress is computed by dividing the tensile load by the surface area of the bars in contact with the concrete. Equation 4 was used to determine each specimen's maximum bond strength.

$$F_{bu} = \frac{P_{ult}}{\pi * d * l} \quad \text{Eq. (4)}$$

Where :

F_{bu} Ultimate bond strength.

P_{ult} The tensile load at failure of the specimen.

D Diameter of the bar.

L The embedment length inside cylinder is 300 mm.



Fig. 17: Samples of pull out test

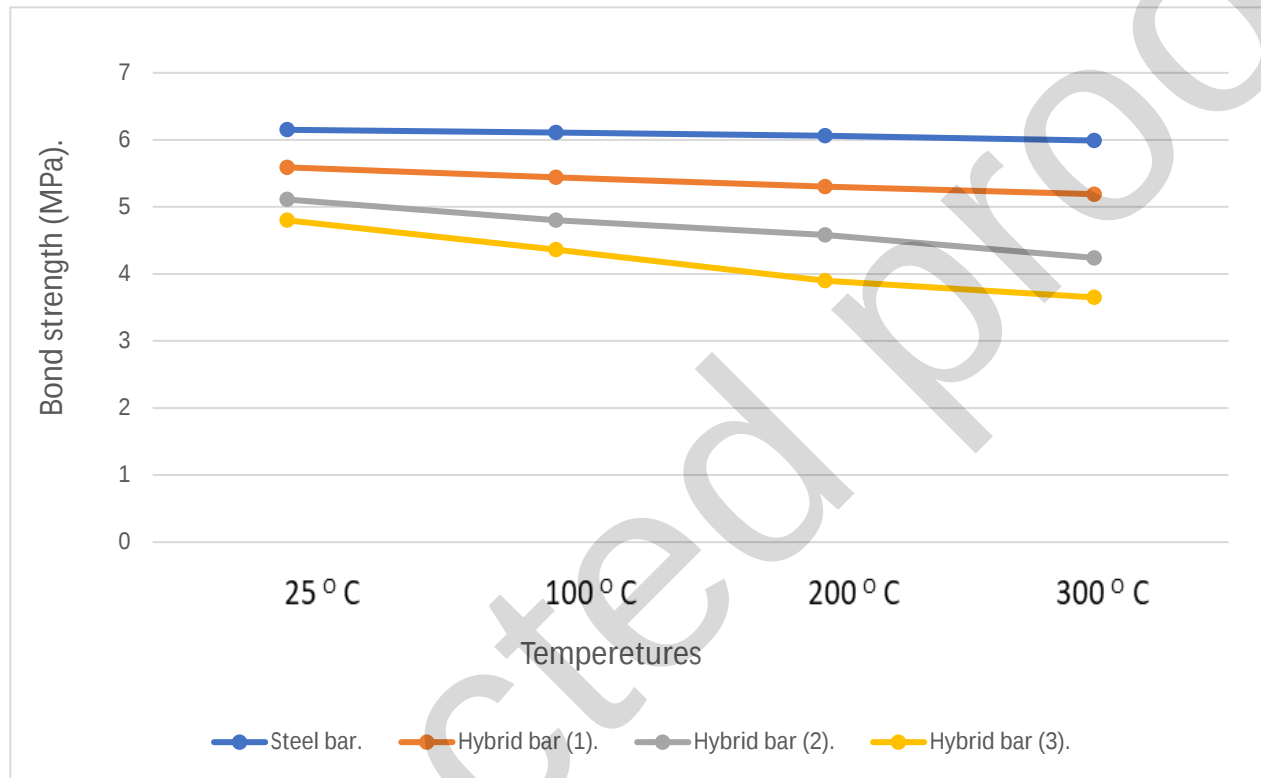


Fig. 18: Pull out test procedure and failure shape

- **Experimental results of the bond strength at different temperatures**

The results of the bonding tests for all specimens are plotted in **Fig. 19** and listed in **Table 5**. The test results show almost no decrease in the ultimate bonding strength of the steel bar cylinder. For the hybrid bar (3) cylinders containing 75% glass fibers and 25% basalt fibers, they show a significant decrease in the ultimate bonding strength by about 9.17% once the temperature rises to 100°C, a decrease in the ultimate bonding strength by about 18.75% once the temperature rises to 200°C, and a decrease in the ultimate bonding strength by about 24% once the temperature rises to 300°C. As for the hybrid bar (2) cylinders containing 50% glass fibers and 50% basalt fibers, they show a relatively average decrease. When the temperature rises to 100°C, the temperature increases to 200°C, and the temperature increases to 300°C, the ultimate bonding strength decreases by 6.1%, 10.4%, and 16.2%, respectively. However, the hybrid bars (1) cylinders, containing 75% basalt

fibers and 25% glass fibers in their composition, achieved a slight decline in the strength of the bond. When the temperature increased to 100°C, 200°C, and 300°C, the maximum strength of the bond dropped by 2.68%, 5.18%, and 6.8%, respectively. Also, these results of the hybrid bar (1) are very small decline percentages, almost negligible. The hybrid bar, containing 75% basalt fibers and 25% glass fibers in its composition, is considered the best hybrid bar because it gives the highest bond strength with concrete at different temperatures because the proportion of basalt fibers in it has increased, as basalt is a promising material in withstanding high temperatures. These results are consistent with previous research, which confirmed that hybrid bars with high basalt fiber content show excellent ability to withstand high temperatures [34, 35]. These findings establish hybrid reinforcement as a practical and effective alternative to conventional steel reinforcement, particularly for structures requiring high durability, strength, and long-term



performance in aggressive environments.

Fig. 19: Bond strength results for all tested samples

Table 5: Bond strength and failure mode for all specimens

Specimen	Bond stress (N/mm ²) at temperature 25 °C	Failure type	Bond stress (N/mm ²) at temperature 100 °C	Failure type	Bond stress (N/mm ²) at temperature 200 °C	Failure Type	Bond stress (N/mm ²) at temperature 300 °C	Failure type
Steel bar.	6.15	Concrete splitting	6.11	Concrete splitting	6.06	Concrete splitting	5.99	Concrete splitting
Hybrid bar (1).	5.59	Concrete splitting	5.44	Concrete splitting	5.3	Concrete splitting	5.21	Concrete splitting
Hybrid bar (2).	5.11	Concrete splitting	4.8	Rebar cutting	4.58	Rebar cutting	4.21	Concrete splitting
Hybrid bar (3).	4.8	Rebar cutting	4.36	Rebar cutting	3.9	Rebar cutting	3.65	Rebar cutting

SUMMARY AND CONCLUSIONS

- 1) This study demonstrated the effectiveness of hybrid bars made with different ratios of basalt and glass fibers as hybrid reinforcement for reinforced concrete elements subjected to tensile stresses. Through extensive experimental investigation, the research sheds light on key insights into the behavior of bars by studying their physical and mechanical properties.
- 2) By studying the physical properties, it was observed that the specific gravity of the hybrid bars ranged from 1.98 gm/cm³ to 2.11 gm/cm³. These results achieve a very small specific gravity compared to the specific gravity of conventional steel reinforcement, which is 7.8 gm/cm³, which helps in designing lightweight concrete sections with hybrid bars. Also, the results of fiber-volume fraction confirmed a very slight, almost negligible difference, which is the biggest evidence that the pultrusion process was carried out efficiently and with high quality.
- 3) By studying the mechanical properties, it was observed that the hybrid bar containing 75% basalt fibers and 25% glass fibers had the highest elastic modulus value among the hybrid bars, which was 765 t/cm². It also achieved the highest bond strength with concrete, which was 5.59 N/mm² at room temperature (25°C). A very slight decrease in the bond strength values was noted to rise as the temperature reached 100°C, 200°C, and 300°C; the bond strength values decreased by 2.68%, 5.18%, and 6.8%, respectively, which are very small percentages that can be overlooked.
- 4) We strongly recommend that the percentage of glass fibers not exceed 25% of the total fiber percentage in the composition of the hybrid bar in concrete facilities that are exposed to high temperatures, such as power plants, tunnels, and chemical factories close to thermal reaction units, due to only a high bond strength between the hybrid skewer and the concrete.

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CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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