

EFFECT OF HIGH TEMPERATURE ON BOND STRENGTH OF GLASS-FIBER REINFORCED POLYMER BARS IN CONCRETE

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Abstract: Corrosion is a significant problem for concrete constructions exposed to harsh conditions, as reinforcement bars can deteriorate rapidly. Due to its great corrosion resistance and lightweight qualities, glass fiber reinforced polymer (GFRP) is a viable alternative for steel reinforcement in concrete buildings. The bonding strength between concrete and GFRP bars is crucial to the stability and durability of concrete buildings. Bond strength is affected by a number of factors, including concrete compressive strength, bar diameter, embedment length, concrete cover, bar position, and bar surface characteristics. This study investigates the impact of elevated temperatures on the adhesive strength between GFRP bars and concrete. Twenty-four pullout tests were performed on 150 mm concrete cubes utilizing GFRP bars of three different diameters (10, 12, and 16 mm) and an embedment length of 100 mm. Twelve specimens had GFRP bars in the core, while the other Twelve had bars at the surface with a clear cover of 40 mm. The specimens were subjected to high temperatures of 400°C for 90 minutes. After cooling to room temperature, the binding strength of the GFRP bars was assessed. Bond strength fell by 25.5%, 36.21%, and 54.1% with rising temperature for GFRP bars with diameters of 10, 12, and 16 mm, respectively, when the bars were in the middle of the specimens. Larger diameter bars showed a greater loss in binding strength. On the other hand, altering the stress type in concrete from tension to compression close to the cube surface lowered the decrease in binding strength to 33%, 29.81%, and 36.8%, respectively, for the same bars when their location was adjusted to be close to the cube surface.

INTRODUCTION

Concrete structures exposed to extreme weather conditions are prone to steel reinforcement corrosion. The expansion of corrosion products in the cross-sectional regions of steel reinforcement bars raises radial pressures, which can fracture the reinforcement and separate the concrete cover, weakening the structure. As a result, in such harsh settings, corrosion-resistant reinforcement must replace typical steel reinforcement. Glass fiber reinforced polymer (GFRP) bars have been developed as an effective replacement for traditional steel reinforcing. GFRP bars have many advantages over steel reinforcement, such as corrosion resistance, non-conductivity, high strength-to-weight ratio, cost-effectiveness, and greater general durability [15], many factors effect on the bond strength of GFRP bars like concrete strength when increased bond strength increased [9].

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Despite these advantages, elevated temperatures, such as those caused by fires or enormously hot climates, might damage the characteristics of GFRP bars. Polymers' mechanical properties, such as strength and stiffness, are known to decline dramatically when temperature approaches their glass transition temperature (T_g) [16]. Furthermore, high temperatures can cause major physical-chemical changes in concrete, such as spalling and flame exposure, which damage the microstructure of the concrete.

Previous investigations have shown that increased temperatures have varied effects on the binding strength of FRP rebars. For example, Katz, et al. [12] reported a 30-38% drop in bond strength when specimens were heated to 250°C. El-Gamal [6] discovered a 20% decrease in binding strength at 200°C and a 50% reduction at 350°C. Özkal, et al. [14] found critical temperature limits of 300°C for GFRP bars and created an empirical model to analyze bond strength loss. Rosa, et al. [16] found a 20-34% drop in binding strength at 100°C. Solyom, et al. [17] discovered losses in bond strength ranging from 53% at 165°C to 31% at 190°C. Aslani [3] observed a 7% drop in bond strength at 100°C, 18% at 200°C, and 47% at 300°C. Kashwani and Al-Tamimi [11] found a 32% drop in binding strength at 350°C. Holly, et al. [8] demonstrated bond strength reductions ranging from 65-20% at 100°C, 80-60% at 150°C, and 90-80% at 220°C when using SCC to improve concrete properties such as compressive strength and tensile strength, which primarily affect bond strength and cover failure splitting [5].

This study aims to investigate the effect of a high temperature on the bond strength between GFRP bars and concrete. Specifically, to examine the effect of bond area, by using different bar diameters, in two different positions within concrete specimens on bond strength. This research seeks to provide a deeper understanding of the performance of GFRP bars under thermal stress, contributing to the development of more resilient and durable concrete structures.

EXPERIMENTAL PROGRAM

Materials

This study used three distinct types of high-strength GFRP bars (10, 12, and 16 mm in diameter). These bars had a unique surface profile (ribs) that helped to improve bonding strength and stress transfer between the concrete and the bars. The tensile properties of the GFRP bars are presented in Table 1. Figure.1 depicts a schematic diagram of the GFRP bars.

The experimental program utilized normal concrete strength with a compressive strength of 30 MPa at 28 days. The impact of elevated temperature on the adhesive strength between GFRP bars and concrete. was tested with standard 150 x 150 mm cubes. The cubes were placed in a furnace and heated to 400°C for 90 minutes. After cooling to room temperature, the specimens underwent a pullout test. The same approach was used for specimens stored at normal temperatures.

Table 1: Mechanical Properties of GFRP Bars.

No	Diameter (mm)	Specific Gravity	Density (kg/m ³)	Initial Area (mm ²)	Tensile Strengths (MPa)	Elongation (%)
1	10	2.09	2084	78.53	1207	2
2	12	2.09	2084	113.09	1310	3
3	16	2.09	2084	201.06	1107	--



Figure 1: Schematic Types of GFRP Bars (10, 12, and 16 Mm in Diameter).

Test Procedure and Device Setup

(twenty-four) pullout tests were performed according to ACI guide [2]. using 150 mm of concrete having a compressive strength of 30 MPa over 28 days. (Twelve) specimens had GFRP bars in the center, whereas the remaining Twelve had bars with a 40 mm clear cover from the face of the concrete. The clear embedment length of the GFRP bars in concrete was 100 mm. To assess the impact of concrete cover, a PVC tube was utilized as a bond breaker to isolate the lower part (50 mm) of the GFRP bars embedded in concrete. The free end of the GFRP bar was sleeved with a 150 mm length and 25 mm diameter steel tube using very hard epoxy, which had a tensile strength of 14 MPa after 7 days.

A data logger captured loading and slippage data at a rate of 80 measurements per second. Two LVDTs were installed, one at the free end of the GFRP bars and the other at the end of the embedment length. A load cell type donut with a 100 kN capacity measured the applied load using a hydraulic jack with the same capacity. The temperature is measured using three thermocouples of type K, one at the core of the concrete, one in the middle of the embedment length of the GFRP bars, and one 40 mm from the concrete face (at the concrete cover). Figure 2 depicts the specimens' dimensions and bar position.

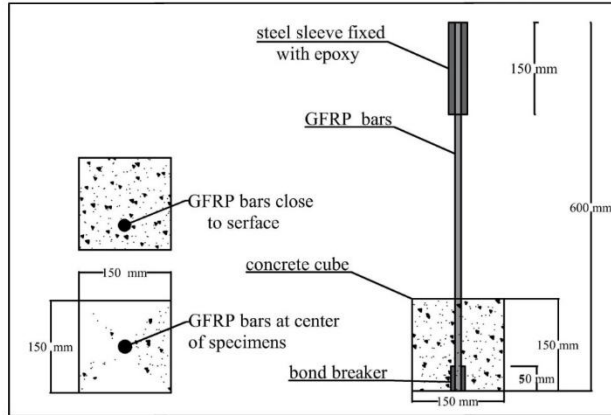


Figure 2: Location of GFRP Bars and Dimensions of Specimens.

To determine the impact of elevated temperature on the adhesive strength between GFRP bars and concrete, specimens were heated to 400°C for 90 minutes in a high-capacity gasoline furnace. The temperature was measured using a four-channel thermometer. For comparison, a series of specimens were evaluated in a laboratory. For each set, the average of the values obtained from testing two specimens is considered. The pullout test was carried out on a steel frame, as indicated in Figure 3.

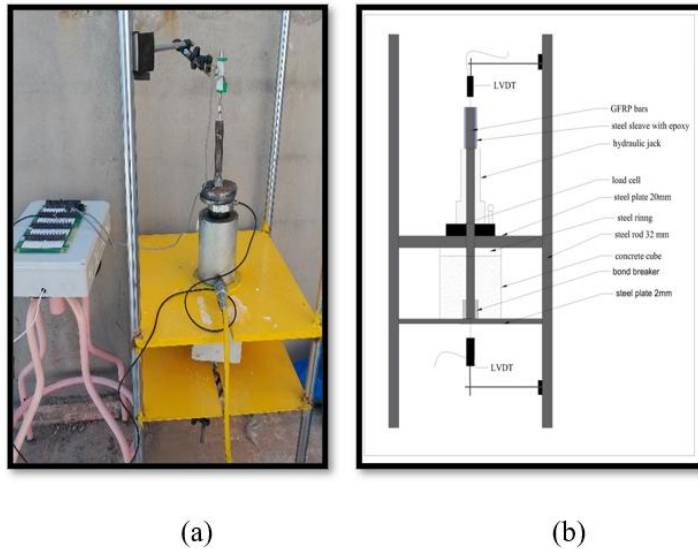


Figure 3: Test Loading Frame Setup (A) Photo (B) Sketching Schematic.

To drive the compression stress zone away from the area around the GFRP bars during the application of the pullout load, a hollow square steel washer was put between the cube face and the loading plate, as illustrated in Figure 4. Figure 5 shows how supplying this steel washer affected stress concentration during the pullout test. the predicted bond strength was determined using Equation (1), which assumes that the bond tension is evenly distributed along the length of the embedded material., l .

$$\tau = \frac{P_{max}}{\pi dl} \dots \dots \dots (1)$$

Where

- τ is the nominal bond strength,
- P_{max} is the peak load applied,
- d is the diameter of the bar,
- l is the embedment length.



Figure 4: The Hollow Square Steel Washer on The Specimen.

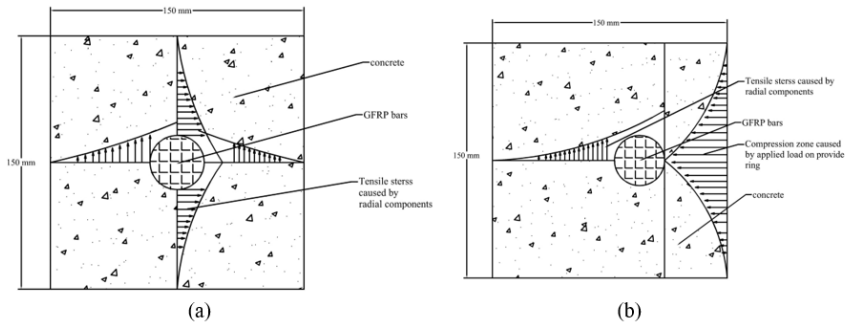


Figure 5: Effect of Providing a Hollow Square Steel Washer on Stress Development During the Pullout Test (A) GFRP Bar at Center of Specimens, (B) GFRP Bar at Edge With 40 Mm Clear Cover.

RESULTS AND DISCUSSION

Time-Temperature Regime

Figure 6 depicts the temperature rise within the furnace and among the specimens over time. Four type K thermocouples were placed to monitor the temperature of the specimens and the furnace throughout the test. After 15 minutes, the furnace maintained a consistent temperature of 400°C. These findings are consistent with prior researches conducted by Abdullah and Kassim [1]. The temperature in the cores of the specimens and within the GFRP bars gradually increased over time. After 70 minutes, the temperature had steadied, with a very slow rate of change.

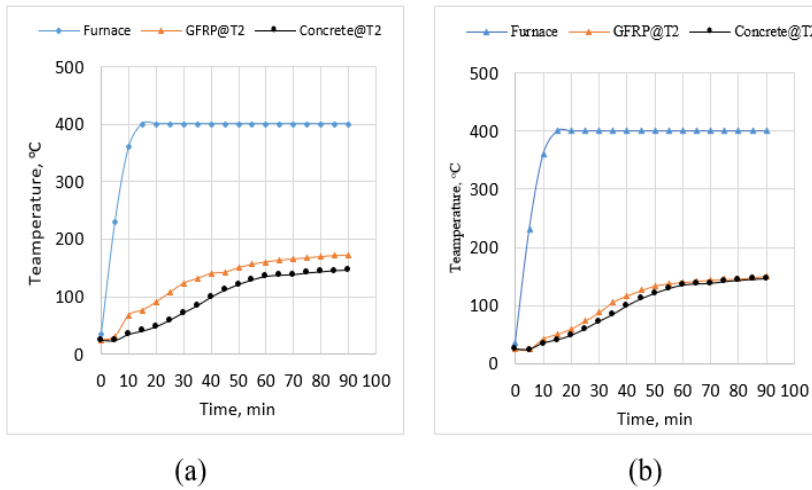


Figure 6: Time-Temperature Relationships At 400°C For Specimens With (A) GFRP Bars with Clear Cover 40 Mm (B) GFRP Bars at Center of Specimens.

This diagram depicts the distribution of temperature changes in the GFRP bars' core and surface areas, as well as the concrete matrix. This helps to understand the thermal conductivity and heat absorption properties of GFRP bars in concrete at high temperatures.

Cover Effect on Bond Strength Capacity

Table (2) displays the bond strength capacity results in relation to the concrete cover and testing ambient temperature, at room temperature, and after the specimens were exposed to a high temperature of 400°C for 90 minutes. At room temperature, GFRP bars in the center of the specimens displayed stronger bond strength than those with a 40 mm clear cover. This is due to the fact that the entire region surrounding the centrally positioned GFRP bars was in a tension zone, whereas the GFRP bars with a 40 mm clear cover were in a tension-compression zone. The binding strength increased with the diameter of the GFRP bars. The bond strengths for 10, 12, and 16 mm bars were found to be 9.7, 7.2, and 7.4 MPa, respectively. The higher bond strength for the 12 mm bars was most likely owing to the reducing surface area and increasing stress distribution, despite some production irregularities in the 12 mm bars.

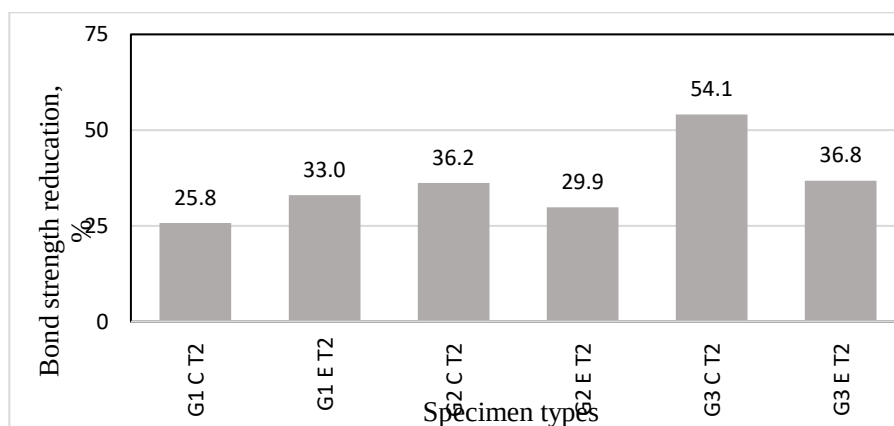
Moreover, the bond strength of GFRP bars (10, 12, and 16 mm) positioned in the center of the specimens decreased significantly by 25.75%, 36.21%, and 54.1%, respectively. While, for GFRP bars with a clear cover of 40 mm, the bond strength fell by 24.8%, 29.89%, and 36.8%, as shown in Figure 6.

Bond strength decreased significantly after exposure to extreme temperatures (400°C for 90 minutes). The reductions in centrally positioned GFRP bars were 25.75%, 36.21%, and 54.1% for diameters of 10, 12, and 16 mm, respectively. The reductions in GFRP bars with a clear cover of 40 mm were 33%, 29.89%, and 36.8%, respectively. The bond strength decreases at higher temperatures due to the softening of the epoxy surrounding the fibers, which weakens the bond contact. Furthermore, the thermal expansion of the GFRP bars increases the tension stress on the bonding area, resulting in higher slippage and bond deterioration when cooled.

Table 2: Bond Strength and Slip of GFRP Bars Before and After Fire Exposure.

No	Samples ID	Ultimate Force (kN)	Force Reduction (%)	Slip (mm)	Bond Strength (MPa)	Mode of Failure
1	G1 C T1	30.36	--	0.314	9.7	P+S
2	G1 C T2	22.54	25.75	0.647	7.2	P+S
3	G1 E T1	27.62	--	0.616	8.8	S
4	G1 E T2	20.77	24.8	1.93	6.6	S
5	G2 C T1	27.06	--	0.467	7.2	P+S
6	G2 C T2	17.26	36.21	1.05	4.6	P+S
7	G2 E T1	21.47	--	0.714	5.7	S
8	G2 E T2	15.24	29.89	0.329	4.0	S
9	G3 C T1	35.91	--	1.12	7.1	S
10	G3 C T2	16.47	54.1	---	3.3	S
11	G3 E T1	31.24	--	0.827	6.2	S
12	G3 E T2	19.75	36.8	0.829	3.9	S

Note: G: Bars diameter (G1: 10 mm, G2: 12 mm, G3: 16 mm), T: Temperature (T1: room temperature, T2: 400°C), Bar's position (C: in center, E: close to surface with clear cover 40 mm), P: pullout, S: splitting

**Figure 6:** Bond Strength Reduction Percentage After Specimens Were Exposed to Elevated Temperature.

This graph demonstrates the relative decline in bond strength across various bar diameters and placements within the concrete specimens following exposure to high temperatures. The statistics show that temperature has a considerable impact on bond strength, especially for bars positioned in the center. However, in the second situation, when the bars were close to the surface, the decrease in bonding capacity for bars 16 mm can be attributed to less slippage produced by the bars' confinement with compression stressed concrete.

These results are consistent with earlier research. Katz, et al. [12] showed a 30-38% loss in bond strength at 250°C, whereas El-Gamal [6] discovered a 50% reduction at 350°C. Özkal, et al. [14] found critical temperature limits at 300°C, which is consistent with the observed reductions in this investigation. Rosa, et al. [16] and Solyom, et al. [17] found significant losses in bond strength at temperatures as low as 100°C and 165°C, respectively. Aslani [3] and Kashwani and Al-Tamimi [11] confirmed similar findings, observing significant losses 32% in binding strength at temperatures ranging from 100°C to 350°C.

Effect of Bonding Area on Strength Capacity

Figure 7 shows the relationship between the generated ultimate bond stress and the area of the GFRP bars. In general, increasing the area of GFRP bars reduces the generated bond stress and increases strength capacity, as shown in equation (1). When the diameter of GFRP bars increased from 10 to 12 mm, bond stress decreased by 26%. Similarly, with GFRP bars with a diameter of 16 mm, bond stress was reduced by 24%. These measurements were acquired at room temperature for the GFRP bars in the center of the specimens.

The binding stress of GRFP bars with a 40 mm clear cover dropped by 36% as the bar diameter grew from 10 to 12 mm. Similarly, with GFRP bars with a diameter of 16 mm, the tension-compression stress zone in the concrete around the GFRP bars reduced bond stress by 30%.

When GFRP bars were exposed to high temperatures, the bond stress around the core of the specimens reduced by 35% for 12 mm GFRP bars and 55% for 16 mm. This significant stress decrease was ascribed to an increase in the weakened surface area of the GFRP bars when exposed to high temperatures. However, when GFRP bars with a 40 mm clear cover were employed, the reduction in bond stress was around 40% for 12 mm GFRP bars and somewhat reduced to 51% for 16 mm GFRP bars. This reduction may be ascribed to the concrete's compression stress containment, despite the increased high temperature effect.

The drop in bond strength capacity generated by GFRP bars reaches the glass transition temperature (T_g) of the polymer matrix, which typically ranges from 65 to 150 °C. Granadeiro [7] identified a manufacturing process differential in rib height, which causes a decrease in bond strength between GFRP bars of 12 mm and 16 mm due to the lower rib height around the 12 mm bars compared to the ribs surrounding the 10 mm and 16 mm bars, also when concrete exposed to elevated temperature of 450 °C to 750 °C, the compressive strength decreased by 93% for normal strength concrete [10].

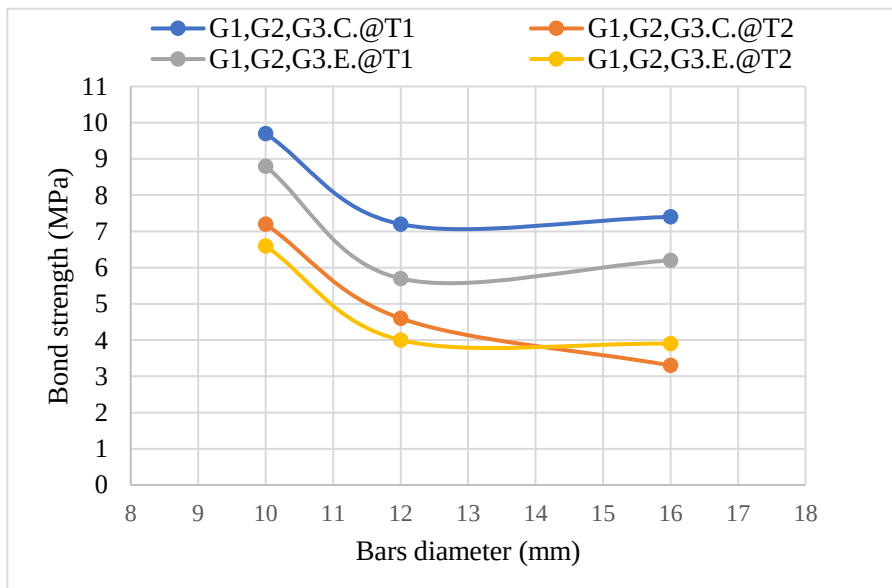


Figure7: The Relationship Between Bonding Area and Created Bond Stress.

Bond Stress-Slip Relationship

Figure 8.a and b. depicts the bond stress and free end slip relationship of the specimens at room temperature and after exposure to 400°C for 90 minutes. The bond-slip curves look similar to those of the control specimens. Notably, the specimens' binding strength decreased after being subjected to extreme temperatures. The extreme bond stress was seen at a low slip value, with an normal range of 0–1.12 mm.

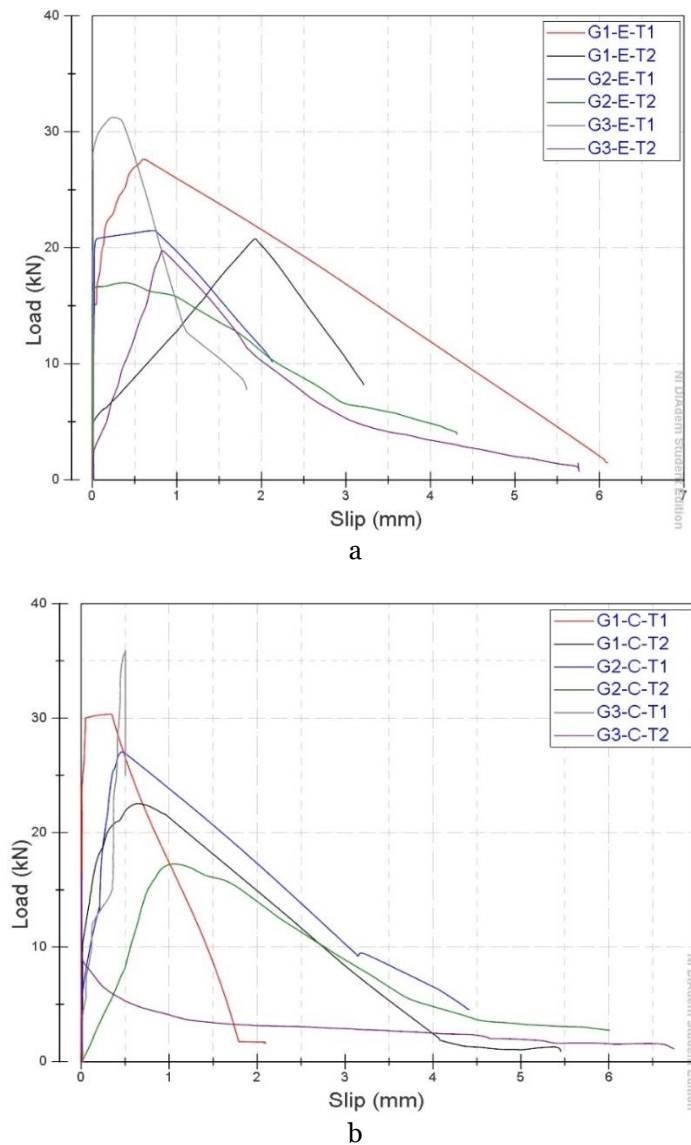


Figure 8: Bond-Slip Relationship.

- (a) GFRP at center of specimen before and after elevated temperature
- (b) GFRP with clear cover 40 mm before and after elevated temperature

This image shows a detailed comparison of bond stress-slip behavior at various temperatures and bar placements. It efficiently depicts how elevated temperatures affect slippage and bond integrity, suggesting a reduction in bar performance.

Failure Mode of Pullout Test

Figure 9 depicts the numerous failure modes identified during the pullout testing, emphasizing the consistent failure patterns both before and after exposure to high temperatures. The findings show that splitting remained the primary mode of failure, independent of temperature exposure.

Expanding on the details supplied in each part improves the clarity and comprehension of the experimental findings and their consequences. This complete presentation of the study's findings emphasizes the importance of elevated temperatures on the binding strength between GFRP bars and concrete.

This study looked at how GFRP bar diameter and position (center of the cube versus 40 mm clear cover) affected bond strength between GFRP bars and concrete at ambient and higher temperatures.

The test results show that at room temperature, when GFRP bars (10, 12, and 16 mm) were inserted in the center of the specimens, the failure mode was largely splitting and pullout for the 10 and 12mm bars, as shown in Figure 9 (a and c). Figure 9 (b) displays a failure mode for 16 mm GFRP bars: splitting. When the GFRP bars were placed under a 40 mm clear cover, all specimens failed due to splitting, as shown in Figure 9 (d, e, f). After being subjected to an elevated temperature of 400°C for 90 minutes, the failure mode of the GFRP bars remained unchanged, whether positioned in the middle of the sample or under a 40 mm clear cover and the failure mode agree with El-Gamal [6] and McIntyre, et al. [13].

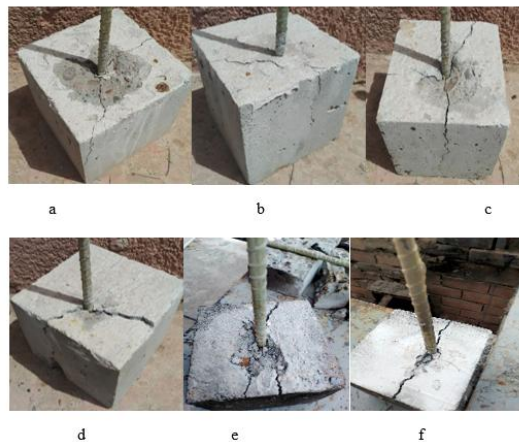


Figure 9: Failure Modes, (A, B, C, D, E) At Room Temperature And (F, G) At Elevated Temperature.

Additional investigations have added context to these findings. Bisby, et al. [5] discovered that bond strength can be greatly reduced at temperatures as low as 150°C, emphasizing the importance of taking temperature effects into account during design. Holly, et al. [8] also emphasized the relevance of fire resistance in FRP-reinforced concrete structures, arguing that design guidelines should include thermal performance parameters. Scholars looked at the larger implications of

high-temperature impacts on different types of FRP composites, emphasizing the importance of thorough testing and defined norms.

CONCLUSIONS

This study provides the results of twenty-four pullout tests on specimens with GFRP bars, twelve at room temperature and twelve at 400°C for 90 minutes. The specimens' bond strength at room temperature was compared to ASTM criteria [4], yielding considerable results. The following conclusions were drawn from this study:

1. As the temperature increased, the bond strength dropped, resulting in all specimens failing due to concrete shearing around the GFRP bars. Bond strength was reduced by up to 54% when compared to room temperature specimens. When exposed to high temperatures, the GFRP bars expanded, putting additional stress on the bonding area. The GFRP bars contracted when cooled to room temperature prior to testing, resulting within the gaps between the metal bars and the solid concrete and decreased bond strength.
2. The GFRP bars embedded in the concrete remained unbroken after fire exposure.
3. The study underscores the need to standardize the manufacturing process of GFRP bars to reduce performance inconsistencies caused by variations in product characteristics.
4. Additionally, existing design recommendations should be changed to reflect more practical and less cautious methods, taking into account empirical evidence on bond strength degradation at elevated temperatures.

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