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AN EXPERIMENTAL INVESTIGATION ON THE IMPROVING THE BOND BEHAVIOR OF GLASS FIBER REINFORCED POLYMER BARS IN CONCRETE

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ABSTRACT

The bond is considered one of the factors that plays an important role in the behavior of the reinforced concrete structural elements. In recent years, using the glass fiber reinforced polymer (GFRP) as an alternative to steel bars is needed to verify its performance in the structures. In this study, the bond between the concrete and GFRP bars is investigated through using two different surface enhancement techniques (sand and steel fibers). Fourteen beam specimens were cast and tested considering three different parameters, concrete compressive strength (55 and 78 MPa), bar diameter size (6mm and 10 mm) and the surface scheme (non-coated, sand-coated and steel fiber-coated). The experimental work included the recording of the bond stress and corresponding slip. For a certain value of concrete grade and 6 mm bar diameter, the bond behavior improved by 206% and 198% for the sand-coated surface and steel fiber-coated bars as compared to non-coated bars, respectively. For the same bar size (6mm), the best enhancement in bond strength was found by (61%) for the non-coated surface when the concrete compressive strength increased from 55 to 78 MPa. The use of larger bar diameter for the same concrete compressive strength, the higher bond strength improvement was 55% for the non-coated surface bar. From the bond stress-slip curves, the tests indicate that when the surface of the GFRP bars is coated by sand, it will give the best enhancement in the bond strength.

KEYWORDS

Bond behavior, GFRP, Steel fibers, Bond-slip curves, Surface coating.

1. INTRODUCTION

Reinforced concrete structures exposed to environmental conditions that affects its strength and durability, one of the most important factors causes the deterioration of the concrete is the corrosion of the steel reinforcing bars, which leads to large repair and rehabilitation costs.

In order to reduce the high expenses, several approaches were proposed to control the corrosion of steel, however, they are still expensive or ineffective to solve this problem (Zhao, 1999).

The quality of bond strength is responsible for reducing the number and width of cracks through the interaction between the concrete and the reinforcing bars. There is an extensive amount of experimental, analytical and numerical work that has investigated the bond strength of steel bars reinforcing concrete which is found very effective to transfer the load between the two materials (CEB Bulletin 151, 1982). However, the corrosion of steel decreases the bond strength and therefore, studies have been made to find alternative materials to resist the corrosion.

The use of composite materials in civil engineering applications has been increasing because of their superior properties in decreasing the problems resulting from the heavy weight and corrosion of the steel. The are many types of FRP composites which differ in their mechanical properties due to the manufacturing of the composing materials, the fibers and the resin. The nature, volume and the orientation of the fibers make each FRP type has its own characteristics. The most important properties of the reinforcing bars in the structural design are the tensile strength and the modulus of elasticity. The elastic modulus of Glass Fiber Reinforced Polymer (GFRP) is 20 of that of steel, while the elastic modulus of Carbon Fiber Reinforced Polymer (CFRP) is 70% of steel.

For FRP concrete members, it is necessary to evaluate the bond strength between the FRP bars and the concrete as it may lead to the failure of members. Most of the available research on the bond behavior have been assessed by experimental work using the pull-out tests. However, the bond behavior is well represented by applying the direct tensile tests because it can explain the tensile stresses resulted in the flexural members (CEB Bulletin 151, 1982).

The bond strength was experimentally investigated on the fiber reinforced concrete beams having different polymer bars, the bars were made of GFRP, AFRP and CFRP and having various surface deformation. The beam specimens were designed to fail in a concrete splitting mode. For these specimens, the observed bond mechanisms were classified depending on the surface configuration that the smooth FRP bars and strands was the friction resistance mechanism while the bond resistance for the ribbed bars was represented by the bearing. The increase of the bond splitting strength is evaluated by using the modulus of elasticity of the lateral reinforcement in case of steel bars, while the type of the longitudinal bars in addition to the modulus of elasticity of the lateral reinforcement have influenced the bond strength of specimens using FRP bars (Kanakubo et al, 1993).

The bond behavior of FRP bars embedded in an epoxy resin matrix was evaluated by (Makitani et al, 1993) using different parameters including FRP material, carbon, glass and aramid, having two types of surface configuration, deformed and sand-coated bars. According to the obtained results, the bond behavior enhances because of the increase of the increase in the chemical adhesive when using sand-coated bars. However, it was observed that a brittle failure occurred resulting from the sudden detaching between the sand grains and the bars.

Larralde and Silva-Rodriguez (1993) performed pull-out tests on specimens of GFRP reinforced concrete, the authors found that the bond stress of steel at failure was larger than that of GFRP, while the maximum slip for GFRP was larger than steel bars. In addition, they deduced that the anchorage design adopted for the steel bars cannot directly applied to the design of GFRP bars.

(Benmokrane et al, 1996) conducted experimental investigations to compare the bond behavior of GFRP and steel bars. The parameters of the study were the bar diameter and the embedment length. The results showed that the steel bars have greater bond strength compared to GFRP bars compared to steel bars, the bond strength was determined to be (5.1 to 12.63 MPa), depending on embedment length and the diameter of the bars. The authors supposed that the main components of bond of the deformed GFRP bars are chemical adhesion and friction.

(Gao, et al, 2019) proposed an experimental and analytical study to estimate the effect of the surface characteristics on the bond stress of the GFRP bars in concrete. The pullout test showed that the friction force between the GFRP bars and concrete governs the failure by bond for the bars which are helical wrapping and bars of helical wrapping with sand-coated surface, while the deformed bars with ribs, the failure mode was by crushing of concrete and shearing of ribs resulted from the lack of the interlock interaction between the concrete and bars. Also, it was observed that the increase in the concrete compressive strength does not always improve the bond behavior, but it depends on the bar surface. Therefore, the authors recommended to choose a suitable concrete mixture based on the GFRP surface.

In the present study, experimental tests were assessed to investigate the bond behavior of the GFRP bars considering three different surface configuration, non- coated surface, sand-coated surface and steel fiber-coated surface with two different concrete compressive strength and two bar diameters.

2. EXPERIMENTAL WORK

2.1. Materials

The effect of concrete strength was investigated in this study using two different concrete mixes. It was planned to get compressive strength values about 50 and 70 MPa for the first and second mix, respectively. The proportions of the mixtures are presented in Table 1.

The steel bars used to test the bond have diameter size 10mm and the yield stress is 578 MPa, while the steel bars which are used to reinforce the concrete block have 6 m and 8 mm bar diameter, and the corresponding yield stress values are 634 and 492 MPa, respectively. The glass fiber reinforced polymer bars used in this study have two diameters of f 6 mm and f10 mm. The outer surface of GFRP bars is helically wrapped by multifilament yarn. The properties of GFRP bars are provided in Table 2.

In order to improve the bond performance, the surface area of GFRP bars were coated using two different materials, the coarse sand which maximum size is 1.18 mm, and the steel fibers of aspect ratio equal to 75. Table 3 presents the properties of steel fibers.

Table 1. Proportion of concrete mixes

Mix	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (Liters)	Superplasticiser (Liter/100 kg cement)
M_1	450	560	740	160	0.8
M_2	550	880	950	180	1

Table 2. Mechanical properties of GFRP bars

Bar size (mm)	Nominal Area (mm^2)	Ultimate tensile strength (MPa)	Ultimate tensile load (kN)	Tensile modulus of elasticity (GPa)	Ultimate strain
6	31.67	896	28.34	46	1.94%
10	71.26	827	58.72	46	1.79%

Source: Supplied by the manufacturer

Table 3. Properties of the steel fiber

Diameter (µm)	Length (mm)	Aspect Ratio	Specific Density (g/cm^3)	Tensile Strength (MPa)
160	12	75	7.8	2700

Source: Supplied by the manufacturer

2.2. BEAM SPECIMENS

The beam specimens used in this study were designed according to the standard beam which based on the bar diameter and reported by RILEM recommendation (RILEM, 1973) to investigate the bond performance of GFRP bars embedded in concrete with different grades. Fig. 1 illustrates the details of the 12 mm diameter bar specimen that was previously used (Desnerck et al, 2010). The experimental work included 14 rectangular concrete beams having cross-sectional area of 100×180 mm and the total length is 800 mm. The beam specimen consists of two connected concrete blocks using a GFRP bar in the bottom and a steel hinge in the top. At the middle of the beam, a 50 mm gap was left to prevent the wedge failure of concrete at edges. Two longitudinal steel reinforcement of 8mm bar diameter were placed at the tension and compression sides of each concrete block in addition to 6 mm transverse steel reinforcement spaced at 50 mm. The bond behavior was investigated by studying the effect of the GFRP bars diameter, concrete compressive strength, and the bar surface enhancement scheme (coarse sand, steel fibers). The surface area is coated by either coarse sand or steel fiber by applying epoxy to the required bonded length of the GFRP bars. This work is an extension of experimental work done by (Hasoon et al, 2023) on the bond behavior of the CFRP bars in concrete, therefore same concrete mixture was used. The beam designation consists of sets of numbers and letters. The first letter refers to the bar type G for GFRP bar, R for the Steel bar, the first number refers to the diameter size, the second letter was set for the compressive strength (C1=55 MPa, and C2=78 MPa).The third letter refers to the type of bar coating surface (N: without coating, S: surface coated by sand and F: bar surface coated by steel fiber). The details of the beam specimens are presented in Table 4. The specimens were prepared by cutting the GFRP bars to the required length, then, the coarse sand or steel fibers were applied to the bar surface area by using epoxy along the required length, Fig. 2 shows the cast specimens, surface enhancement scheme. The concrete compressive strength was evaluated by testing standard cubes of dimensions (150 × 150 × 150) mm.

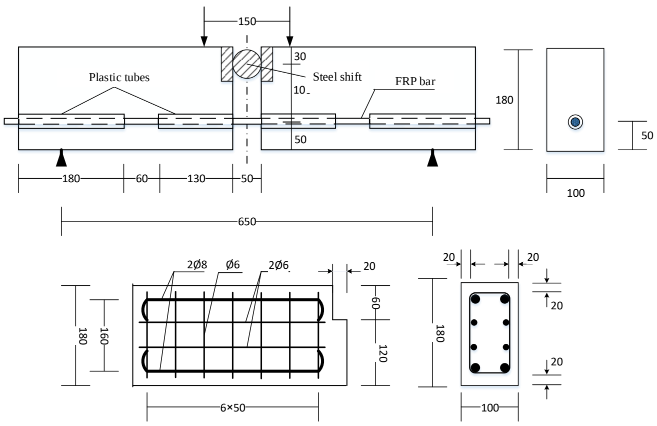

Fig.1. Details of the tested specimens (Desnerck etal.,2010)

Fig. 2. Specimen preparation and casting process

Table 4. Details of the test specimens

Specimens	Bar Type	Bar Diameter (mm)	Coating Type
G6C1N	GFRP	6	Without coating
G6C1S	GFRP	6	Coarse sand
G6C1F	GFRP	6	Steel fiber
G6C2N	GFRP	6	Without coating
G6C2S	GFRP	6	Coarse sand
G6C2F	GFRP	6	Steel fiber
G6C1R10	Steel	10	Without coating
G10C1N	GFRP	10	Without coating
G10C1S	GFRP	10	Coarse sand
G10C1F	GFRP	10	Steel fiber
R10C2	Steel	10	Without coating
G10C2N	GFRP	10	Without coating
G10C2S	GFRP	10	Coarse sand
G10C2F	GFRP	10	Steel fiber

2.3. BEAM TEST SETUP

The simply supported beams were loaded using four-point flexural test until failure. The load was applied at a velocity of 10 N/s. The slip at the free ends of the beam was measured using two dial gage as shown in Fig. 3.

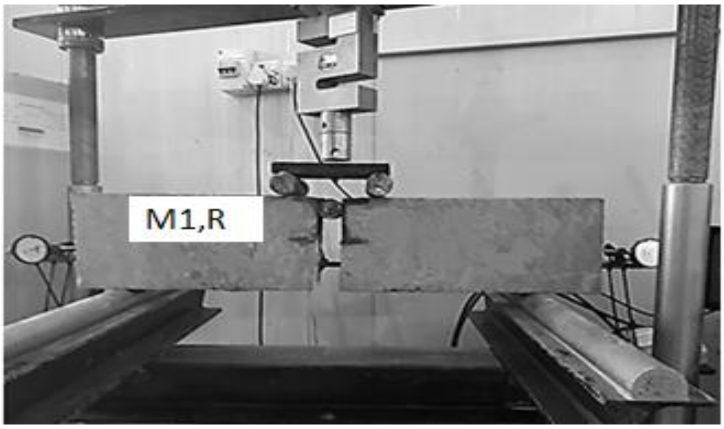

Fig. 3. Test setup

2.4. RESULTS AND DISCUSSION

2.4.1. General

Based on the experimental results, the ultimate load and free end slip were obtained. The factors affecting the bond strength including the concrete compressive strength, the diameter of GFRP bar, and the bond strength enhancement using the different techniques are discussed. The obtained compressive strength values of the first concrete mixture (C1) were 36 MPa and 55 MPa at 7 days and 28 days, respectively, while the second concrete mixture (C2) gave a compressive strength of 52 MPa and 78 MPa at 7 days and 28 days, respectively.

The summary of the experimental results is presented in Table 5.

Table 5. Summary of the experimental results

Specimens	Bond stress (MPa)	Relative bond stress (MPa)	Slip (mm)	Strength ratio
G6C1N	10.35	1.39	0.45	0.344
G6C1S	31.70	4.26	0.76	1.053
G6C1F	30.81	4.14	0.62	1.024
G6C2N	16.67	1.88	0.73	0.544
G6C2S	41.52	4.69	0.9	1.38
G6C2F	39.27	4.44	0.83	1.305
R10C1	46.08	6.19	0.45	
G10C1N	16.06	2.16	1.09	0.429
G10C1S	35.26	4.74	1.13	0.943
G10C1F	30.14	4.05	0.94	0.806
R10C2	60.01	6.78	0.45	
G10C2N	23.2	2.62	1.16	0.62
G10C2S	43.76	4.94	0.45	1.17
G10C2F	35.50	4.01	0.54	0.949

2.4.2. Effect of Compressive Strength

In general, the increase of the concrete compressive strength leads to the bond strength improvement. For GFRP bars of 6 mm diameter without enhancement, it is found that the bond and relative bond stress increase by 61% and 35% when the compressive strength of concrete increases from 55 to 78 MPa. While the increase in the bond stress and relative bond stress for bars enhanced with coarse sand is found to be 31% and 10% for, and by 27.5% and 7.2% for bars with surface area enhanced using steel fibers. For 10 mm size GFRP bars, the increase in compressive strength from 55.3 to 78.3MPa, the bond stress and relative bond stress enhanced by 44%, and 21% for bars without enhancement in the surface area, for bars enhanced with coarse sand the bond stress and relative bond stress enhanced by 24%, and 4%, while for bars enhanced by steel fiber the bond stress increased by 18% , however, the relative bond stress decreased by 1%.

The higher concrete compressive strength enhances the bond strength due to the reduction in pores in the mixture which improves crack resistance. Similar conclusion was found by some researchers (Ipek et al, 2020;De Almeida et al, 2008).

2.4.3. Effect of Bar Diameter

Regarding the effect of bar diameter, at certain value of concrete compressive strength, 55 MPa and without coating, it was found that both the bond stress and relative bond stress increased by 55% for increasing GFRP bar diameter from 6 mm to 10mm, however, when the surface coated with sand, both the bond stress and relative bond stress increased by 11% for increasing GFRP bar diameter from 6 mm to 10mm and finally the bond stress and relative bond stress decreased by 2% for the surface enhanced by steel fibers.

For the second concrete mixture, 78 MPa it was found that both the bond stress and relative bond stress increased by 39% for specimens without bar coating when increasing GFRP bar diameter from 6 mm to 10mm, however, when the surface coated with sand, both the bond stress and relative bond stress increased by 5% for increasing GFRP bar diameter from 6 mm to 10 mm and finally the bond stress and relative bond stress decreased by 10% for the surface enhanced by steel fibers.

The results show that the bond strength is affected by the bar diameter in different ways depending on the surface coating scheme. As the bar diameter increases for specimens without bar coating and with sand coating, the bond strength increases due to the higher force resistance (Majain et al, 2022; Arezoumandi et al, 2018; Khaksefidi et al, 2021;Qi et al, 2021;Prince and Singh 2013) While for specimens with steel fiber coating, the lesser bar diameter increases the bond strength by small amount due to the larger voids performed around the bar which decreases friction force between the concrete and the bar (Law et al, 2011;Osifala et al, 2017; Pop, et al, 2015; Trabacchin et al, 2022).

2.4.4. Effect of Surface Coating Configuration

In general, the bond strength of the FRP bars embedded in concrete is improved when the bar surface treated by sand (Ma et al, 2019; Shukur and Alkhudery 2023). In order to estimate the effect of surface coating on the bond strength of GFRP bars, three specimens with the same concrete compressive strength and bar diameter were cast. For the 6 mm bar diameter and 55.3MPa compressive strength, it is observed that the bond strength increases by 206% and 198% when the bar surface coated by sand and steel fibers, respectively.

For the 10 mm bar diameter and 55.3MPa compressive strength, the bond strength increases by 120% and 88% when the bar surface is coated by sand and steel fibers, respectively.

For the 6 mm bar diameter and 78.3MPa compressive strength, it is observed that the bond strength increases by 149% and 136% when the bar surface is coated by sand and steel fibers, respectively. For the 10 mm bar diameter and 78.3MPa compressive strength, the bond strength increases by 89% and 53% when the bar surface is coated by sand and steel fibers, respectively.

It can be noticed that there is a significant enhancement in the bond strength for the coated GFRP bars, the less bar diameter, the better improvement in the bond strength. That can be attributed to the interlock mechanism and the increase in the induced friction force between the bar surface and the surrounding concrete. However, it is obvious that using sand as bar surface coating is more effective than using steel fibers.

2.4.5. Effect of Bar Material

For comparing the use of reinforcing bars made of traditional material, steel, with GFRP material related to the bond strength, 10 mm steel bar was used in specimens with two different concrete mixtures. For M1, the bond strength decreased by 65% for specimen with GFRP without coating as compared to specimens reinforced by steel bar, while it reduced by 23% for the specimen of GFRP bar with sand coating, the last specimen which reinforced with GFRP bar coated with steel fiber had bond strength 35% less than that reinforced with steel bar.

For M2, the bond strength decreased by 61% for specimen with GFRP without coating as compared to specimens reinforced by steel bar, while it reduced by 27% for the specimen of GFRP bar with sand coating, the last specimen which reinforced with GFRP bar coated with steel fiber had bond strength 41 % less than that reinforced with steel bar.

It is obvious that the steel bars have stronger bond due to the interlock between the ribs and the concrete, in addition to the higher tensile strength of the GFRP which leads to bond failure before reaching the ultimate splitting stress in comparison to steel bars.

Fig. 4 shows a comparison of the percentage of the strength ratio for all beams, it can be seen that the series with the lower bar diameter have higher strength ratio and the most affected factor is the concrete grade that the higher compressive strength gives higher strength ratio.

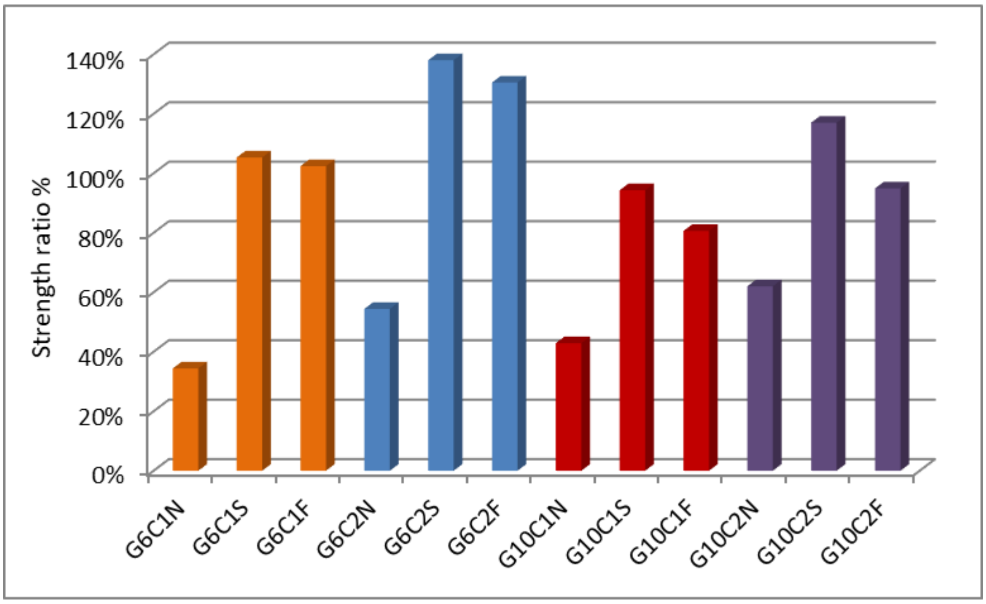

Fig.4. The increasing percentage of the Bond Strength Ratio comparison of the Tested specimens

2.4.6. Bond stress- slip relationship

In the experimental work, by applying the gradual load the corresponding slip was recorded to determine the bond stress-slip relationship. Figs. 5 and 6 show the bond stress-slip relationship for all specimens.

From the figures, all the curves have the same trend, at the first stage there is no slip corresponding to the applied load due to the chemical adhesive between the materials. At the second stage, with a gradual increase in the applied load, a linear relationship is observed up to the maximum bond stress because of the mechanical interlock. At the third stage, the bond stress starts to drop with significant increase in the slippage that the curve becomes nonlinear because of losing the interaction between the bar and the surrounding concrete. However, there is a difference in the behavior of the specimens depending on the factors influencing the bond strength. The specimens with sand-coated bar and steel fiber-coated bar show enhancement in the bond stress-slip curve. For M1-G6-N, the maximum slip is 0.45 mm, 0.76 mm for M1-G6-S and 0.62 mm. When the concrete compressive strength increases, the bond behavior becomes weaker, that may be attributed to the brittleness of concrete when it has higher grade.

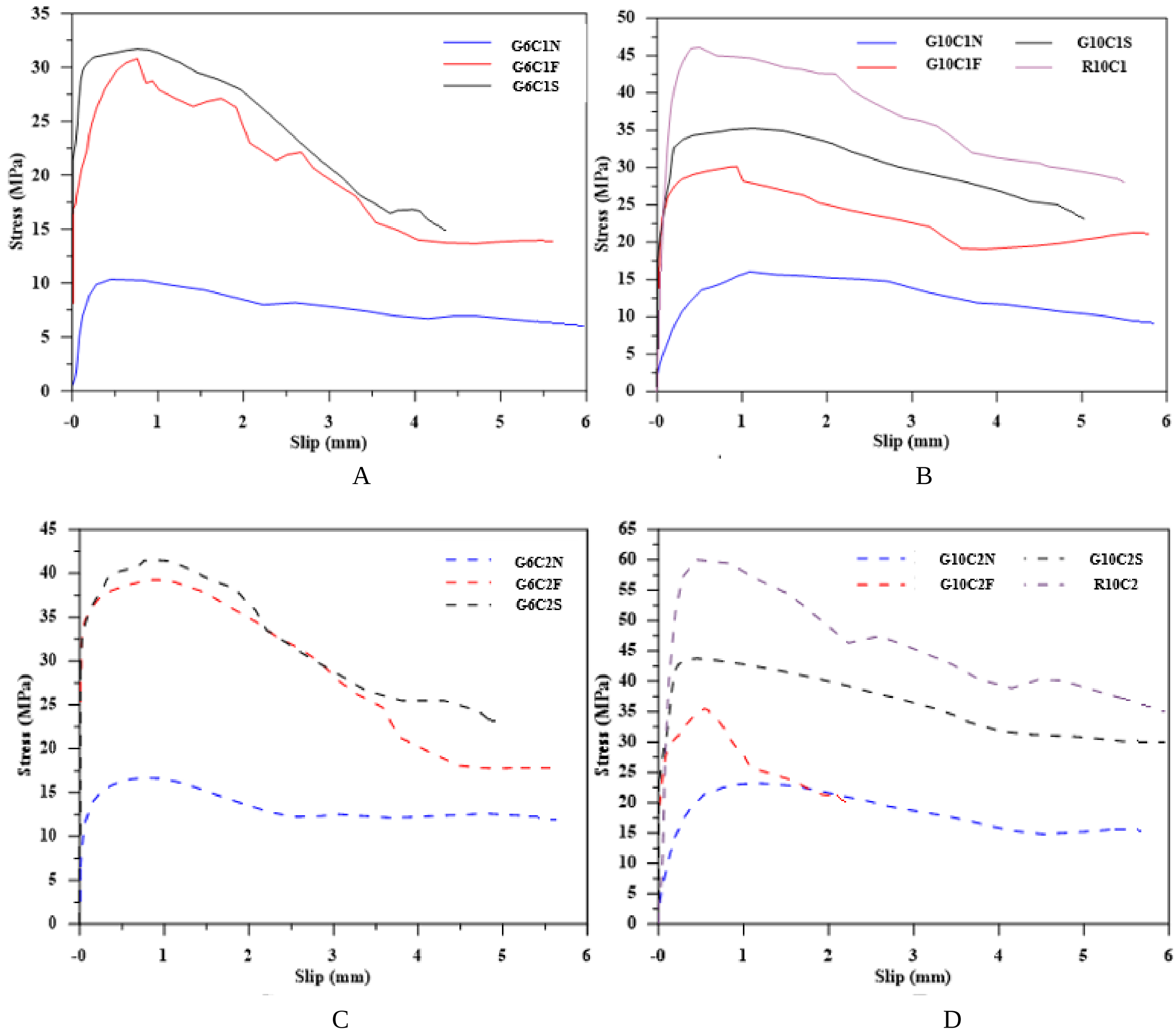

Fig.(A) Effect of surface coating on the bond-slip curves of 6 mm GFRP for concrete mix C1, (B) Effect of surface coating on the bond-slip curves of 10 mm GFRP for concrete mix C1, (C) Effect of surface coating on the bond-slip curves of 6 mm GFRP for concrete mix C2, (D) Effect of surface coating on the bond-slip curves of 10 mm GFRP for concrete mix C2

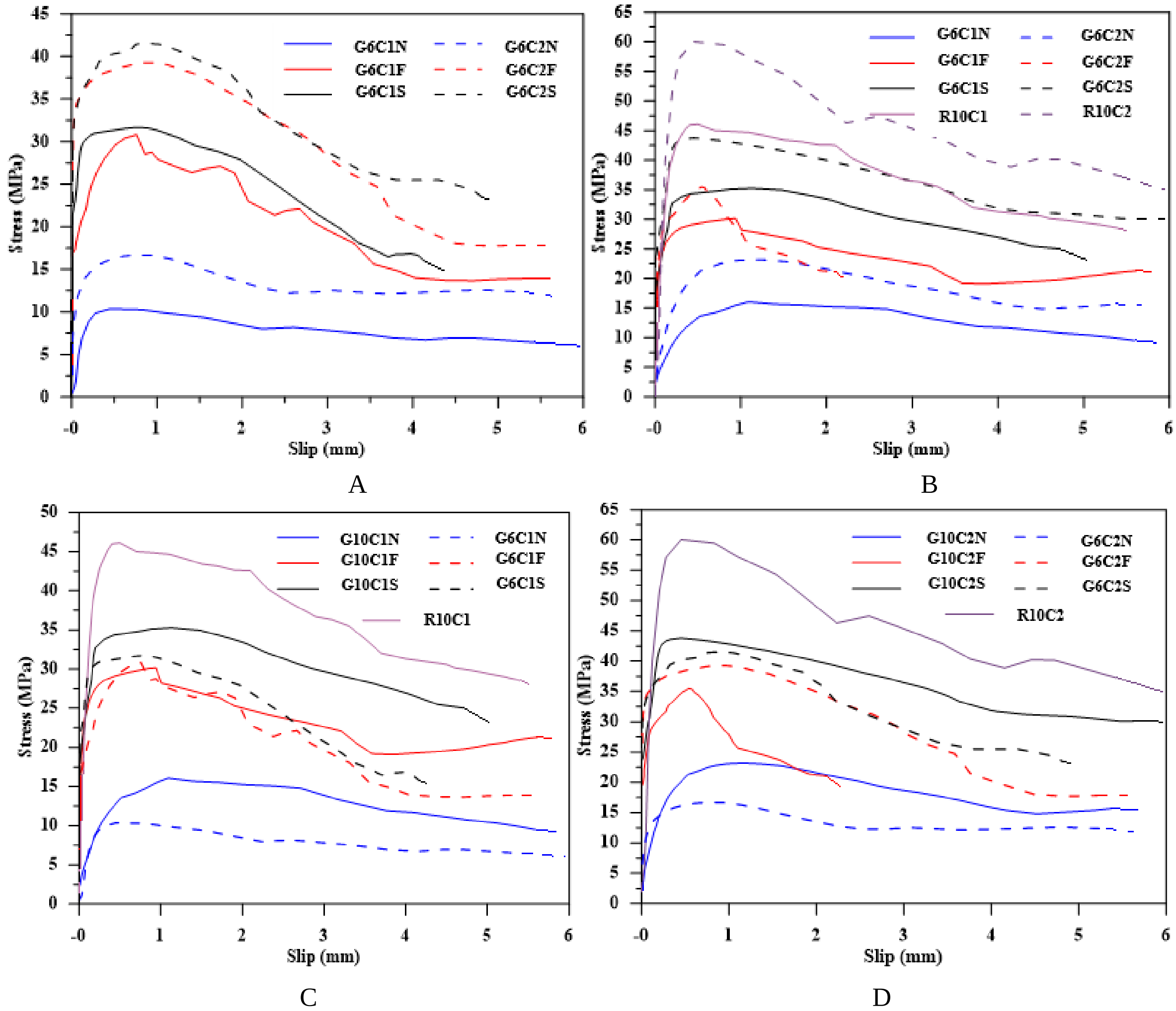

Fig. 6. (A) Effect of concrete mix on the bond-slip curves of 6 mm GFRP, (B) Effect of concrete mix on the bond- slip curves of 10 mm GFRP , (C) Effect of bar size on the bond-slip curves for concrete mix C1, (D) Effect of bar size on the bond-slip curves for concrete mix C2

3. CONCLUSIONS

In order to investigate the influence of surface coating on the bond properties of GFRP bars embedded in concrete, experimental tests were conducted on 14 beam specimens and based on the results, the following conclusions were drawn:

1. The increase in the concrete compressive strength improved the bond strength for all specimens, however, the effect of this parameter was more significant for the specimens having 6 mm GFRP bar diameter.

2. When the bar diameter increased from 6 mm to 10 mm, the bond strength increased for the specimens that have no coating for both concrete mixtures, also it was observed that the sand-coated specimens have less increase in the bond stress values. But the increase I bar diameter has a negative effect on the bond strength of the steel fiber-coated specimens.

3. Regarding the bar surface coating, it was found that the bond properties of the specimens with sand-coated bars were greatly enhanced compared with the specimens which have bars without coating.

Using the steel fiber as a bar surface coating improved the bond strength in comparison with specimens without coating, but still the sand coated GFRP bars give the best performance.

4. The bond strength of GFRP bars is smaller than the bond strength of the steel bars, but its superiority over the steel bars in other properties like corrosion resistance make it good alternative in some structural elements.

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