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RESEARCH ARTICLE

Effect of Fibers on Bond Performance of Lightweight Reinforced Concrete

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Abstract

Integrity of a reinforced concrete member, or structure composed of such members cannot be ensured if there is inadequate bond between reinforcement and concrete around it. In current experimental work, effect on bond performance of lightweight concrete is discussed after addition of steel fibers. For the purpose, modified Pull-out specimens were tested at 28 days. Hooked end steel fibers having length of 35 mm and 0.5 mm in diameter, developing aspect ratio of 70 were used. Fiber contents of 0, 20 and 40 kg/m^3 were added to the lightweight concrete mixes. Besides bond behavior, results of fresh and hardened properties are also presented. Results indicate higher tensile strengths and pull-out loads for higher fiber contents. The fresh concrete density and compressive strength of mixes reduced, whereas air-content values increased with higher fiber content.

Keywords

Bond · Lightweight · Steel fibers · Pull-out

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1 Introduction

In construction industry lightweight concrete and fiber reinforced concrete are being used for many years. The former is known for brittle nature, light in weight and low thermal conductivity properties. It also offers better workability when compared to the normal weight concrete for the same slump value [1] These properties are affected by addition of discrete fibers; the effect being variable with the type and volume fraction of fibers [2].

Use of steel fibers in structural concrete is particularly encouraged in members of structural system where geometrical constraints restrict use of traditional reinforcement. Guecna and Serna [3] suggest fiber reinforced concrete as a possible solution to shear failure problem in hollow core slabs where use of stirrups is challenging. High performance fiber reinforced cementitious composites having hardening behavior perform better as a strengthening material at serviceability and ultimate limits when compared to other strengthening techniques [4].

Type of performance required from particular structural element usually governs the selection of fiber type and fiber content. Different fiber types, glass, steel, polypropylene, are being commercially produced and used for various applications. Since past few decades most of the research in concrete industry has been done on studying properties and behavior of different concretes, be it normal, high strength or lightweight, after fiber inclusion. For structural concrete used in load carrying members, steel fibers of different shapes and geometry are preferred over other fiber types due to their improved post cracking performance in flexure.

Current experimental work encompasses the effect of steel fiber addition on bond strength of Lightweight Fiber Reinforced Concrete (LWFC); in addition to this, effect on other mechanical properties is also discussed. Integrity of a structural element is not ensured in the absence of proper bond between the reinforcement and the concrete surrounding it. It is now established, that the bond strength is influenced by different factors, categorized by structural, geometrical and material properties. ACI 408 [5] provides a good overview of these parameters. Many of the studies [6–10] have discussed some of these parameters and their influence on the interaction of reinforcement and concrete of different types, in most cases normal weight concrete was used, but little information is available on bond behavior of LWFC.

2 Experimental Program

2.1 Materials

Expanded clay (Commercial name Liapor 6.5) , round in shape (Fig. 1), having particle density of 1190 kg/m^3 and particle size ranging from 2 to 10 mm was used as a coarse aggregate. Aggregates had water absorption of 14% and was found within the specified range provided by the supplier of material. Natural sand having particle size in the range of 0 - 2 mm and particle density of 2570 kg/m^3 was used as a fine aggregate, whereas, Ordinary Portland Cement (CEM-1/ 42.5N) was selected as binding material.

Fibrous mixes incorporated steel fibers 35 mm in length and 0.5 mm in diameter having aspect ratio (l/d) of 70 . For controlling workability, Polycarboxylate Ether-based superplasticizer was used. 10 mm bar size having yield and ultimate strength of 500 and 600 MPa respectively was used in bond specimens. Detail of mix design used in experimental work is tabulated in Table 1.

Fig. 1. Expanded clay used as coarse aggregate

Tab. 1. Mix design for Lightweight Concrete

Content	Quantity
Cement (kg/m^3)	360
Fine aggregate (kg/m^3)	772
Coarse aggregate (kg/m^3)	472
Total Water (kg/m^3)	204
Superplasticizer (%*)	0.5
Effective w/c	0.35

* Percent weight of cement

2.2 Specimens

For bond strength evaluation through Pull-out test, RILEM guidelines [11] suggest 200 x 200 x 200 mm^3 size of the specimen for the size of reinforcement used in current experimental work. Thus leaving concrete cover of 95 mm around reinforcement, which is not common in routine construction practice. For this reason modified RILEM pull-out specimens were used. Fig. 2 shows the details of specimen used. Besides Pull-out specimens, beam and cylinders were also cast to determine the effect of fibers on other mechanical properties. Bond specimens were numbered as LWFC-N1-N2, where LWFC represents lightweight fiber reinforced concrete and N1, N2 denote fiber content in kg/m^{3}and specimen number respectively. Parameters like diameter of the bar ($d_b = 10$ mm) and bond length ($L_d = 5d_b$) were held constant throughout the testing.

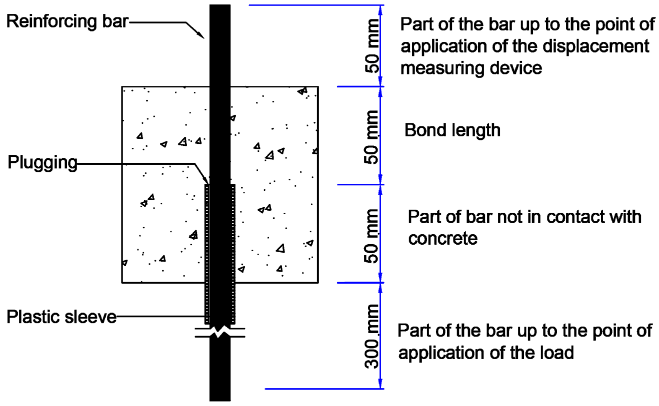

Fig. 2. Pull-out specimen details

2.3 Test set-up

Bond tests were performed using the 600 kN displacement controlled testing machine. Specimens were loaded at displacement rate of 0.005 mm/s; compared to the load controlled, this method produces better post-cracking patterns that help in understanding well fiber performance. Displacement of pull-out bar was recorded using six LVDTs, three on loaded side of specimen and three on the free side were attached (Fig. 3). However because of the noticeable local disturbance during loading, data from free-end LVDTs only is used in the analysis.

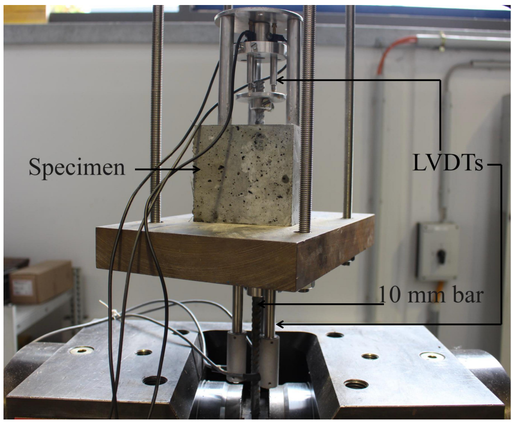

Fig. 3. Specimen ready for Pull-out test

3 Results

3.1 Fresh concrete properties

Fresh concrete density for all mixes was determined using 0.005 m^3 cylindrical mold. The mold was filled in two layers, each layer being externally vibrated at frequency of 115 Hz. It was observed that mix with higher fiber content attained the lowest concrete density while those without fibers had the highest (Fig. 4). Reason for reduced density is increased air content. With increasing fiber dosage matrix could not compact fully, thus creating air voids. ASTM C-138 [12] procedure was adopted to find out the air content.

Effort required for working with fiber reinforced concrete is reduced when lightweight aggregate is used instead of normal weight aggregate. Due to their lower density, LWFC having even low slump values can attain sufficient workability, which is comparable to high slump normal weight fiber reinforced concrete. In current experimental work slump cone method was used to determine the workability of both types of concrete i.e. lightweight and LWFC. Following the guidelines of ACI [13], target slump value for lightweight concrete was chosen as 17 cm so that the final slump for LWFC in the range of 2 to 10 cm could be attained. Fig. 4 shows the effect of fiber addition on workability in terms of slump. Even for lower slump values, LWFC was found easy to handle because of round shape of coarse aggregate and also because of their lower density.

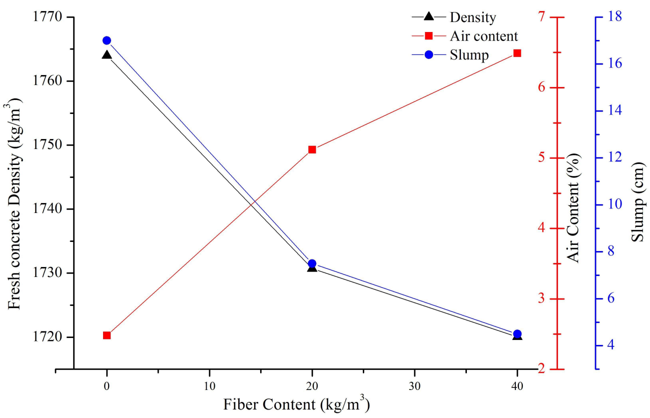

Fig. 4. Effect of fibers on fresh concrete properties

3.2 Hardened concrete properties

28-days compressive strength for all mixes was determined using ASTM C-39 [14] procedure. Cylinders (100 mm dia, 200 mm height) were kept in water for 7 days and later were placed in a controlled environment, where relative humidity and temperature were maintained at 65% and 20°C respectively. Pressure rate of 0.25 MPa/sec was maintained throughout the test. Compression test results indicate decreasing strength trend with increasing fiber content. Although specimens with 40 kg/m^3 fiber content attended higher strength than those having 20 kg/m^3 fiber volume, however, in general, all the specimens with fibers had lower compressive strength when compared with specimens without fibers. Difference in compressive strength results was not significant, for example in extreme case there was a variation of only 4 MPa, which can sometimes occur to concrete of the same batch.

Split cylinder tests on 100 mm by 200 mm cylinders and flexural tests on beams (150 mm x 150 mm x 550 mm) were performed using ASTM C496 and ASTM C1609 [15, 16] respectively to assess the tensile capacity and flexural performance. Although cylindrical specimens with fibers developed failure crack at much lower loads, they kept on absorbing the energy as the fibers continued resisting crack propagation. The values in Fig. 5 for split cylinder tensile strength are not the ones noted at the first crack but represent the maximum values recorded by the testing machine for LWFC specimens. Tensile strength, when judged from modulus of rupture values at first crack, shows percent increase of 25.6 and 26.5 for specimens LWFC-20 and LWFC-40 respectively. Previous study by Ashour et al. [17] on high strength fiber reinforced cement concrete reported an increase of 10 to 20% in modulus of rupture values after fiber addition.

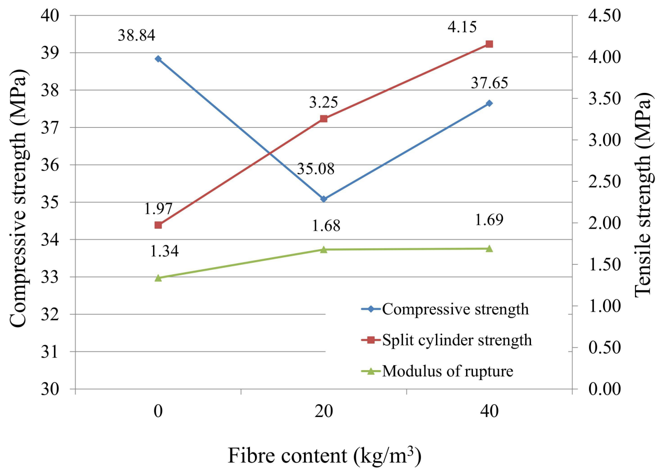

Fig. 5. Effect of fibers on hardened concrete properties

In terms of flexural performance, all beams failed in the maximum moment region (Fig. 6). Specimens with higher fiber content attained higher first cracking load i.e. an increase of 26% was observed in modulus of rupture values for both 20 and 40 kg/m^3 fiber contents. Since post cracking behavior under load is greatly influenced by fiber content [18], therefore significant improvement was noted in post cracking performance of specimens with fibers, these specimens attained higher peak loads and an increase in peak strength up to 62% was observed for specimens with fiber dosages of 40 kg/m^3.

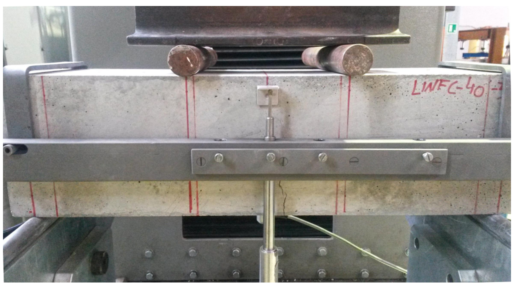

Fig. 6. Failure crack propagation in maximum moment area during four point bending test

3.3 Bond behavior of specimens

All Pull-out specimens failed by splitting of concrete (Fig. 7), crack resistance offered by aggregates in specimens without fibers was of no appreciable magnitude. On slight higher loads aggregates crushed due to their lower density and lower grain strength - around 9 MPa

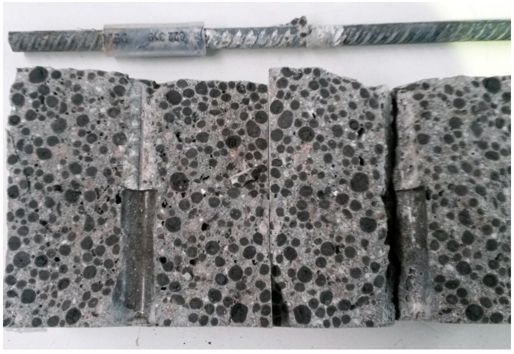

Fig. 7. Specimen (LWFC-0-1) overview after Pull-out test

Interesting to note is that the effect of increase in modulus of rupture value was not observed in these tests as the first cracking load for all the pull-out specimens was around 12 kN. From which it can be concluded that fibers did not add to the tensile strength of concrete before first crack. This is in agreement with the previous reports by Balauru & Shah [19, 20]. Specimens with 20 kg/m^3 fiber content had an average ultimate bond strength value of 12 MPa which is only 2% higher than specimens without fibers. Whereas 28% increase was observed in ultimate bond strength of specimens with 40 kg/m^3 fiber content. This improvement in performance can be attributed to the better confinement to concrete by fibers and increasing resistance to crack propagation, as the quantity of fibers is increased. Table 2 and Fig. 8 present test results of all the pull-out specimens

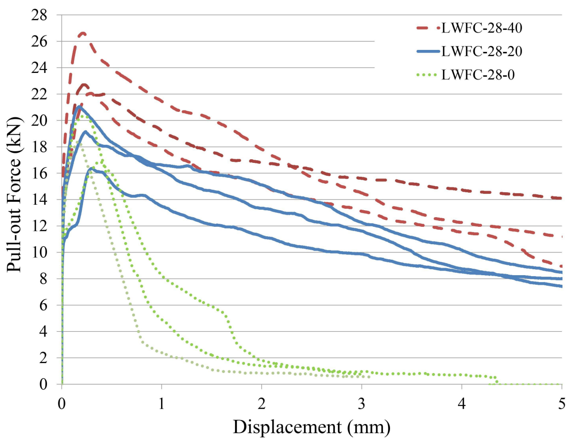

Fig. 8. Load v/s Displacement curves of Pull-out specimens

The well-known descriptive equations (1), (2) and (3) by Orangun et al., Zuo & Darwin and ACI 408 [3] respectively, are used for prediction of bond strength of current specimens. These equations are:

$$\frac{u_c}{\sqrt{f_c'}} = 0.10 + 0.25\frac{c_{\min}}{d_b} + 4.15\frac{d_b}{l_d} \qquad (1)$$

$$\frac{T_c}{f_c'^{1/4}} = \frac{A_b f_s}{f_c'^{1/4}} = = [1.43 l_d (C_{min} + 0.5 d_b) + 56.2 A_b]\left(0.1\frac{C_{max}}{C_{min}} + 0.9\right) \qquad (2)$$

$$\frac{T_c}{f_c'^{1/4}} = \frac{A_b f_s}{f_c'^{1/4}} = = [1.43 l_d (C_{min} + 0.5 d_b) + 57.4 A_b]\left(0.1\frac{C_{max}}{C_{min}} + 0.9\right) \qquad (3)$$

Since these descriptive equations do not consider the effect of fibers, hence it can be seen in Fig. 9 that the ultimate bond resistance is underestimated by these expressions for LWFC-40 specimens.

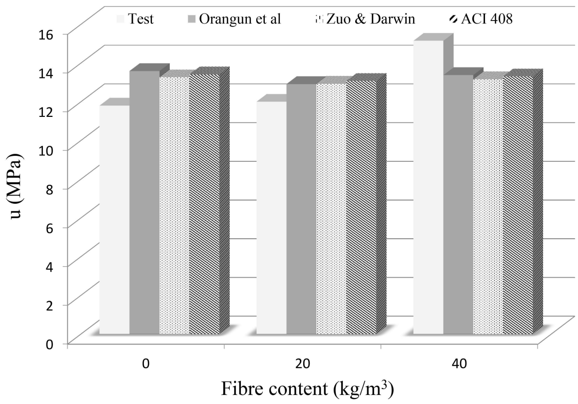

Fig. 9. Bond strength of specimens & prediction by different equations

The trend in the graph shows that as fiber dosage increases to 20 kg/m^3, bond resistance reaches to a comparable value of normal weight concrete and surpasses the performance of normal strength concrete for 40 kg/m^3 fiber content.

Based on regression analysis results (Fig. 10) performed on test to prediction by Eq. (3) ratio and fiber content, factor "x" is suggested to be incorporated in ACI 408 eqution to acknowledge the contribution of fibers in enhancement of bond capacity of fiber reinforced concrete.

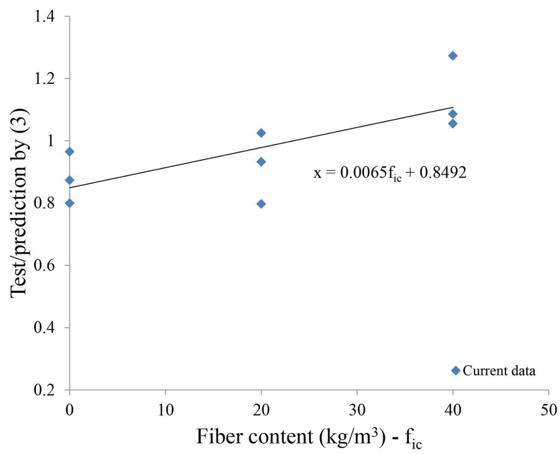

Fig. 10. Relation between "x" and fiber content

According to ACI 408

Tab. 2. Pull-out test results

Specimen	Fiber content (Kg/m^3)	Ultimate pull-out load (kN)	Ultimate bond strength (MPa)
LWFC-00-1	0	20.33	12.94
LWFC-00-2	0	16.85	10.73
LWFC-00-3	0	18.41	11.72
LWFC-20-1	20	19.15	12.19
LWFC-20-2	20	16.37	10.42
LWFC-20-3	20	21.05	13.40
LWFC-40-1	40	26.62	16.94
LWFC-40-2	40	22.70	14.45
LWFC-40-3	40	22.06	14.04

$$\frac{T_c}{f_c'^{1/4}} = \frac{A_b f_s}{f_c'^{1/4}} =$$
$$= [1.43 l_d (C_{min} + 0.5 d_b) + 57.4 A_b] \left(0.1 \frac{C_{max}}{C_{min}} + 0.9\right)$$

Dividing by circumferential area $\pi l_d d_b$

$$\frac{u_c}{f_c'^{1/4}} = \frac{[1.43 l_d (C_{min} + 0.5 d_b) + 57.4 A_b] \left(0.1 \frac{C_{max}}{C_{min}} + 0.9\right)}{\pi l_d d_b}$$

For current experimental work $C_{\max} = C_{\min} = C$

$$\frac{u_c}{f_c'^{1/4}} = \frac{[1.43 l_d (C + 0.5 d_b) + 57.4 A_b]}{\pi l_d d_b}$$

Introducing the adjusted multiplier "x" from regression analysis to above equation, the equation for estimating bond strength of lightweight or lightweight fiber reinforced concrete is suggested as

$$\frac{u_c}{f_c'^{\frac{1}{4}}} = x \frac{[1.43 l_d (C + 0.5 d_b) + 57.4 A_b]}{\pi l_d d_b} \tag{4}$$

Where $x = 0.005 f_{ic} + 0.8$

f_{ic} = Steel fiber content in kg/m^3

Bond strength calculated using Eq. (1) is compared in Fig. 11 with the previously mentioned equations, it also shows test to prediction ratios for all these equations. For the current range of steel fiber content, proposed equation presents better bond strength prediction. This suggests that a factor involving contribution of fiber content be incorporated in equations for bond strength calculations of concretes that are reinforced with fibers.

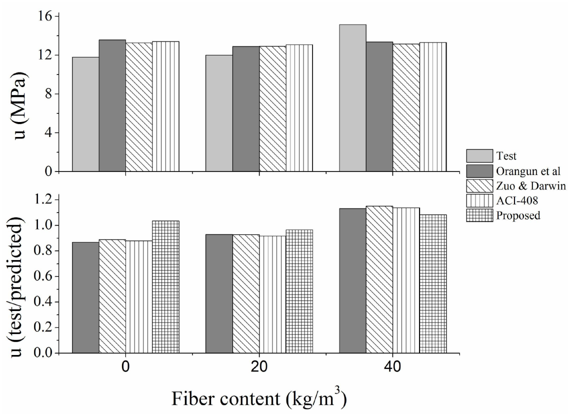

Fig. 11. Test to prediction ratios of bond equations

4 Conclusion

Addition of steel fibers in lightweight concrete proved to be advantageous for most of its properties. Lower weight and round shape of coarse aggregate helped in minimizing the handling (workability) issue, which is a common problem in fiber reinforced concretes.

Although compressive strength decreased slightly for higher fiber content, tensile strength calculated from modulus of rupture value increased. More experimental work is needed to understand the effect of fiber addition to tensile capacity of LWFC before cracking, because the impact of improvement in modulus of rupture value was not observed in pull-out test results for current experimental work.

Splitting failure was seen in all the pull-out specimens. Ultimate bond strength of lightweight concrete increased with the addition of fiber content. It is believed that fibers tend to increase ultimate bond strength through confinement mechanism. An increase up to 28% was observed with 40 kg/m^3 fiber content. It is recommended that the contribution of fibers, in enhancing the ultimate bond strength be acknowledged, and a factor incorporating fiber content be considered in design expressions.

More research data, covering different bond lengths, confinement conditions and reinforcement sizes is needed for evaluation of bond strength of lightweight fiber reinforced concrete. Such data would also help in development and refinement of numerical model that could be used for predicting crack pattern and bond capacity of LWFC.

Notations

A_b = Area of reinforcement
C_{max} = Maximum concrete cover
d_b = Reinforcing bar diameter
f_c' = 28-days compressive strength
f_s = Stress in reinforcing bar
l_d = Bond length/Development length
T_c = Bond force

u	= ultimate bond strength
P	= Applied load in flexure test
γ	= Fresh concrete density
Δ	= Beam deflection

References

1 **Neville AM**, *Properties of Concrete*, Trans-Antlantic; England, 2011.

2 **Mehta PK, Monteiro PJM**, *Concrete: Microstructure, Properties and Materials*, McGraw-Hill; New York, 2013.

3 **Cuenca E, Serna P**, *Failure modes and shear design of prestressed hollow core slabs made of fiber-reinforced concrete*, Composites: Part B, **45**(1), (2013), 952–964, DOI 10.1016/j.compositesb.2012.06.005.

4 **Martinola G, Meda A, Plizzari GA, Rinaldi Z**, *An application of high performance fiber reinforced cementitious composites for R/C beams strengthening*, In: Fracture Mechanics of Concrete and Concrete Structures; Cantania, Italy, 2007.

5 **ACI Committee 408**, *Bond and Development of Straight Reinforcing Bars in Tension*, American Concrete Institue; Farmington Hills, MI, 2003.

6 **Kim DJ, Kim MS, Yun GY, Lee YH**, *Bond Strength of Steel Deformed Rebars Embedded in Artificial Lightweight Aggregate Concrete*, Journal of Adhesion Science and Technology, **27**(5-6), (2013), 490–507, DOI 10.1080/01694243.2012.687552.

7 **Harajli MH**, *Bond Behavior in Steel Fiber-Reinforced Concrete Zones under Static and Cyclic Loading: Experimental Evaluations and Analytical Modeling*, Journal of Materials in Civil Engineering, **22**(7), (2010), 674–686, DOI 10.1061/(ASCE)MT.1943-5533.0000067.

8 **Barbosa MTG, Sánchez Filho EDS, Oliveira TMD, Santos WJD**, *Analysis of the relative rib area of reinforcing bars pull out tests*, Materials Research, **11**(4), (2008), 453–457, DOI 10.1590/S1516-14392008000400013.

9 **Mitchell DW, Marzouk H**, *Bond Characteristics of High-Strength Lightweight Concrete*, ACI Structural Journal, **104**(1), (2007), 22–29.

10 **Harajli M, Hamad B, Karam K**, *Bond-slip Response of Reinforcing Bars Embedded in Plain and Fiber Concrete*, Journal of Materials in Civil Engineering, **14**(6), (2002), 503–511, DOI 10.1061/(ASCE)0899-1561(2002)14:6(503).

11 **RILEM**, *Technical Recommendations for the Testing and Use of Construction Materials*, Taylor and Francis; London, 2006.

12 **ASTM C138 / C138M - 14**, *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*, ASTM International; West Conshohocken, PA, 2014, DOI 10.1520/C0138_C0138M-14.

13 **ACI Committee 544**, *Guide for specifying, proportioning, and production of fiber-reinforced concrete*, American Concrete Institue; Farmington Hills, MI, 2008.

14 **ASTM C39 / C39M – 14a**, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM International; West Conshohocken, PA, 2014, DOI 10.1520/C0039_C0039M-14A.

15 **ASTM C496 / C496M – 11**, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*, ASTM International; West Conshohocken, PA, 2004, DOI 10.1520/C0496_C0496M-11.

16 **ASTM C1609 / C1609M – 12**, *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)*, ASTM International; West Conshohocken, PA, 2012, DOI 10.1520/C1609_C1609M-12.

17 **Wafa FF, Ashour SA**, *Mechanical Properties of High-Strength Fiber Reinforced Concrete*, ACI Materials Journal, **89**(5), (1992), 449–455.

18 **Soulioti DV, Barkoula NM, Paipetis A, Matikas TE**, *Effects of Fibre Geometry and Volume Fraction on the Flexural Behaviour of Steel-Fibre Reinforced Concrete*, Strain, **47**, (2011), 535–541, DOI 10.1111/j.1475-1305.2009.00652.x.

19 **Shah SP**, *Do Fibers Increase the Tensile Strength of Cement-based Matrix?*, ACI Materials Journal, **88**(6), (1992), 595–602.

20 **Balaguru PN, Shah SP**, *Fiber-reinforced cement composites*, McGraw-Hill; New York, 1992.