Fiber Reinforcement Influence on the Tensile Response of UHPFRC

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Abstract:

The tensile response of ultra-high performance fiber reinforced concrete (UHPFRC) is a fundamental material property and its engagement in the design of structural components requires a throughout understating of the different factors affecting it. In particular, the tensile cracking strength is one of the main parameters adopted for the idealization of the tensile constitutive law. However, the tensile response of UHPFRC is not an intrinsic property as it depends on several factors including the material formulation, the geometry of the components, the casting process, and the testing method and specimen. In this paper, the effect of the fiber reinforcement on the tensile cracking strength is discussed through the analysis of experimental results reported in plain UHPC and UHPFRC with different preferential fiber alignments.

Keywords: UHPFRC, tensile strength, fiber orientation, tension test, pull-off test

1. Introduction

Advances in concrete material technology have enabled the development of a new generation of cementitious materials that might offer alternative solutions for the large infrastructure needs and the increasing performance demands. In particular, ultra-high performance fiber reinforced concretes (UHPFRC) are cementitious composite materials that exhibit exceptional mechanical and durability properties. These materials are usually characterized by compressive strength greater than 150 MPa and the use of fibers as reinforcement, which allows for sustained post-cracking tensile strength and toughness increase [AFGC-SETRA, 2013]. These exceptional mechanical properties might lead to novel design and construction approaches and eventually to new infrastructure solutions. However, a reliable quantification of the mechanical properties is required in order to foster confidence among the civil engineering community and facilitate the engagement of these properties in design guidelines and eventually in UHPFRC structural components.

2. Tensile response

The singular tensile response and increased toughness observed in UHPFRC materials is usually associated with the occurrence of multiple and stable cracking. The cracking mechanism is governed by the effectiveness of the fiber reinforcement in bridging and transferring load across microcracks spreading in the cementitious matrix subjected to tensile stresses. Therefore, fiber properties (e.g., strength, stiffness, Poisson's ratio, geometry, shape, and volume), matrix properties (e.g., strength, stiffness, Poisson's ratio, compactness), as well as fiber-matrix interface properties are key in understating and tailoring the tensile response. Furthermore, the material formulation is not unique and thus several characteristic tensile responses might be observed for UHPFRC materials, some of them are illustrated in Figure 1.

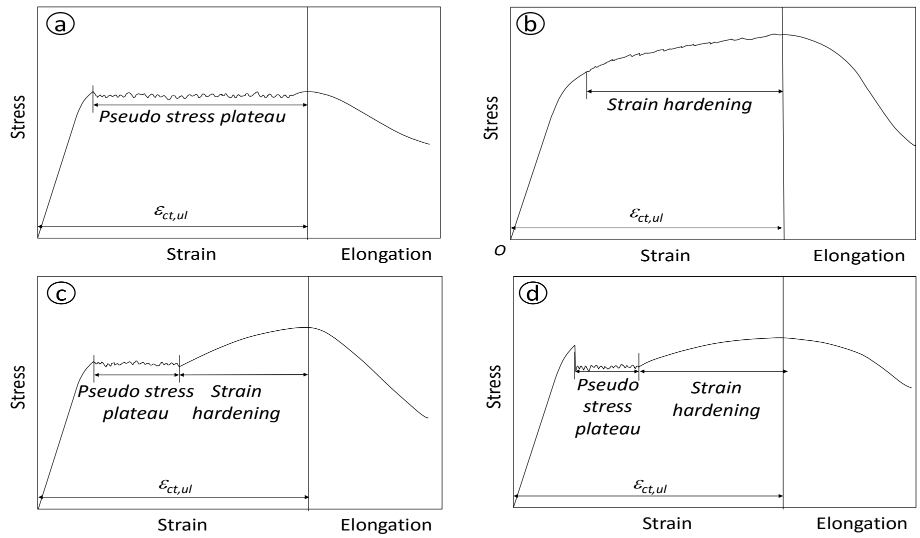

Figure 1. Characteristic tensile response in UHPFRC materials

2.1. Tensile response quantification

In terms of material property characterization, a series of key parameters needs to be defined and experimentally assessed in order to properly quantify the tensile response of UHPFRC materials. Those parameters must provide a reliable description of the material tensile response regardless of the material response idealization that might be adopted for further design considerations.

The initial elastic response in tension might be described through the quantification of the initial elastic modulus and the elastic tensile strength. Depending on the test method, the elastic modulus could be determined directly or indirectly from the initial stress-strain response in the assumed uncracked section or it might be quantified in a specific test procedure, such as the test method for conventional concrete in ASTM C469 [ASTM, 2014]. The elastic tensile strength corresponds to the stress at which the loss of linearity in the tensile response is observed. Although the elastic tensile strength may be visually evident for some tensile characteristic responses, the development of standard procedures for its determination is required in order to evaluate the parameter properly and accurately.

After the occurrence of the first crack a clear stress discontinuity is observed in some of the tensile characteristic responses. The stress value at the moment of that discontinuity might be regarded as the first cracking stress. Although the first cracking stress has been sometimes related to the matrix cracking stress, the equivalence might be debatable as the identification of the individual and couple contributions of fiber reinforcement and matrix to the composite response at the moment of the first crack formation may not be straightforward. Furthermore, for those materials exhibiting non-discontinuous responses, such as the tensile response in Figure 1b, the determination of the first cracking stress from the stress-strain diagram is not evident and there is a need for standard procedures for its determination.

The post-cracking response might vary significantly for different material formulations, as illustrated in Figure 1. In general, a cracked strain domain could be defined between the strain corresponding to the first cracking stress and the strain corresponding to the ultimate stress. The latter stress level is defined as the maximum average stress registered during the tension tests.

The cracked strain domain in UHPFRC materials could be characterized by a pseudo stress plateau, a strain hardening response, or a combination of them. In the case of pseudo stress plateau, the average stress at the plateau might provide an estimation of the average multi-cracking stress. The strain hardening response might be characterized by a residual tangential stiffness defined between the strain levels after the first crack and at ultimate strength.

2.2. Fiber orientation distribution

The unique tensile response of UHPFRC is affected not only by the material formulation but also by the casting method and element production process. Therefore, the tensile response of UHPFRC is not intrinsic mechanic property, and its quantification must account for both material formulation and manufacturing related factors. The impact of the casting method and the production process on the final orientation and distribution of the fibers have been experimentally studied through a number of different approaches including image analysis [Ferrara et al., 2011; Wille et al., 2014, Xia and Mackie, 2014] and non-destructive methods based on electrical resistivity measurements [Martinie and Lataste, 2015] and alternating current-impedance spectroscopy (AC-IS) [Ozyurt et al., 2006]. Probabilistic approaches have also been developed to account for the fiber distribution and the fiber orientation [Naaman, 1972; Xia and Mackie, 2014], as well as numerical models to simulate flow patterns and fiber distribution [Kang and Kim, 2012, Martinie and Lataste, 2015].

The fiber orientation factor concept has been widely adopted to account for the effect of the fiber orientation distribution on the tensile mechanical response of fiber reinforced concretes. Several analytical and empirical formats have been discussed in the literature [Naaman, 1972; Soroushian and Lee, 1990; Xia and Mackie, 2014]. However, the translation of the fiber orientation factor assessments into robust design safety factors is not completely straightforward and better understanding of the main parameters affecting the tensile response at structural level is required, which may allow for a more suitable material reduction factor concept and thus fuller exploitation of the materials properties.

3. Tensile test methods

Several test methods are available to assess the tensile strength of concrete materials. These include the split-cylinder test (ATM C496) [ASTM, 2011], and the flexural test (ASTM C1609) [ASTM, 2012]. These indirect methods which are more common and somewhat easier to execute could be applied to UHPFRC materials; however, the results of such tests could be misleading or not sufficient. On the other hand, direct test methods are also available, including the test method developed by Graybeal and Baby [Graybeal and Baby, 2013] and a modified version of the standardized "pull-off" test (ASTM C1583) [ASTM, 2013], both of which are described in this paper.

3.1. Direct tension test (DTT)

This test emulates DTT methods commonly used in the mechanical testing of metals, thus addressing many of the hurdles that can hinder the implementation of new test methods. The test specimen consists of prisms cast in mold or extracted from structural components. Aluminum plates are glued onto two sides of each end of the specimen for gripping purposes. This is also done in order to increase the likelihood of specimen failure within the instrumented gauge length. During the tensile loading, the strain is captured with a parallel ring extensometer similar in concept to the parallel ring compressometer used in the testing of concrete cylinders for modulus of elasticity. The extensometer contains four linear variable differential transformers.

3.2.Pull-off test

In this test, a 50.8 mm (2 in) diameter steel disc is glued on the top surface of the concrete material. Then, the test specimen is formed by partially drilling a core perpendicular to the surface, at a depth of approximately 25.4 mm (1 in), and leaving the intact core attached to the concrete. The glued disc serves as a guide to avoid any eccentricity during the coring operation. A tensile load is then applied to the steel disc at a constant rate of 35 ± 15 kPa/sec (5 ± 2 psi/sec) until failure occurs. The failure load is recorded and the nominal tensile stress can be calculated.

4. Fiber orientation assessment

As part of the research initiative on UHPFRC at the U.S. Federal Highway Administration's Turner-Fairbank Highway Research Center in McLean, VA, a number of experimental studies have been completed over the last years to characterize the tensile response of UHPFRC materials. Although tests have been completed through all the test methods described in section 3, a large effort has been devoted to further develop and validate the DTT method.

In particular, a specific study on the fiber orientation distribution was completed using the DTT methodology. The details of the experimental campaign are discussed briefly in this section; further details can be obtained from Maya and Graybeal [Maya and Graybeal, 2015]. Prismatic specimens were extracted from a slab element cast using a proprietary UHPFRC and under a confined flow regime mimicking usual manufacturing processes for some UHPFRC structural elements. The slab was 914 mm (36 in) wide, 3048 (120 in) mm long and 50 mm (2 in) thick and it was first cut in three square sections. Then, prismatic specimens were extracted from each square section at three different inclinations with respect to the flow direction; parallel (F0), perpendicular (F90) and at 45 degrees (F45). Along with the slab, companion specimens were cast for material characterization purposes. A total of twelve cylinders for compression tests (76 mm (3 in) diameter and 152 (6 in) mm height) and twelve prismatic elements for tension tests (50.8 mm (2 in) wide, 50.8 (2 in) mm thick and 431.8 (17 in) mm long) were cast. The UHPC used in this study is a proprietary material, which basic formulation has been detailed elsewhere [Graybeal and Baby, 2013]. The steel fibers were non-deformed, cylindrical, high tensile strength steel with a diameter of 0.2 mm, a length of 12.7 mm, and a minimum tensile strength of 2.4 GPa. A fiber reinforcement volume fraction of 2.0 % was used for this study. The compressive strength of the UHPFRC was evaluated according to the ASTM C39 [ASTM, 2015] on 76 mm (3 in) diameter cylinders at a load rate of 1 MPa/s. Average compressive strengths of 176.5 MPa and 162.8 MPa were obtained for the specimens tested at the time the direct tension tests and the pull-off tests were completed, respectively.

The results from the direct tension tests are presented in Figure 2 in terms of stress versus average axial strain for the extracted (F0, F45, F90) and the cast in mold specimens (FEC). The individual specimen results are shown in thin lines, while the averages for each specimen set are presented in thick lines. Moreover, Table 1 summarizes the main average results for each specimen set, i.e., compressive strength, elastic modulus, first cracking stress, average multi-cracking strength, and strain at localization.

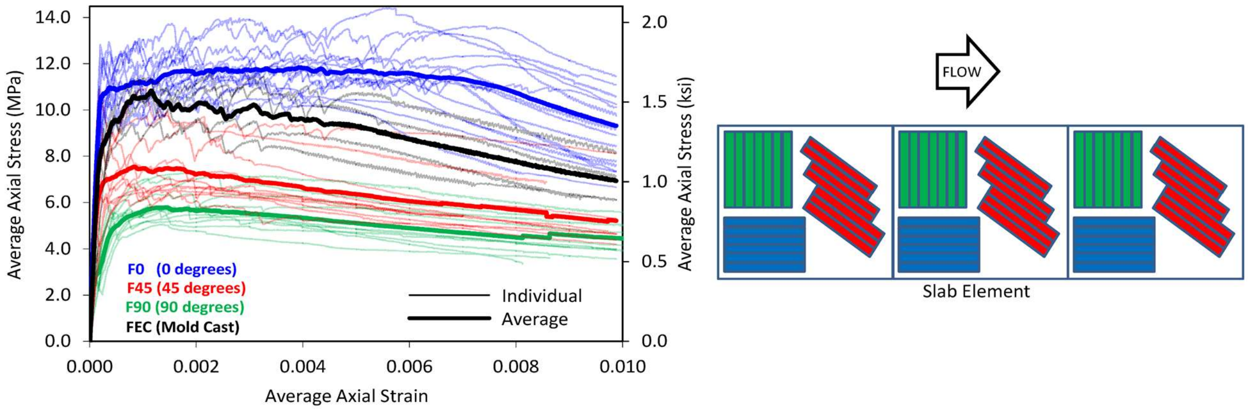

Figure 2 Tensile response of prismatic specimens

The results indicated a clear influence of the fiber orientation distribution on the material tensile response. The specimen sets with fiber preferentially oriented in the direction of the tension forces applied, i.e. *F0* and *FEC*, overperformed the specimens extracted in other directions. The loading direction corresponds as well with the main flow direction of the UHPFRC during the casting of the slab elements and the prismatic specimens. Therefore, the results highlight the need of properly accounting for the fiber orientation induced by flow patterns and mold constrains. The preferential fiber orientation was also validated through image analyses on representative cross sections of the different specimen sets, in which fiber counting and fiber orientation assessment were performed [Maya and Graybeal, 2015]. Table 2, summarizes the fiber counting and the fiber orientation factor assessment based on the fiber footprints on the cut sections and calculated according to Equation 1 [Soroushian and Lee, 1990]. Where the angle θ is defined by the fiber axis and the vector normal to the cross section, *N* is the total number of fibers in the cross section, and a_i and b_i correspond respectively to the short and large axes of the elliptic footprint of each fiber in the cross section.

Table 1. Tensile response of prismatic specimens

Set	Compressive strength (MPa)	Elastic Modulus (GPa)	First cracking stress (MPa)	Average multi-cracking stress (MPa)	Strain at localization
F0	176.5	63.5	9.9	11.4	0.0060
F45		60.3	7.0	7.1	0.0027
F90		57.1	5.1	5.6	0.0029
FEC		59.3	8.5	10.1	0.0035

Table 2. Fiber orientation factor values for specimen sets F0, F45, F90, and FEC

	N fibers		
Specimen set	Average	COV	Orientation factor
F90	555	0.12	0.65
F45	852	0.10	0.74
F0	1103	0.06	0.83
FEC	1047	0.04	0.85

$$\alpha = \frac{1}{N}\sum_{i=1}^{n} Cos\theta_i = \frac{1}{N}\sum_{i=1}^{n}\frac{b_i}{a_i} \qquad (1)$$

In particular, a significant influence of the fiber orientation on the average first cracking strength was observed for specimens sets F45 and F90 in comparison to specimen set F0. Those reductions, over 40%, might suggest that the fiber orientation distribution could not only affect the post-cracking response, governed by the fiber bridging mechanisms, but also the first cracking stress.

The pull-off tests represents a feasible alternative for qualitatively assessing the tensile response of fiber reinforced concrete [Ghavidel et al., 2015]. The nominal tensile strength of the material can be estimated based on the maximum load recorded during the test. As part of an ongoing research project at the TFHRC a series of pull-off tests have been completed in UHPFRC samples. The testing specimens were thin slabs cast by pouring the material at the center and letting the material flow to fill the open formwork. The square slabs were 457 mm (18 in) side long and 101.6 mm (4 in) thick. The depth of the core drilled for the specimens cast in UHPFC was 38.1 mm (1.5 mm). Figure 3 shows the calculated nominal tensile strength for different batches of a proprietary UHPFFRC material tested over a period of seven months. Although all the samples corresponded to the same proprietary material, small changes in the material formulation were reported by the provider over the period study. Despite the inherent variability within material batches, the calculated tensile strengths agreed well with the values reported in the literature for the same product [Graybeal and Baby, 2013]. Moreover, the result exhibited low variability with a coefficient of variation of 7%.

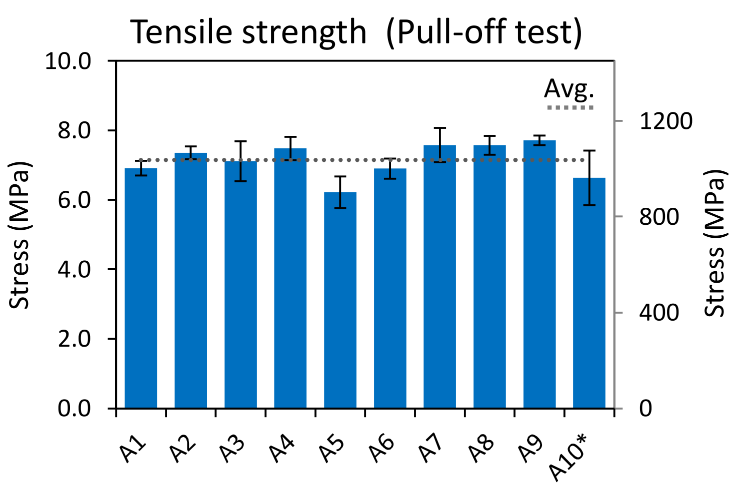

Figure 3. Nominal tensile strength of UHPC material E, Pull-off tests

In general, the casting process of the slab might be characterized by an extensional flow and thus the potential orientation of the fibers in a direction perpendicular to the radial direction [Martinie and Lataste. 2015]. In order to study elements with a potential different fiber orientation distribution, a pilot experimental program was completed using two beam elements made of the same proprietary UHPFRC material. The beam elements were 1016 mm (40 in) long with a 152.4 mm (6 in) square cross section. The dimension of the cross section was defined by the size of the pull-off device, while the length aimed at achieving a stable flow pattern. The specimens were cast from one side of the formwork and the material was let flow to fill the open formwork completely. Along with the beams, two slabs elements were cast; one of them using the described UHPFRC material and other using the plain UHPC material without the fibers. Likewise, a total of six cylinders for compression tests (72 mm (3 in) diameter and 152 mm (6 in) height) and twelve prismatic elements for tension tests (50.8 mm (2 in) wide, 50.8 mm (2 in) thick and 431.8 (17 in) mm long) were cast. All the elements were cured at lab environment of 23 ± 2 ºC (73.4 ± 3.8 F) and 50 ± 5 % relative humidity, and covered with wet burlap to prevent moisture loss. Each beam element was cut into three sections. The cuts were perpendicular to the longitudinal axis for the first element (Beam1) and inclined 45 degrees with respect to the longitudinal axis for the second element (Beam2).

Pull-off tests were completed on the interior faces defined by the cuts as well as on a lateral face and on the top open surface. The average compressive strength of the UHPFRC was 163 MPa around the time of the tests (34 days). Figure 4 shows the average tensile strength calculated from the pull-off test results along with the average cracking strength obtained from the companion direct tension tests. In general, the pull-off test results provided a reliable estimation of the cracking strength. The influence of the potential preferential fiber orientation was not evident as it was for the specific study carried out using the direct tension test method. However, there were consistent differences in the failure surfaces observed for specimens in each specimen set. Figure 5 shows photos of samples for some of the specimen sets studied. Samples taken from slabs, with and without fibers, as well as those taken from the sides and top of the beam elements exhibited a better defined failure surface, which resembles an ideal spherical failure surface. In turn, the failure surfaces of samples taken at the cut interior face of the beam elements were rougher and tend to be in general inclined, the latter more evident for internal samples coming from Beam 2.

Moreover, a visual inspection of the failure surface indicated differences in the amount of fibers crossing the cross section. Although images analyses were not conducted for these samples, those differences were not as marked as the observed for the prismatic specimens in the first specific study described. In particular for the beam elements, the large cross section adopted to accommodate the testing device as well as the open flow regimen during the casting might have favored a more random distribution of the fibers than the observed for the thin specimens in the first study. Further research is deemed necessary to study other structural typologies as well as elements cast in such a way that fibers are intentionally and truly oriented along preferential axis, so that the reliability of the tensile strength quantified through pull-off tests can be broadly validated.

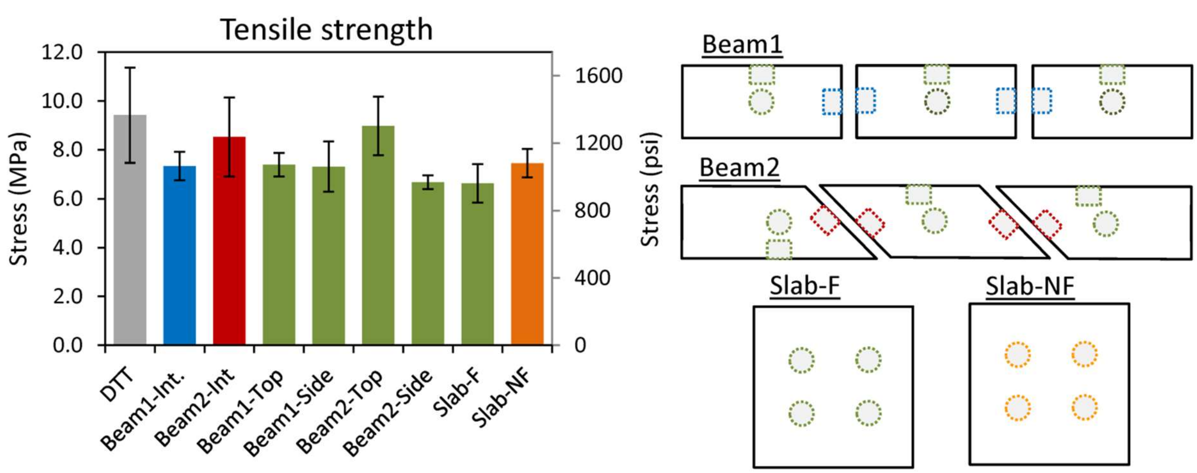

Figure 4. Pull-off tests results

Figure 5. Failure surface for different pull-off specimens

5. Conclusions

This paper highlights the need of properly characterizing the tensile response of UHPFRC materials in order to facilitate the development of specific design guides and thus foster the engagement of these properties in UHPFRC structural components. The key parameters required for providing a reliable description of the UHPFRC tensile response were discussed along with some of the tensile test methods available to quantify them.

In particular, the results from direct tension tests on thin slab elements showed the effect of the flow pattern and the mold constrains on the final fiber orientation distribution and thus on the tensile mechanical properties; first cracking stress, average multi-cracking strength, and strain at localization. A significant reduction on the average first cracking strength was observed for element with fibers oriented perpendicular to the tension loading direction, which suggest that the fiber orientation distribution could not only affect the post-cracking response, mainly governed by the fiber bridging mechanisms, but also the first cracking stress.

The pull-off test proved to be a reliable tests method for quantifying the tensile strength of UHPFRC materials providing consistent and conservative estimations when compared to the tensile tension tests results. However, further research is required to investigate the reliability of the test to account for the effect of preferential fiber orientation due to flow patterns, casting process and mold interactions on the tensile strength quantification.

6. References

AFGC, SETRA. "Bétons fibrés à ultra-hautes performances."Recommandations provisoires. Paris, (2013).

Ferrara, L., Ozyurt,N., Prisco, M.D., "High mechanical performance of fiber reinforced cementitious composites: The role of "casting-flow induced" fibre orientation", *Mater Struct*, 74, 2011, pp. 109-128

Ghavidel R., Madandoust, R., Ranjbar M, "Reliability of pull-off test for steel fiber reinforced self-compacting concrete", *Measurement*, Vol 73, 2015, pp. 628–639

Graybeal, B., Baby, F., "Development of a direct tension test method for ultra-high-performance fiber-reinforced concrete", *ACI Struct J*,110(2), 2013, pp. 177-186

Kang, S., Kim, J., "Numerical simulation of the variation of fiber orientation distribution during ow molding of Ultra High Performance Cementitious Composites (UHPCC)", *Cement Concrete Comp.,*34, 2012, pp. 208-217

Martinie, L., Lataste, J.F., "Fiber orientation during casting of UHPFRC: electrical resistivity measurements, image analysis and numerical simulation", *Mater Struct*, 48, 2015, pp. 947-957

Maya, L.F., Graybeal, B., "Quantification of tensile response of UHP-FRC", *Proceedings of 7th RILEM workshop on High Performance Fiber Reinforced Cement Composites: HPFRCC-7,* International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM), 2015, pp. 209-216

Naaman, A., "A statistical theory of strength for fiber reinforced concrete", PhD dissertation, Massachusetts Institute of Technology, Cambridge, MA, 1972

Ozyurt, N., Woo, L.Y., Mason, T.N., Shah, S.P., "Monitoring fiber dispersion in fiber-reinforced cementitious materials: Comparison of AC-Impedance spectroscopy and image analysis", *ACI Mater J*, 103 (5), 2006, pp. 340-347

Soroushian, P., Lee, C.D., "*Distribution and orientation of fibers in steel fiber reinforced concrete*", ACI Mater. J., 87 (5), 1990, pp. 433-439

Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM ASTM C39-15a, ASTM International, West Conshohocken, PA, 2015, pp. 7

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading), ASTM C1609/C1609M-12, ASTM International, West Conshohocken, PA, 2012, pp. 9

Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM C496/C496M-11, ASTM International, West Conshohocken, PA, 2011, pp. 5

Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM C469/C469M-14, ASTM International, West Conshohocken, PA, 2014, pp. 5

Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method), ASTM C1583/C1583M-13, ASTM International, West Conshohocken, PA, 2013, pp. 9

Wille, K., Tue, N.V., Parra-Montesinos, G.J.," Fiber distribution and orientation in UHP-FRC beams and their effect on backward analysis," *Mater Struct*, 47(11), 2014, pp. 1825-1838

Xia, J., Mackie, K., "Axisymmetric fiber orientation distribution of short straight fiber in fiber-reinforced concrete", *ACI Struct J*, 111(2), 2014, pp. 133-142

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