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Influence of Synthetic Fibres on the Bond Performance of Glass Fibres Reinforced Polymers Concrete: An Experimental Investigation and Regression-Based Analysis

Abstract

Fibre-reinforced polymer bars are considered as an alternative to conventional steel bars in harsh and corrosive conditions. However, the utilisation of glass FRP-reinforced elements has certain limitations due to the poor bond performance compared to steel-reinforced concrete. This research experimentally investigated the impact of synthetic fibres on the bond behaviour of concrete reinforced with glass fibre-reinforced polymer. The experimental programme comprised pull-out tests conducted on GFRP bars embedded in synthetic fibre-reinforced concrete cubes considering different parameters like concrete cover, type of reinforcement, bar diameter and fibre content. In total 36 cubic specimens were tested. The influence of the parameters on the bond behaviour of GFRP-reinforced concrete was discussed in terms of the bond strength, overall bond stress-slip response, and the mode of failure. Experimentally, results showed that incorporating synthetic fibres resulted in more considerable ductile behaviour under pull-out tests. Analysis of Variance (ANOVA) and multiple linear regression analysis were conducted on the experimental results obtained from bond strength using Minitab. Equations for bond strength and contour plots were generated for each type of reinforcement. Results indicated that the influence of the bar diameter and concrete cover on the bond strength is more important than that of fibre content. Moreover, the utilisation of synthetic fibres allows for the reduction in the concrete cover.

Keywords
Pull-out; synthetic fibres; bond strength; stress-slip; ANOVA; linear regression; GFRP.

1. Introduction

Fibre-reinforced concrete (FRC) has been increasingly introduced in various structural and non-structural uses. Available research revealed that incorporating fibres in the concrete mixes contributes towards bridging cracks leading to improved crack control, enhanced mechanical properties, and flexural performance in the cracked state [1-3]. Steel fibres are typically favoured for applications where the fibres' structural contribution is intended to be substantial [4, 5]. The study conducted by Abdolpour et al. [4] investigated the impact of steel fibres in producing ultrahigh-performance concrete. Results indicated that the inclusion of steel fibres as a structural material resulted in excellent mechanical properties and improved seismic resistance. In contrast, non-metallic fibres have lower tensile strength and modulus of elasticity compared to steel fibres. They are generally used in applications where their primary function is to limit the formation of plastic cracks and reduce shrinkage cracking [6-8].

However, the performance of non-metallic FRC concrete has drawn the interest of several researchers. The influence of glass fibres on concrete mechanical properties was investigated recently by Pérez et al. [9], and results showed significant improvements in concrete mechanical properties including compressive and tensile strength, elastic modulus, and flexural strength. Improvements were up to 40.3%, 38.3%, 18.5%, and 37.3%, respectively. Moreover, Zainal et al. [4] investigated the influence of micro-synthetic fibres on the structural performance of reinforced concrete slabs and observed an improvement in the load-carrying capacity and cracking resistance, and a reduction in deflections. Recently, Muñoz et al. [10] investigated the mechanical properties of concrete mixes with different combinations of steel and plastic fibres, findings reported noticeable improvements in the mechanical properties of concrete mixes having 0.44% steel fibres and 0.11% plastic fibres.

Moreover, the advantage of achieving a reduced carbon footprint and hence improving the sustainability of concrete structures has also triggered the interest of researchers [8, 11, 12] for evaluating the mechanical properties and structural behaviour of reinforced concrete using non-metallic fibres. Ali et al. [13] evaluated the environmental and economic benefits of the inclusion of glass and polypropylene fibres in concrete mixes and concluded that non-metallic fibres can be reliably used as eco-friendly materials for reducing the concrete carbon footprint. Besides the use of synthetic fibres in concrete, research [14, 15] have also found the naturally occurring materials ichu and coconut fibres to be of great value for reducing carbon emissions associated with Portland cement as well as improving the mechanical characteristics of resulting concretes.

Fibres have also displayed the ability to provide passive confinement, thereby improving the bond strength, strain capacity and energy absorption in cracked sections [16]. Experimental investigations [17-21] evaluated the influence of fibres on the bond behaviour considering conventional steel reinforcement and fibre-reinforced polymers (FRP) such as aramid, carbon and glass in different concrete types. These studies investigated the influence of various parameters including the concrete strength, fibre content, type and diameter of reinforcing bars, embedded length and concrete cover on the bond performance. Results revealed fibres can be employed as an effective method of enhancing the bond performance and toughness of concrete due to their crack bridging capability. Moreover, fibres have also been found to increase friction and mechanical interlocking which eliminates the problem of poor toughness and low bond capacity of FRP bars [22-24]. Won et al. [25] observed the volume fraction of steel and macro-polypropylene fibres to be instrumental in improving the flexural strength, achieving higher bond strength and lower slip in specimens with GFRP-FRC concrete.

Lee et al. [19] analysed the bond performance of GFRP reinforcement in various grades of concrete and reported that the bond strength of GFRP increased at a constant rate in high-strength concrete but remained inferior to that of steel-reinforced specimens. Moreover, the mode of bond failure was investigated in the recent research [26] by considering different concrete strengths and covers. It was noticed that the specimens with normal-strength concrete exhibited slip failure, whereas failure of specimens with high-strength concrete occurred due to interlaminar delamination at the interface between the resin material and the fibre. Generally, the bond failure between concrete and reinforcing bars occurs either in splitting mode or in pull-out mode depending on the confinement; if the concrete is well confined and the concrete cover is high, the failure mechanism occurs in pull-out mode. On the contrary, in the case of unconfined concrete or where the bars are closely spaced, splitting failure occurs as a result of cracks developing in the surrounding concrete [27].

A critical review of the currently available research indicates that previous investigations have focused on the analyses of the effect of individual parameters, in isolation, on the bond strength of GFRP reinforcement in FRC. However, for a better understanding of the interaction between several parameters in fibre-reinforced concrete, extensive investigations of multiple parameters in the same scenario are required to evaluate the relative contribution of different factors. Accordingly, the work presented here involves an experimental and statistical investigation of the combined influence of several variables including concrete cover, reinforcement diameter and type, volume fraction of fibres, and embedded length on the bond performance of GFRP by analysing their significance, identify potential synergies with other factors, and analyse non-linear patterns. Moreover, a multiple linear regression analysis was performed using ANOVA to establish the statistical significance of considered parameters and to develop a bond strength equation which was further employed to develop the contour plots for illustrating the relationship between the different factors.

2. Experimental Programme

2.1. Research Methodology

The methodology adopted for this research involved experimental investigation on GFRP bars embedded in FRC cubes. The outcomes of experimental campaign were utilised for statistical analysis using ANOVA. Various components of the research methodology are summarised in a flow chart presented in Figure 1.

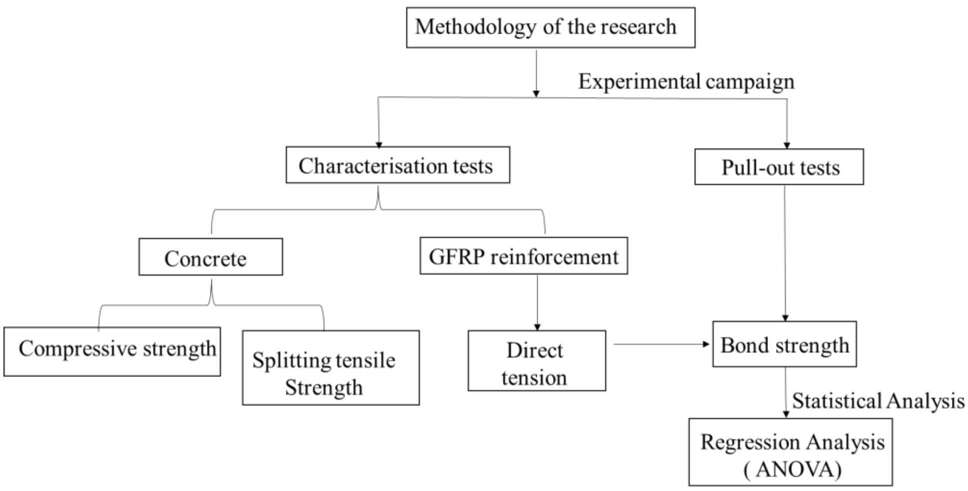


Figure 1: Research Methodology.

2.2. Materials

Concrete mix with a target compressive strength of 60 MPa at 28 days, having a water-to-cement ratio (w/c) of 0.29 and prepared with CEM I (52.5N) cement was used in this research. Natural river sand with a maximum particle size of 5 mm was used as fine aggregate and the crushed Limestone coarse aggregate ranging between 4-20mm in size was utilised. Three groups of concrete mixes were categorized by the fibre content of i.e. 0, 0.55% and 1.1% represented as Mixes 1, 2, and 3, respectively. Macro synthetic fibres referred to as polypropylene macro with 54 mm polymeric fibres length, 0.34 mm diameter, and 600 MPa tensile strength were used. High range water reducing admixture known as SikaViscoCrete 25MP was used at 1.8, 2.4 and 2.7% by weight of cement for mix 1, mix 2 and mix 3, respectively. Details about the proportions of mix constituents are presented in Table 1.

Table 1. Mix designs (per cubic metre)

Ingredients	Quantity (kg/m^3)		
	Mix 1	Mix 2	Mix 3
Water	147	147	147
Cement	510	510	510
Fine aggregate	950	950	950
Coarse aggregate (20 mm)	300	300	300
Coarse aggregate (10 mm)	580	580	580
Synthetic fibres	0	5	10
Superplasticiser	9.4	12	14

The mixing sequence and procedure used was the same for all mixes. Cement and aggregates were added to the mixer in the amounts indicated in Table 1, and were dry mixed for three minutes. Following that, 80% of the total water was added and further mixed for another three minutes. For concrete mixes containing fibres, the synthetic fibres were added to the mix at this stage gradually until they were evenly distributed throughout the mix. Thereafter, the remaining 20% of water containing the selected proportion of superplasticizer for each mix was added, and the mixing process was continued for further four minutes. The test specimens were prepared using mixed concrete and stored in a curing room with average temperature of 20°C and average relative humidity of 99%.

Pultruded GFRP rebars with three different bar diameters i.e., 12, 16 and 20 mm were embedded in the concrete cubes of 225mm sides. The control specimens for each mix were reinforced with ribbed steel bars of 16mm diameter. Mechanical properties of GFRP bars were obtained by following the ACI 440.3R-04 standard [15]. Tests were conducted on five bars for each bar diameter.

2.2. Testing

2.3.1. Characterisation tests

Control cylinder specimens of 150x300 mm were used to obtain concrete tensile strength, compressive strength, and modulus of elasticity at 28 days. The concrete specimens for concrete for compressive strength, tensile strength, and modulus of elasticity were prepared, cast and tested according to BS EN 12390-3 [28], BS EN 12390-6 [29], and BS EN 12390-13 [30], respectively.

2.3.2 Pull-out tests

The pull-out tests were carried out on cube samples to evaluate the influence of inclusion of synthetic fibres on the bond behaviour of GFRP bars and FRC considering several parameters as described below. For pull-out tests, the GFRP and steel bars were embedded in each FRC cube specimen. This test considered different factors: rebar diameter (D_b), concrete cover (C_c, C_1=2.5D_b, C_2= 0.5(C_1+C_3), C_3=5D_b), synthetic fibre content, and reinforcement type. Cubic samples reinforced with the same bar diameter had a constant bond length (L_t) equal to 5D_b. Concrete mixes with different synthetic fibres dosages of 5, and 10 kg/m^3 were considered, and control concrete mixes with no fibres were also tested as reference samples. Following the design of the experiment strategy (DOE), 12 combinations were considered, and three typical samples for each combination were produced and tested to ensure the reliability of more conclusive results, in total experimental regime comprised 36 samples. The combinations are listed in Table 2.

Table 2: Pull-out combinations

Combination	No. of sample	Cc(mm)	Fibre conte (kg/m^3)	Bar type	Φ (mm)	L_t(mm)
Comb.1	3	30	0	GFRP	12	60
Comb.2	3	80	0	GFRP	16	80
Comb.3	3	75	0	GFRP	20	100
Comb.4	3	80	0	Steel	16	80
Comb.5	3	45	5	GFRP	12	60
Comb.6	3	40	5	GFRP	16	80
Comb.7	3	100	5	GFRP	20	100
Comb.8	3	40	5	Steel	16	80
Comb.9	3	60	10	GFRP	12	60
Comb.10	3	60	10	GFRP	16	80
Comb.11	3	50	10	GFRP	20	100
Comb.12	3	60	10	Steel	16	80

The POT specimen's dimensions and the test set-up complied with the RILEM TC 162-TDF [31] and ASTM D7913/D7913M [32]. The specimen cross-section was (225x225) mm, in which the total length (L_t) of samples was selected as 225mm because the length had to be more than 10 times the bar diameter, and 200 mm.

To prevent rupture and crushing of GFRP bars while applying tensile force, the bars were enclosed in grout-filled steel tubes of 460 mm length and 48.3 mm outer diameter as recommended by ASTM D7205/D7205M standard [33]. Steel tubes, as shown in Figure 2, were filled with SikaGrout-3200 grouting material with a mixing ratio of 11-12.5% were used. Special wooden moulds were prepared and used, and a bond-breaker was utilised to ascertain the required unbonded length in each sample as a function of the bar size.

Figure 2: Moulds and samples preparation.

The pull-out test was performed under direct tension, and the linear variable differential transformer (LVDT) was placed at the surface of loaded ends to measure the relative displacements (slip values were calculated based on ASTM D7913/D7913M). The machine was operated at 4kN/min at a constant rate and load was applied through a steel tube which was clipped vertically in the universal testing machine for gripping, load and slip were monitored and recorded through the data acquisition system. Figure 3 illustrates the pull-out test setup.

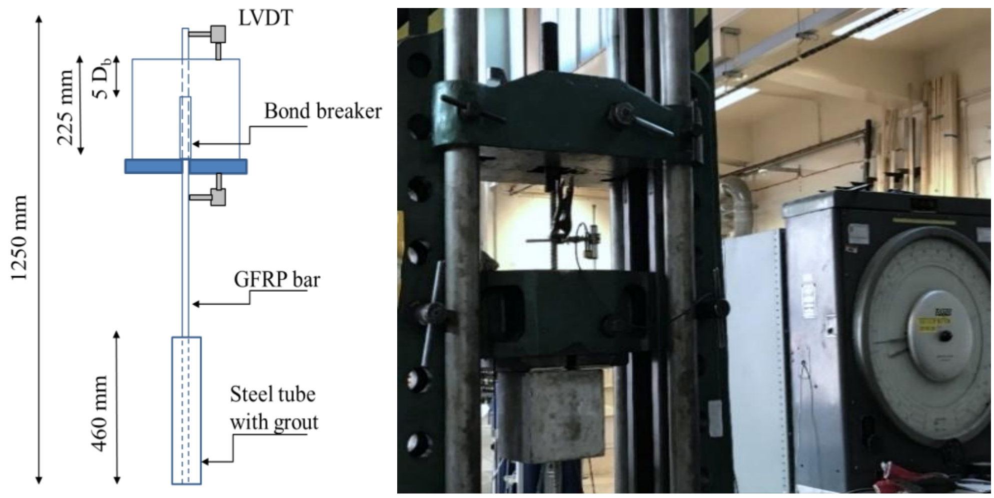


Figure 3: Pull-out test set-up.

3. Results and discussion

The results from this experimental investigation were focussed on evaluating the influence of various parameters considered i.e., concrete cover, volume fraction of fibres, bar type and bar diameter. The influence of these parameters on the concrete mechanical properties, bond strength, bond stress-slip response, and the mode of failure are discussed in this section.

3.1. Concrete characterisation tests results

Concrete mechanical properties obtained from characterisation tests carried out on control samples are summarised in Table 3.

Table 3: Concrete mechanical properties in (MPa)

Properties	Mix 1	Mix 2	Mix 3
	Average (Standard deviation)		
Compressive strength (MPa)	60.3 (0.8)	60.1 (0.7)	59.7 (1.0)
Tensile strength (MPa)	3.90 (0.3)	4.40 (0.2)	4.60 (0.5)
Modulus of elasticity (10^3) (MPa)	39.6 (0.8)	40.9 (0.8)	39.8 (1.0)

3.1.1 Concrete compressive strength

Compressive strength of concrete did not vary significantly due to variations of fibre content. Moreover, it was also concluded, in a detailed investigation [34], that the type and content of non-metallic fibres do not influence the concrete compressive strength. These findings align with those of Mazaheripour et al. [35] and [36] who evaluated the influence of different volume fractions of non-metallic fibres on compressive strength and noticed no significant improvements in concrete compressive strength. According to ACI 544 [37], steel fibres tend to increase the compressive strength of concrete by up to 15%, however, it is not clear if this is applicable to non-metallic fibres.

3.1.2 Concrete splitting tensile strength

Results of splitting strength presented in Table 3 indicate an increase in tensile strength due to the addition of fibres in concrete. The inclusion of synthetic fibre contents of 0.55% and 1.1%, increased the tensile strength of concrete by 13% and 18%, respectively. This is in good agreement with the findings of the previous studies [36, 38, 39] which reported that concrete splitting tensile strength was observed to increase by up to 19% with the inclusion of polypropylene fibres based on the volume fraction considered. Ahmad and Zhou [40] investigated the optimum proportion of synthetic fibres for improvement of tensile strength and reported the optimum fibre content as 1.0%. Moreover, ACI 544 [32] also reported noticeable improvements in concrete tensile strength based on type and volume fractions of non-metallic fibres. However, it has been reported by researchers that steel fibres can result in a higher increase in tensile strength as compared to non-metallic fibres primarily because of the lower elastic modulus of synthetic fibres. Abbass et al. [41] in their study found that steel fibres contributed to an increase of 47% in the direct tensile strength.

3.2. GFRP tensile strength results

Direct tensile tests were performed on 12, 16, and 20 mm diameter GFRP bars using a universal testing machine by embedding the ends of the bars in grout-filled steel tubes to prevent crushing of bars at the gripped ends. Tensile strength results for each bar diameter are summarized in Table 4. The results indicated similar tensile strength and elastic modulus for the tested bars irrespective of the bar diameter. Average tensile strength, modulus of elasticity, and the ultimate strain of GFRP bars were found to be 694 MPa, 40 GPa, and 1.76%, respectively.

Table 4: Reinforcement (GFRP bars) mechanical properties

Mechanical properties	12 mm	16 mm	20 mm
Tensile strength (MPa)	690 S.D (6.2)	698.3 S.D (7.92)	689.5 S.D (5.59)
Modulus of elasticity (MPa)	40000 (2154)	40000 (2425)	40000 (1587)
Ultimate strain (%)	1.77 (0.05)	1.79 (0.08)	1.73(0.1)

S.D, standard deviation

3.3. Pull-out test results

Experimental results obtained from the POT campaign have been analysed and discussed in terms of the mode of failure and the bond stress-slip profiles. The mode of failure namely pull-out or splitting was observed in each test and also retained as a non-quantitative experimental outcome. Experimental results obtained from POT include the peak bond strength and the slip to the peak which were quantified from the bond stress-slip curves. The corresponding bond stress (τ) values were calculated using the formula given in Equation (1) below.

$$\tau = \frac{P}{\pi D L} \quad (1)$$

Where; P is the pullout load (in kN), D is the bar diameter (in mm), and L is the embedded length (in mm). Experimental results obtained from the pull-out test are given in Table 5.

Table 5: Pull out samples and test results

Combination	C_c	V_f (kg/m^3)	ϕ	Rebar	L	τ (MPa)
Comb.1	30	0	12	GFRP	60	21.66
Comb.2	80	0	16	GFRP	80	27.11
Comb.3	75	0	20	GFRP	100	17.35
Comb.4	80	0	16	Steel	80	30.09
Comb.5	45	5	12	GFRP	60	29.18
Comb.6	40	5	16	GFRP	80	19.65
Comb.7	100	5	20	GFRP	100	22.28
Comb.8	40	5	16	Steel	80	24.37
Comb.9	60	10	12	GFRP	60	26.97
Comb.10	60	10	16	GFRP	80	25.37
Comb.11	50	10	20	GFRP	100	17.51
Comb.12	60	10	16	Steel	80	30.84

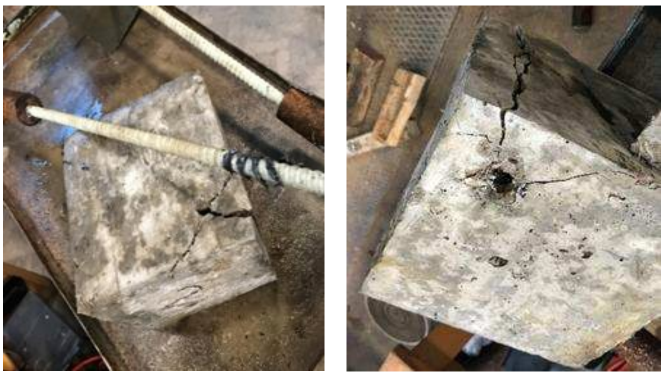
3.3.1 Modes of failure

In all cases where concrete had no fibres, specimens showed splitting failure modes, whilst specimens with synthetic fibres exhibited pull-out failures. Fibre-reinforced concrete samples presented a ductile behaviour in which the softening curve showed a gradual decrease with higher values of slip. Previously, similar behaviour was also observed by Sivakumar and Santhanam [42], Kim, et al. [43] who reported that fibres changed the failure mode, and more ductile behaviour was observed in FRC samples. Figure 4 illustrates samples that exhibited pull-out failure.

(a) (b)

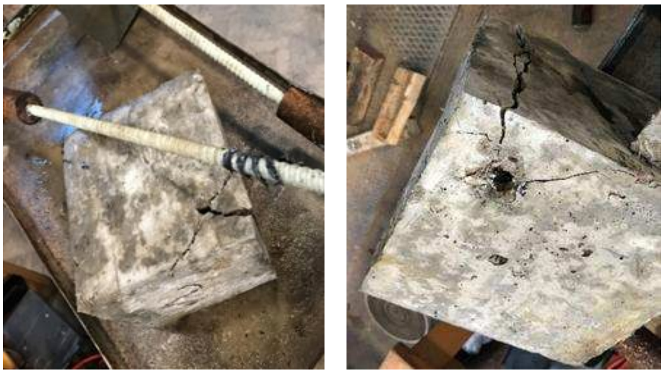
Figure 4: Pull-out failure of samples reinforced with (a) 12 mm, and (b) 16 mm GFRP bars

Samples that exhibited pull-out failure had a significant initial increase in the bond stress without any noticeable slip, representing the linear increase up to the formation of micro-crack (increasing load resulted in increased bond stress up to the peak value). It is worth mentioning that bond stress was developed in this stage due to the adhesion between the bar surface and the concrete. As the free end of the bar developed higher slip values, the stiffness of the bond stress decreased, this descending part reflects the bond failure where adhesion was lost, hence friction resistance governing the bond behaviour. However, few samples with plain concrete developed longitudinal cracks, and those cracks broke out through the whole cover and resulted in a splitting failure as shown in



(a) (b)

Figure 5. This can be attributed to the high level of anisotropy of FRP bars which results in weak matrix bond performance. Similarly, Peng et al. [44] found that samples reinforced with carbon FRP in plain concrete exhibited splitting failure.



(a) (b)

Figure 5: Splitting failure of samples reinforced with (a) 16 mm, and (b) 20 mm GFRP bars.

In some samples, it was observed that the bond breaker did not work efficiently, and a better bond developed between bars and concrete along the length, accordingly, higher bond strength was observed. The bond breaker is shown in Figure 6.

(a) (b)

Figure 6: Interfacial bond failure of the GFRP bars; (a) unbonded length attained, (b) bond breaker inefficacy.

3.3.2 Bond stress-slip profiles

Generally, bond stress-slip relationship is used to represent the bond performance of reinforced concrete members, where the slip is defined as the relative displacement of the reinforcement bar with reference to the surrounding concrete. Bond stress-slip profiles for each combination as given in Table 2 are discussed for each bar diameter by varying the fibre content and concrete cover.

Figure 7 demonstrates the behaviour of three different combinations of samples reinforced with 12 mm diameter GFRP bars. Each combination represents the average of 3 tested samples.

Combination 1 represents plain concrete samples with a concrete cover of 30 mm, combination 5 corresponds to samples that had a concrete cover of 45 mm and 5 kg/m^3 fibre content (0.55% volume fraction), and combination 9 pertains to samples with a 60 mm concrete cover and fibre content of 10 kg/m^3 (1.1% volume fraction). Samples in combination 1 had no fibres and were observed to exhibit splitting failure after reaching the peak, whilst FRC samples in combinations 5 and 9 showed ductile behaviour with a 16% increase in bond stress. Increasing the fibre content to a volume fraction of 1.1% resulted in higher bond strengths with reduced slip values. Results of samples with volume fractions of 0.55 and 1.1% indicated that the maximum force required to pull out the 12 mm GFRP bar increased by 24% and 34%, respectively. Findings of the previous study conducted by Qasem et al. [45] on 12mm carbon FRP bars in FRC (containing steel fibres) revealed that the bond stress increased by 176% due to the presence of fibres.

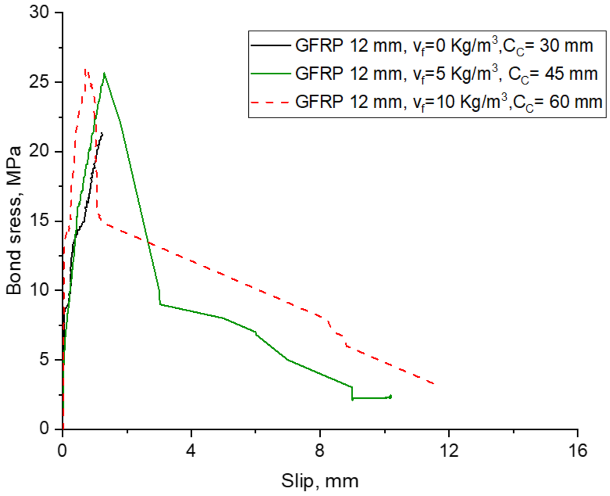


Figure 7: Bond stress-slip for 12 mm GFRP bar with varying fibre content and concrete cover.

Results from three combinations of samples reinforced with 16 mm GFRP bars and various concrete cover and fibre volume fractions are presented in Figure 9. Results revealed no significant increase in bond stress; however, the observed bond behaviour was more ductile in samples with fibres. Combination 10 (10 kg/m^3 fibres and 60 mm concrete cover) exhibited a higher slip value compared to combination 6 (5 kg/m^3 fibres and 40 mm concrete cover). Samples of combination 10 exhibited a very close bond strength to plain concrete samples in combination 2 which had relatively higher concrete cover of 80mm, which indicated that the use of synthetic fibres can allow a reduction in concrete cover. Results are in good agreement with the findings reported by Qi et al. [46] where the plain concrete with higher concrete cover resulted in an increase in the pullout energy and bond strength.

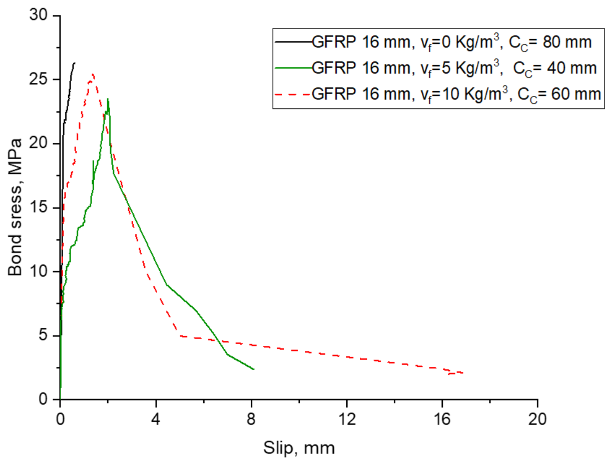


Figure 8: Bond stress-slip for 16 mm GFRP bar with different fibre content and concrete cover

Bond stress-slip profiles of the 20 mm diameter GFRP bar samples are presented in Figure 9. It can be noticed that FRC samples from combination 7 (5 kg/m^3 fibres and 100 mm concrete cover) exhibited splitting failure and developed lower bond strength when compared to combination 3 (no fibres and 75 mm concrete cover). This is attributable to the poor dispersion of fibres which tends to reduce the bond performance of reinforced concrete. A similar tendency of fibre dispersibility and lower bond performance was reported by Huan et al. [47]. Azammi et al. [48] investigated the bond performance of concrete containing synthetic fibres and reported that lower fibre dosages can lead to low interfacial bonding. However, more ductile behaviour was observed in the case of combination 11 (10 kg/m^3 fibres and 50 mm concrete cover) as compared to the other two combinations. Improved ductile behaviour can be attributed to higher dosage as well as better dispersion of fibres.

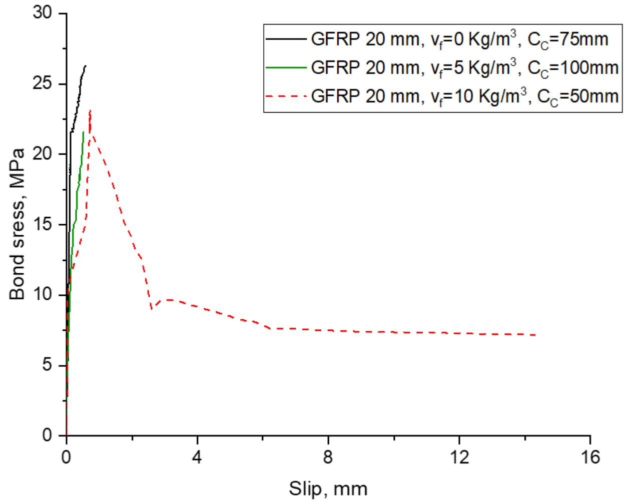


Figure 9: Bond stress-slip for 20 GFRP bar combinations.

In terms of using the conventional steel reinforcement, samples reinforced with 16 mm steel bars exhibited a ductile behaviour for all combinations with and without fibres as presented in Figure 10. Results revealed that adding fibres improved the ductility of bond behaviour where more ductile behaviour was obtained as the fibre content was increased. Moreover, comparing the results of FRC samples in combination 12 (10 kg/m^3 fibres and 60 mm concrete cover) with plain concrete samples in combination 4 (no fibres and 80 mm concrete cover), it can be noticed that both combinations developed the same bond strength. In the case of combination 8 (5 kg/m^3 fibres and 40 mm concrete cover), a reduction of 34% in bond stress was observed which is attributed to the poor dispersion of synthetic fibres in the concrete mix. In general, fibres are randomly scattered in concrete mix and have the tendency to clump together. Previous experimental studies carried out by Chu et al. and Karim and Shafei [49, 50] for investigating the influence of non-metallic fibre on the bond performance of steel-FRC revealed that fibres introduced a significant improvement in the pull-out resistance. Moreover, it was also reported that increasing the fibre content resulted in a more ductile performance.

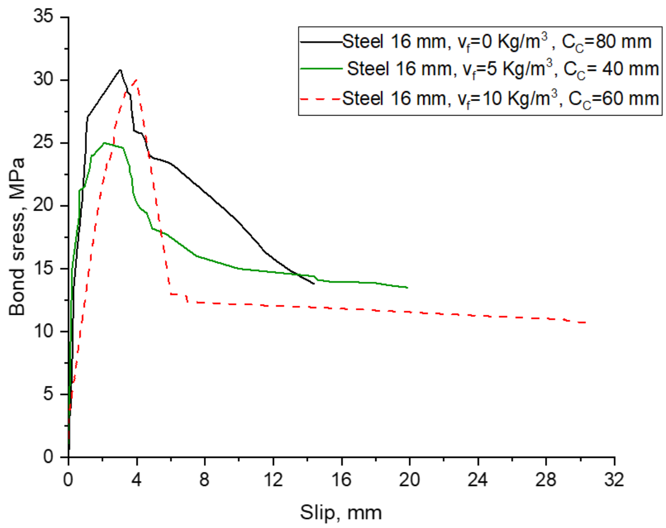


Figure 10: Bond stress-slip for 16 steel bar combinations

In general, the bond behaviour of various combinations of GFRP-fibre reinforced concrete revealed that the synthetic fibres improved the ductility of samples under POT. Samples in combinations 6, 8, 10,11 and 12, having lower concrete cover but various additions of fibres in the concrete mix, displayed better bond performance than those in combinations 2, 3, and 4 with higher concrete cover and no fibres. This comparison indicates that using synthetic fibres allows for reducing the concrete cover. From the experimental observations, it can be deduced that the addition of synthetic fibres significantly improved the ductile behaviour primarily due to the enhancement of concrete confinement and consequently, interception of the propagating cracks by fibres. This aligns well with the findings reported by Won, et al. [17], and Ding, et al. [18] who observed the interface toughness and pullout strength of synthetic fibre-reinforced concrete and reported that specimens with fibre displayed significant improvements in concrete confinement.

It was also observed that combinations reinforced with lower GFRP bar diameters (12 and 16 mm) resulted in relatively higher bond strength compared to 20 mm. These bars were embedded in concrete with different fibre contents and higher concrete covers. Better bond performance with smaller bar diameters is in good agreement with the bond behaviour observed in previous investigations [51-53]. However, it is worth mentioning that these findings reported by previous work correspond to samples designed and tested considering only one variable factor each time.

4. Statistical Analysis

The selected combinations of samples were such that each combination had two variables i.e., fibre content and concrete cover for the selected bar diameter. However, these combinations were limited due to time and resource constraints, which made it difficult to analyse each variable individually. Therefore, the Analysis of Variance (ANOVA) was utilised to assess the significance of distinct parameters analysed in this research. Several researchers employed artificial intelligence and ANOVA in their investigations to provide predictive modelling of the influential parameters on concrete performance considering several properties [54-56]. Parvizi et al. utilised the ANOVA tests to determine the significance of using seawater on the bond strength. Similarly, Chumacero et al. [56] employed the K-OPLS model to optimize the plastic fibre content on the geological characteristics of a specific soil.

In this research, a multiple linear regression analysis was carried out on the bond strength results to fit an equation to the experimentally obtained data so that this equation could be plotted with respect to the different variables as shown in Figure 11 and Figure 12. The final adopted model considered only the terms and interactions with the highest statistical significance. The obtained R-squared value of the model using ANOVA was 89.34% which indicated that the bond equation fits the data relatively well.

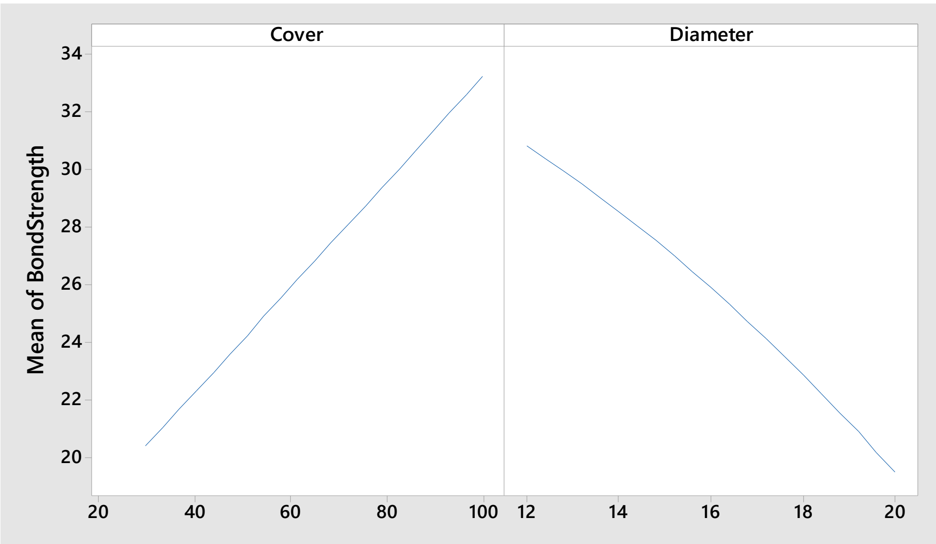


Figure 11: Main effects plot for bond strength, fitted means.

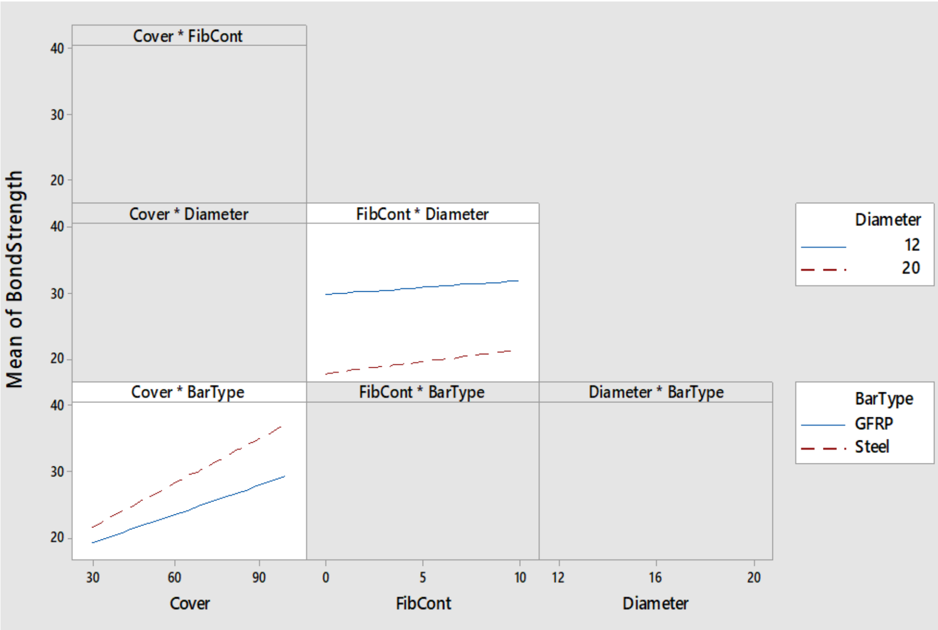


Figure 12: Interaction plot for bond strength fitted means

Two versions of the bond strength equation were generated by using Minitab based on the type of reinforcement, where the only difference is the multiplicative coefficient of concrete cover. Bond strength for GFRP bars and conventional steel bars are given in Equations 2 and 3, respectively.

$$\text{Bond strength} = 25.52 + 0.1435C_c - 0.04685{*}D^2 + 0.01789\ V_f{*}D \qquad (2)$$

$$\text{Bond strength} = 25.52 + 0.2214\ C_c - 0.04685{*}D^2 + 0.01789\ V_f{*}D \qquad (3)$$

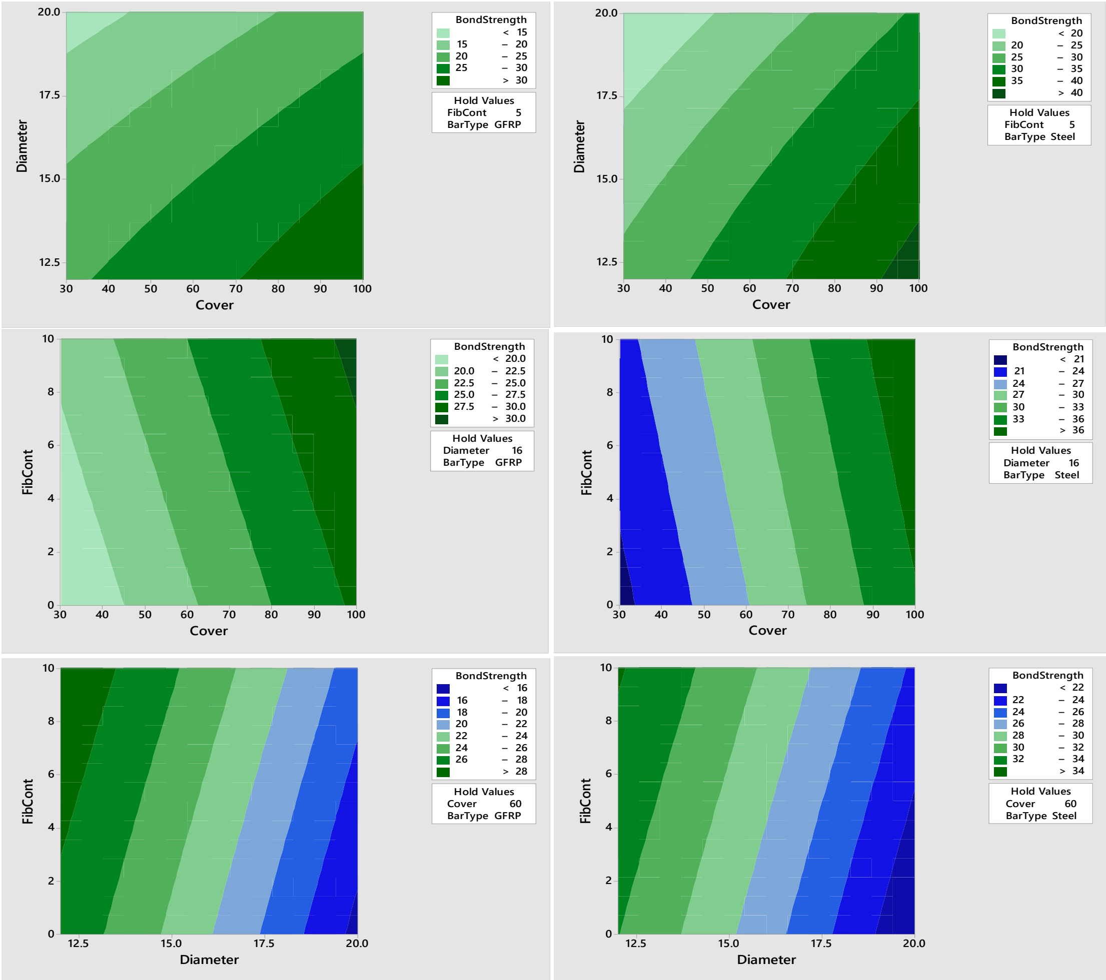
Further, contour plots were generated for both types of reinforcement, GFRP bars and steel bars considering one variable constant each time in Minitab. This type of plotting helps to show how the fitted response relates to two continuous variables using a two-dimensional view in which all points having the same response are connected to produce the contour lines as shown in

Figure 13 (a) and (b), where darker green regions indicate higher bond strength. For instance, in the contour plot for the cover-diameter shown in

Figure 13 (a) where the fibre content of 5 kg/m^3 is held constant, the lowest values of the bond strength are in the top left corner of the plot, which corresponds to the lowest value of concrete cover and the highest value of bar diameter. In the next plot, fibre content and the concrete cover were increased and the bar diameter was constant, increasing the concrete cover significantly increased the bond strength while no noticeable improvement was observed when fibre content was increased from 5 to 10 kg/m^3. The same behaviour was observed when the bar diameter was considered against the fibre content with a constant 60 mm concrete cover (the highest bond strength value was obtained when the concrete cover was 100 mm with 10 kg/m^3 fibre content - top right corner).

Similarly, for 16 mm steel bar shown in

Figure 13 (b), results obtained from variation in bar diameter-concrete cover, concrete cover-fibre content and bar diameter-fibre content indicated that the influence of the fibre content on the bond strength is less important than that of diameter and concrete cover for both types of reinforcement. In the statistical Investigation conducted by Bankir [57] on the bond strength of FRC, the significance of each independent variable on the responses was assessed considering one variable each time. Multilinear regression using ANOVA was applied to investigate the significance of w/c, cement content, and fibres (steel and plastic fibres) [57]. According to the ANOVA results, w/c and cement dosage were found to be statistically significant and the most influential parameter was the cement dosage with effect rate of 33.2% and the then steel and glass fibres with less significance factor of 29% effect rate.



(a) (b)

Figure 13: Contour plots for cubic reinforced with (a) GFRP bars, and (b) steel bars.

5. Conclusions

Pull-out test carried out in this study aimed at understanding and characterising the bond between GFRP bars and concrete with different contents of synthetic fibres considering several factors (concrete cover, bar diameter, and type of reinforcement). Findings obtained from the experimental campaign on the inclusion of synthetic fibres in concrete mixes were presented and discussed. Moreover, the results of the ANOVA analysis conducted based on statistical analysis using Minitab are presented and discussed. Based on the discussion and results presented herein, the following conclusions are drawn:

- The addition of synthetic fibres with the dosages considered in this study did not introduce any significant improvement to concrete compressive strength. However, the inclusion of fibres noticeably increased the tensile strength of concrete by up to 18%.

- The incorporation of synthetic fibres in volume fractions of 0.55 and 1.1% resulted in more ductile behaviour during pull-out tests. Specimens without fibres exhibited brittle failure irrespective of the reinforcement ratio (bar diameter).
- Samples with relatively lower concrete cover but having fibres in the concrete mix showed more ductile behaviour than those in the plain concrete with higher concrete cover. This indicates that the utilisation of synthetic fibres allows for a reduction in the concrete cover.
- Multiple linear regression was conducted on the experimental results obtained from bond strength using Minitab. ANOVA test was utilised to determine the significance of the effect of the parameters considered in this study and their possible interactions on the response variables. The final adopted model considered only the terms and interactions with the highest statistical significance at significance level of 89.34%. Equations for bond strength and contour plots were generated for each type of reinforcement. Results indicated that the influence of the bar diameter and concrete cover on the bond strength are more important than that of fibre content.

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