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NON-METALLIC REINFORCEMENTS WITH DIFFERENT MODULI OF ELASTICITY AND SURFACES FOR CONCRETE STRUCTURES

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Abstract

The use of Fibre Reinforced Polymer (FRP) bars as internal reinforcement for concrete structures is increasing in civil engineering due to their advantageous properties, e.g. being insensitive to electrolytic corrosion. FRP bars have different mechanical and physical properties than traditional steel reinforcement, that makes the interaction between the FRP bars and concrete different to that of steel and concrete. One of the controversial aspects of structural behaviour of RC elements which are reinforced with FRP bars is the bond development. In this paper two experimental studies are presented investigating the bond development of FRP bars. Series 1 aimed to study the effect of the modulus of elasticity of FRP bars on the bond behaviour in concrete. Two types of FRP bars were used with similar properties (same surface profile and diameter), but with different modulus of elasticity. Series 2 meant to study the effect of the surface profile of FRP bars. Three types of GFRP bars were used (same nominal diameter of 16 mm, similar tensile strength and modulus of elasticity), with different surface profiles.

Based on the results it was concluded that both the surface profile and the modulus of elasticity of FRP bars have effect of the bond behaviour in concrete. Bars with higher modulus of elasticity provided higher bond strength values.

Streszczenie

Zastosowanie prętów z włókien sztucznych (FRP) do zbrojenia konstrukcji betonowych w budownictwie rośnie z uwagi na ich korzystne właściwości, w tym np. odporność na korozję elektrolityczną. Właściwości mechaniczne i fizyczne prętów FRP różnią się w stosunku do tradycyjnego zbrojenia ze stali, co sprawia, że współpraca między prętami FRP i betonem różni się od współpracy stali z betonem. Jednym z kontrowersyjnych aspektów pracy elementów żelbetowych, które są zbrojone prętami FRP, jest rozwój przyczepności. W niniejszym artykule przedstawiono dwa badania eksperymentalne badające rozwój przyczepności prętów FRP. Pierwsza seria miała na celu zbadanie wpływu modułu sprężystości prętów FRP na przyczepność w betonie. Zastosowano dwa rodzaje prętów FRP o podobnych właściwościach (tak samo użebrowanych i o tej samej średnicy), ale o innym module sprężystości. Druga seria miała na celu zbadanie wpływu użebrowania prętów FRP. Zastosowano trzy rodzaje prętów GFRP (o tej samej średnicy nominalnej 16 mm, o podobnej wytrzymałości na rozciąganie i modułach sprężystości) o różnych użebrowaniach.

Na podstawie uzyskanych wyników stwierdzono, że zarówno użebrowanie, jak i moduł sprężystości prętów FRP mają wpływ na przyczepność do betonu. Pręty o wyższym module sprężystości zapewniały wyższe wartości przyczepności.

Keywords: **Bond; Bond strength; Concrete strength; FRP internal reinforcement; Modulus of elasticity; Surface profile.**

1. INTRODUCTION

Steel reinforced concrete (RC) is one of the most widely used structural materials in construction. Nevertheless, it is well known that, under certain environmental conditions the corrosion of steel reinforcement can lead to the deterioration or even to the collapse of structural RC elements, requesting expensive repairing and strengthening. This detrimental property of the steel reinforcement directed the interest to alternative reinforcing materials [1–7].

Using FRP material can be one possible way to replace the corrodible steel reinforcement. FRP bars have various advantageous properties, such as high tensile strength and resistance to electrochemical corrosion [8].

To manufacture FRP bars different fibres (glass, carbon, aramid and basalt) are used. Fibres are bound together with diverse resins (e.g., polyester, vinyl ester and epoxy). Mechanical properties as well as the surface profile of FRP bars can be considerably different from that of the conventional steel reinforcement [9–11]. Such non ferrous bars provide excellent resistance to environmental factors such as freeze-thaw cycles, chemical attack, etc. [12].

Tensile strength and elastic modulus of FRP bars are governed mainly by the type of fibre, the volumetric ratio of fibres (usually 60–75 V%) and the angle between the fibres and the longitudinal axis of the bar. Tensile strengths of FRP bars are in the range of 450 to 3 500 N/mm^2, while the Young's moduli are between 35 000 and 580 000 N/mm^2 and the failure strains are in the range of 0.5 to 4.4% [1]. Furthermore, the mechanical and physical properties of FRP bars can be tailor made to fit the best a specific application. The most important difference between FRP and steel bars is that FRP bars have linear elastic behaviour up to failure without any plasticity and considerable release of elastic energy [13].

The bond stress transfer between reinforcement and the surrounding concrete is the basis of the theory of RC [14, 15]. Without a proper transfer of stresses between concrete and bar, RC structures would not be viable [13, 16, 17]. One of the controversial aspects of structural behaviour of RC elements which are reinforced with FRP bars is the bond development. As presented above, FRP bars have different mechanical and physical properties than traditional steel reinforcement, that makes the interaction between the FRP bars and concrete different to the interaction between steel and concrete. Main differences are caused by properties such as: linear elastic behaviour, surface profiles, modulus of elasticity, temperature dependent properties of FRP bars, etc.

The type and geometry of the surface of FRP bars can be considerably different than the surface of traditional ribbed steel bar. Different surface types involve different bond mechanisms and failure modes. While in case of steel bar bond failure happens by crushing the concrete in front of the ribs, this is usually not the case for FRP bars. Bond failure can happen either at the surface of FRP and concrete or in the FRP bar (interlaminar shear between fibres and outer surface) [13].

FRP bars have different modulus of elasticity than that of steel bar which affects the bond stress distribution along the bond length, hence the bond behaviour. Furthermore, modulus of elasticity varies also with the fibre type (e.g. carbon, glass, basalt or aramid) and the ratio of fibre content. Modulus of elasticity can affect the stiffness of the bond, which is the steepness of the ascending part of bond stress slip diagram). Bond stiffness is particularly important in Serviceability Limit State (SLS) design, since crack opening is dependent on the slip value associated with the bond stress level.

This paper presents two experimental series to study the bond behaviour of FRP bars in concrete. In Series 1 the effect of modulus of elasticity of FRP bars is studied, while in Series 2 the effect of surface profile is studied. Due to the different possible bond failure modes, compared to that of steel, the concrete strength influences differently the bond behaviour of FRP bars [17]. Hence, in experimental plan different concrete compositions were included to investigate the effect of studied parameters. Surface profiles of FRP bars can have different effects depending on bond failure mode, thus eccentric pull-out tests were performed as well.

1.1. Bond strength calculation

There are several standards and guidelines [18–21] which propose equations for the calculation of bond strength of FRP bars, additionally, there are few studies which present a modification of these equation or a proposal for simplified equations [22–25]. Furthermore, there are available studies that collect and review the different available equations [25,26].

In this study only the CSA-S806-12 [27] is presented and studied, since both the effect of the surface profile and modulus of elasticity of the FRP bar are taken into consideration. The following equation (Eq. 1) is proposed for bond strength calculation:

$$\tau_{b,max} = \frac{d_{cs}\sqrt{f_c'}}{1.15(k_1k_2k_3k_4k_5)\pi d_b} \quad (1)$$

that takes into account different factors, such as: k_1 – bar location factor, k_2 – concrete density factor, k_3 – bar size factor, k_4 – bar fibre factor, k_5 – bar surface profile factor, d_{cs} – the smaller of the distance from the closest concrete surface to the centre of the bar being developed; or two-thirds of the centre-to-centre spacing of the bars being developed (it shall not be greater than $2.5d_b$), f'_c – specified compressive strength of concrete (shall not be taken to be greater than 25 MPa), d_b – nominal diameter of FRP. The recommended values for k_4 parameter are 1.0 for CFRP and GFRP and 1.25 for AFRP bars. However, no values have been proposed for BFRP bars yet. The proposed values for k_5 parameter are 1.0 for surface-roughened or sand-coated surfaces; 1.05 for spiral pattern surfaces; 1.0 for braided surfaces; 1.05 for ribbed surfaces; 1.80 for indented surfaces.

Based on authors' previous experimental studies [28] and available data in literature from various researchers [17, 29–31], the proposed values seem to be not totally appropriate in all cases. Present study is directed to verify the proposed values of k_4 and k_5 parameters, based on the experimental results, as well as to give recommendation of new values.

2. EXPERIMENTAL PROGRAMME

The experimental program was designed to study the effects of the modulus of elasticity of FRP bars (Series 1) and their surface profiles (Series 2) on the bond behaviour in concrete.

Pull-out test was chosen to compare the bond behaviour of different FRP bars in various concrete compositions. Although, the stress condition developed in concrete during pull-out test can differ from that developed in RC elements, pull-out test is still a reliable method to study and compare the effect of diverse factors on bond behaviour, owing to its simplicity and ease of application. Pull-out test was design according to CSA-S806 [27], however, the bond length was modified to 5Ø (Ø – bar diameter) so that comparison can be done to available data from literature.

In Series 1 two types of sand coated 9.5 mm diameter FRP bars with different fibre types (carbon and glass) were employed. Manufacturer's specification of the GFRP and CFRP bars indicated a minimum guaranteed tensile strength of 880 MPa and 1356 MPa as well as a nominal tensile modulus of elasticity of 42.5 GPa and 127 GPa, respectively [32]. Four different concrete compositions were considered and were referred to using different symbols for the traditional concrete (C1, C2 and C3) and for the self-compacting one (S1). The average values and the corresponding standard deviations of the concrete compressive strength and splitting tensile strength on the day of testing (28 days) is presented in Table 1. The concrete strength results were obtained by testing three nominally identical specimens 150 mm side length cubes for compressive and 150 mm cylinders (both in diameter and height) for splitting tensile strength, respectively.

Table 1.
Mechanical characteristics of concrete mixes (MPa)

Symbol	Compressive str.		Splitting tensile str.	
	Avg.	St.D.	Avg.	St.D.
C1	39.14	1.26	2.91	0.36
C2	48.80	1.10	3.40	0.33
C3	54.21	1.50	3.72	0.19
S1	67.16	3.57	4.13	0.08

In Series 2, three types of GFRP bars with different surface profiles but having the same nominal diameter (16 mm), a characteristic tensile strength over 1000 MPa and a modulus of elasticity between 55–60 GPa were used [33]. The investigated profiles included sand coated finishing and two types of indented surfaces. Type 1 indented bars have 4.86 mm FRP bar lug width, while the indentation is 3.58 mm wide and 0.86 mm deep, respectively. In case of Type 2 bar, corresponding values are 4.00, 3.07 and 1.20 mm, respectively. The dimensions of the bars were measured and represented as an average of 6 individual measurements. Type 2 bars are made by filling a polypropylene conduit pipe with glass fibres and a vinyl ester resin, thus the surface of the FRP bar is the above mentioned polypropylene material, while in case of Type 1 bars the surface is the FRP bar itself (vinyl ester resin and fibres). C2 concrete composition was used to prepare the specimens for this Series 2.

The specimens consisted of a concrete cube, 150 mm side length, with a single FRP bar embedded vertically along a central axis, while in case of eccentric pull-out specimens, FRP bars were placed parallel to central axis, as that the clear concrete cover to the closest edge is Ø (Ø – bar diameter). Metallic cubic moulds were used to prepare the pull-out specimens. The bars were vertically placed in the moulds as that

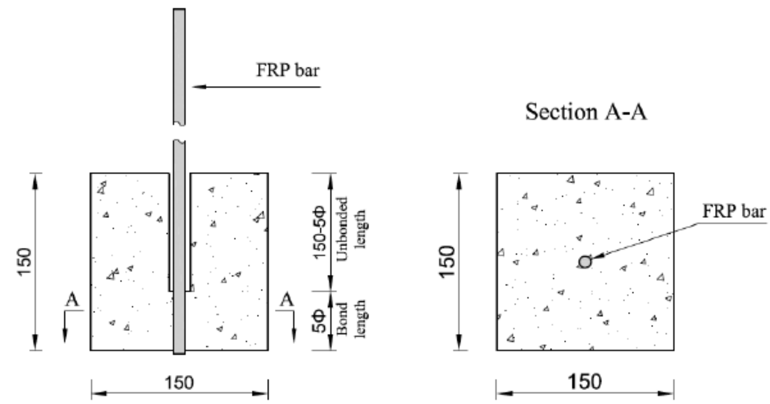

Figure 1.
Schematic representation of the pull-out specimen

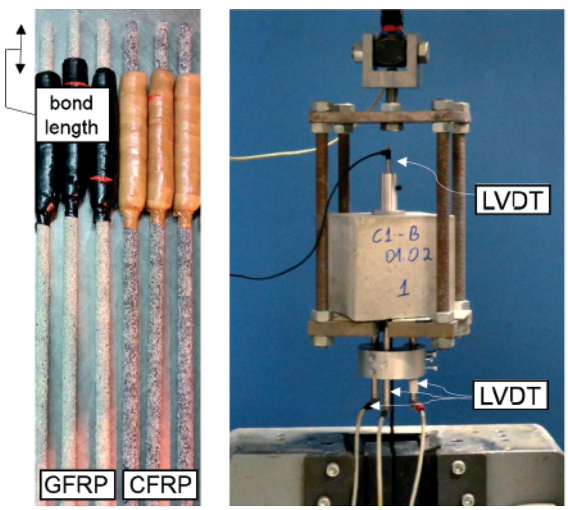

Figure 2.
Left: CFRP and GFRP sand coated bars prepared with 5Ø (Ø – bar diameter) embedment length. Right: pull-out test setup

the bond length of bars was in the lower part of the moulds. Concrete was poured with the FRP bars in position inside the mould. After concreting, the specimens were kept in the moulds in laboratory ambient condition for one day, then de-moulded, marked and placed under water for 6 days. After removing from the water specimens were kept under laboratory ambient conditions until testing. A schematic representation of pull-out specimens is presented in Fig. 1.

In Fig. 2 (left) the bars are presented with the prepared embedment (bond) length, being five times the bar diameter (5Ø) in all cases. In Fig. 2 (right) a photo of the pull-out test setup is visible. The FRP bars are placed into a metal frame and gripped into testing machine (lower part of the pictures). This part is considered as the loaded end of the test specimen, the relative displacement between the FRP bar and concrete is measured with three Linear Variable Differential Transducers (LVDTs). At the other end, which is usually referred to as free end, the slip is measured by one LVDT.

The pull-out tests were performed by using a servo-hydraulic testing machine with a capacity of 600 kN. Displacement control was selected for testing to be able to capture the post-peak behaviour. The load was applied at a rate of 1 mm/min (displacement controlled test method). An automatic data acquisition system was used to record the measurements of LVDTs and the electronic load cell. Three nominally identical specimens, for each configuration, were tested [28].

3. RESULTS AND DISCUSSION

In this section the experimental results of Series 1 and Series 2 are used to discuss the effects of the modulus of elasticity of FRP bars and their surface profiles on the bond behaviour in concrete, respectively. The outcomes are summarized in Table 2 and Table 3 for Series 1 and in Table 5 for Series 2, including the calculated values of bond strength, loaded and free end slips at maximum bond stress as well as their average (Avg.), standard deviations (St.D.) and coefficient of variations (C.O.V.). In particular, the bond strength values ($\tau_{b,max}$) are calculated by dividing the maximum load (F_{ult}) by the shear surface (Eq. 2), considering a uniform bond stress distribution along the bond length (l_b) of the FRP bars. Finally, the bond stiffness, reported in the last column of each table, was calculated as the inclination of the ascending branch of the bond stress-loaded end slip diagram (which was assumed to be linear).

Table 2.
Pull-out test results, CFRP sand coated #3 (9.52 mm diameter) bars

Symbol		Bond strength				Loaded end slip				Free end slip				Bond stiffness
		$\tau_{b,max}$	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Avg.
		(MPa)	(MPa)	(MPa)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(N/mm^3)
	1	19.82				0.261				0.130				
C1	2	20.25	19.31	1.27	6.5	0.196	0.234	0.034	14.5	0.112	0.100	0.038	38.2	82.61
	3	17.86				0.245				0.057				
	1	14.30				0.163				0.038				
C2	2	17.29	15.57	1.54	9.9	0.213	0.259	0.125	48.1	0.054	0.051	0.011	22.5	60.18
	3	15.14				0.400				0.060				
C3	1	12.60	15.95	4.74	29.7	0.291	0.245	0.065	26.5	0.067	0.065	0.004	5.5	65.15
	2	19.30				0.199				0.062				
	1	16.47				0.358				0.036				
S1	2	15.25	16.30	0.97	6.0	0.254	0.260	0.095	36.4	0.039	0.038	0.002	5.4	62.58
	3	17.18				0.169				0.040				

Notes: [a] Slip corresponding to bond strength

Table 3.
Pull-out test results, GFRP sand coated #3 (9.52 mm diameter) bars

Symbol		Bond strength				Loaded end slip				Free end slip				Bond stiffness
		$\tau_{b,max}$	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Avg.
		(MPa)	(MPa)	(MPa)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(N/mm^3)
	1	12.87				0.397				0.038				
C1	2	18.85	14.11	4.26	30.2	0.566	0.406	0.156	38.3	0.134	0.075	0.052	69.5	34.76
	3	10.60				0.255				0.052				
	1	9.54				0.255				0.040				
C2	2	8.30	9.16	0.74	8.1	0.188	0.256	0.069	27.0	0.022	0.026	0.012	48.0	35.74
	3	9.63				0.326				0.016				
C3	1	8.21	13.03	6.82	52.3	0.238	0.374	0.192	51.4	0.034	0.054	0.028	52.4	34.87
	2	17.86				0.509				0.074				
S1	1	9.24	10.97	2.44	22.3	0.297	0.297	0.001	0.2	0.044	0.057	0.018	32.3	36.98
	2	12.70				0.296				0.070				

Notes: [a] Slip corresponding to bond strength

$$\tau_{b,max} = \frac{F_{ult}}{\pi * \emptyset * l_b} \qquad (2)$$

3.1. Effect of modulus of elasticity

Owing to the size of pull-out specimen, the centric placement and the size of the diameter of the FRP bars, bond failure always happened by "pull-out" of the FRP bar, no splitting cracks were observed. The typical failure, brittle and at low slip values, occurred by interlaminar shear within the bar at the interface between the fibres and the external sand coating. However, when higher strength concrete compositions (C3 and S1) is used in combination with bars with lower modulus of elasticity (GFRP), bond failure happened by gradually pulling the bar out of the concrete block, yielding considerably higher slip values.

In Fig. 3 it can be observed that CFRP bars have higher bond strength regardless the concrete mix or type. The results of analysis of variance (ANOVA) are listed in Table 4, it can be observed that the significance level of what the bond strength of CFRP bars are higher than those of GFRP bars varies between 3.9 and 29.7%. However, it must be noted that while in case of CFRP bars the COVs of bond strengths are acceptably low, this is not the case when GFRP bars are considered.

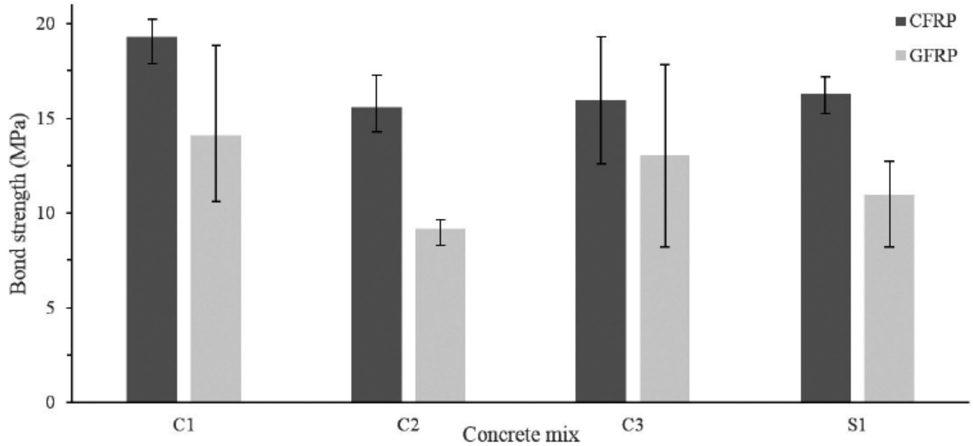

Figure 3.
Effect of modulus of elasticity of FRP bars on bond strength in concrete

Table 4.
Analysis of variance (ANOVA) between bond strength results of CFRP and GFRP bars

Concrete mix	Significance level (%)
C1	11.2
C2	3.9
C3	29.7
S1	8.3

Higher bond strength values associated with higher modulus of elasticity can be explained by the fact that higher modulus involves less slip at the loaded end, consequently less damage at the bond surface is expected, which can result in higher average bond strength.

The experimental data (Table 2 and Table 3) shows that the bond strength of FRP bars is visibly affected by the type of fibre (modulus of elasticity), when CFRP and GFRP bars are considered. It can therefore be inferred that using a single value for the bar fibre factor (k_4) to calculate the bond strength of CFRP and GFRP bars could yield unreliable results. In fact, the current CSA-S806-12 [27] prediction would be overly conservative for CFRP bars. Using the least square method, curve fitting of parameter k_4 was performed on the presented experimental data. A value of 0.85 is recommended to be used for k_4 when CFRP bars are considered.

Furthermore it can be noted that the bond stiffness of CFRP bars are always higher (about double) than in case of GFRP bars (Table 2 and Table 3).

Table 5.
Pull-out test results for Series 2

Symbol		Bond strength				Loaded end slip				Free end slip				Bond stiffness
		$\tau_{b,max}$	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Slip[a]	Avg.	St.D.	C.O.V.	Avg.
		(MPa)	(MPa)	(MPa)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(N/mm^3)
Sand coated	1	23.24				0.718				0.266				
	2	22.36	23.01	0.57	2.5	0.545	0.638	0.088	13.7	0.256	0.247	0.024	9.8	36.05
	3	23.43				0.652				0.220				
Indented type 1	1	20.02				0.581				0.317				
	2	17.69	18.91	1.17	6.2	0.473	0.606	0.148	24.4	0.252	0.319	0.068	21.3	31.19
	3	19.03				0.765				0.388				
Indented type 2	1	11.21				1.138				0.957				
	2	11.84	12.25	1.29	10.5	1.138	1.198	0.103	8.6	0.957	0.917	0.069	7.5	10.23
	3	13.69				1.316				0.838				

Notes: [a] Slip corresponding to bond strength

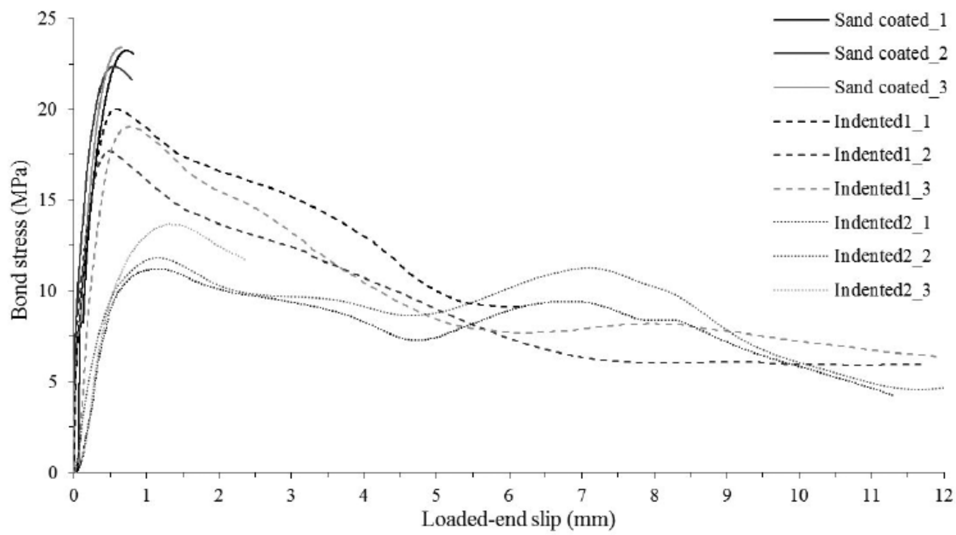

Figure 4.
Bond stress-slip relationships of GFRP bars with different surface profiles

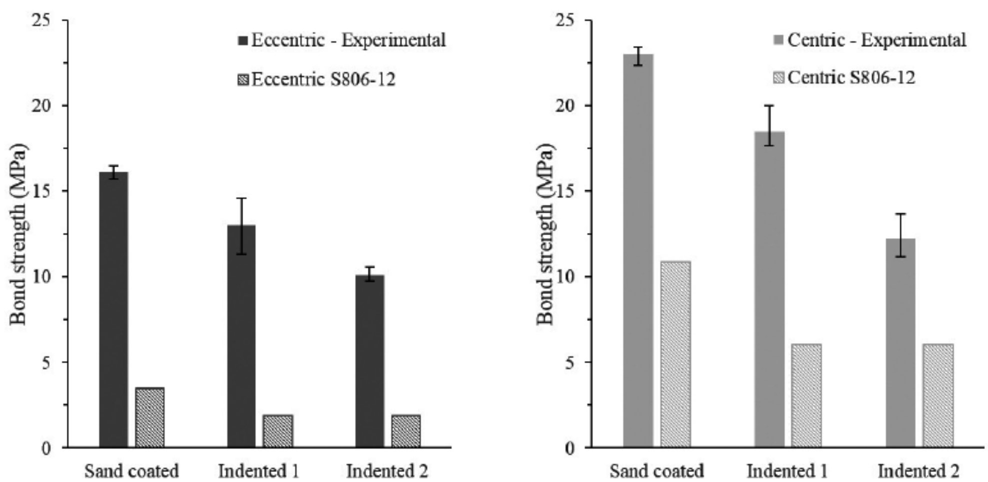

Figure 5.
Effect of surface profile of GFRP bars on bond strength. Eccentricity (left) and centric (right) pull-out test

3.2. Effect of surface profile

For better visualization of the bond characteristics of GFRP bars with different surface profiles, results are plotted in Fig. 4 in terms of bond stress-slip relationships. It is visible in the figure (Fig. 4) how the different surface types affect the bond behaviour of FRP bars in concrete. The highest bond strength values are reached in case of sand coated bars, as well as the highest bond stiffness (steepness of curves) values.

In case of bars with indented surfaces the different bond behaviour can be explained by the different surface material, since the CLR (Concrete Lug Ratio) is about the same (approx. 0.43) for both types of indented surfaces. CLR was first defined in [29] as the ratio of concrete lug width (width of indentation of the bar) and the sum of lug and indentation widths.

Additionally to the results of centric pull-out tests (presented in Table 5) eccentric results are presented as well in Fig. 5. The bond stiffness of GFRP bars varies depending on the surface profile, as well.

Bond failure happened through pull-out of the FRP bar in case of centrally placed bars (Fig. 5 right), however, when the bars were placed eccentrically, splitting failure was observed (Fig. 5 left). Moreover, bond failure mode was significantly affected by the surface profile: sand coated bars failed in a brittle manner at low slip values, while indented bars failed in a gradual manner. The surface of the FRP bars was sheared off, in case of sand coated bars, while the concrete failed in case of indented bars (owing to the geometry of the FRP indentation). Both in case of Type 1 and Type 2 bars the lug widths of FRP bars are larger than the width of indentation, which made the concrete to fail earlier than the lugs of the FRP bars could be sheared off. The concrete was sheared off at the level of bond surface.

In terms of bond strength, highest results were achieved by sand coated bars (Fig. 5). It can be noticed that the bond strength results of the two different indented bars are considerably different, even though they both belong to the same surface category, when it comes to define the surface factor (k_5) according to CSA-S806-12 [27]. This highlights that surface factors cannot be based solely on the current surface categories proposed in CSA-S806-12 and a standardized methodology along the line of CAN/CSA-S6-06 [20] should be introduced to estimate k_5. However, there should be no limitation about the bond performance of FRP bars compared to that of steel.

4. CONCLUSIONS

This paper presents two experimental series performed to study the bond behaviour of Fibre Reinforced Polymer (FRP) bars in concrete, focusing on the effect of two factors: modulus of elasticity and surface profiles of FRP bars. Various concrete compositions and FRP bars have been used in this study. Based on the test results the following conclusions can be drawn.

Effect of modulus of elasticity on bond of FRP

- Bond strength is always higher of the bars with higher modulus of elasticity (CFRP). It highlights the importance of the revision of factors proposed to take into account the effect of fibre type of FRP bars (k_4 in CSA S806-12)
- Higher bond strength values can be explained by the fact that higher modulus of elasticity involves less slip at the loaded end of the bond length, hence less damage at the bond surface is expected
- Values for fibre type factor (k_4) of CFRP bars should be lower than for GFRP bars. A value of 0.85 is proposed to be used for k_4 when CFRP bars are considered.
- Bond stiffness is also affected by the modulus of elasticity of FRP bars (E_{FRP}), it increases with the increase of E_{FRP}.

Effect of surface profile on bond of FRP

- The bond strength of sand coated GFRP bars is higher than those of indented surfaces. Furthermore, bond strength was considerably different in case of two indented surface profiles. This leads to the conclusion that generalization of surface factors taking into consideration solely the surface type is not suitable. Subgroups within the same surface types are necessary, or a standardized test method should be defined to be used for determination of such a parameter by experimental testing (e.g., k_5 in CSA S806-12).
- The slope of the ascending branch (bond stiffness) of the bond stress-slip relationships varies when similar FRP bars with different surface profiles are used. However, the variation within the same surface type (with different finishing materials) can be even larger than among different surface types.
- Failure mode is affected by the surface profile. In case of sand coated bars the most common failure mode is through a sudden shearing off of the whole FRP surface, however, in case of indented bars the bond failure happens by gradually pulling out the FRP bar, resulting in high slip values.

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