Methodologies for determination of tensile strength and toughness of UHPC

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***Abstract*— This work aims to identify publications that approach UHPC and to perform a comparative study between different test methods utilized to determination of tensile and toughness behavior. UHPC is one of the latest developments in the concrete technology area. It's a material with compression strength above of 150 MPa, ductile behavior and high durability. From the realization of a systematic literature mapping in different data bases, it was possible to analyze this research area. At first moment, the evolution of studies on UHPC in a period from 2016 and 2020 is analyzed, identifying the countries that have the largest production of articles and periodicals with more publications about the topic. The specific analysis corresponds to the content referring to mechanical properties, with a focus on ductility, tensile and toughness characteristics. From the selection of articles that contained the three key-words concomitant a comparative study was accomplish. The comparation was made between the different test methods used in each article, with it respective results obtained, and the test methods specified by the French standard NF P18-470, one of the first normative standards published for the characterization of the UHPC. Between the series of standards that were used for the determination of tensile strength, it was possible to observe that the 4-points bending test has been the most used. On the function of the quantity of standards and variation of procedures of used test, it can be affirmed that it's necessary to create a normative standard for determination of these parameters.**

Keywords*— *Ultra High Performance Concrete (UHPC); tensile strength; toughness; systematic literature mapping

I. INTRODUCTION

The civil construction industry has undergone a remarkable evolution in recent decades. The market has increased the demand for increasingly resistant and durables materials that value sustainability and that are easy to be casted. The UHPC (Ultra High-Performance Concrete) has been developed to satisfy this demand. It's about a material that has high mechanical characteristics as compressive strength above than 150MPa, high ductility, toughness and excellent durability [1]. French Association of Civil Engineering (AFGC) affirms UHPC satisfy a series of sustainable measures. Its high strength is associated with saving materials, since it's possible to reduce transversal cross-sections [2]. The reduction in the overall volume of material used makes the cost to be similar or slightly lower than the cost of a structure built with regular concrete [1], with the difference that its high durability implies a low maintance requirement, in other words, longer life project useful. This characteristic is closely associated with a low porosity and higher packing density, since there is no coarse aggregate and the use of ultrafine particles [3]. In addition to the advantages already mentioned, the production of thin structures in UHPC provide freedom to architectural design [4]. The materials most commonly used in the production of UHPC is cement Portland, silica fume, quartz powder, quartz sand, fibers, PCE-based superplasticizer (polycarboxylate ether) and low water-cement ratio [5]. High quality raw material is one of the biggest limitations to the development of UHPC, such as silica fume, since its availability is limited and the price is high. The absence of a Brazilian technical standard about UHPC is another factor that hinders the application of this concrete in Brazil. Therefore, in order to provide a broad view of the UHPC research area, a Systematic Literature Mapping was developed. The aim of this work was to qualify and analyses the existing literature on the UHPC, from a systematic mapping, and to carry out a comparative study between the different test methods for determination of tensile strength and toughness, comparing them with the test methods specified by the French standard NF P18-470.

II. SYSTEMATIC LITERATURE MAPPING

The present research used the method elaborated by [6] as reference to carry out the systematic mapping. The sequence of steps that were accomplished can be verified through the process flowchart shown in Fig. 1. The search string ("Ultra High-Performance Concrete" OR "UHPC") was inserted in ten data bases that have relevant content related to Civil Engineering area: ASCE Library, Compendex on Engineering Village, CAPES Journal Portal, ProQuest Engineering Database, Research Gate, SciELO, Science Direct, Scopus, Springer and Web of Science. It was established that only journal articles would be considered and the period of analysis from 2016 to 2020 was determinated.

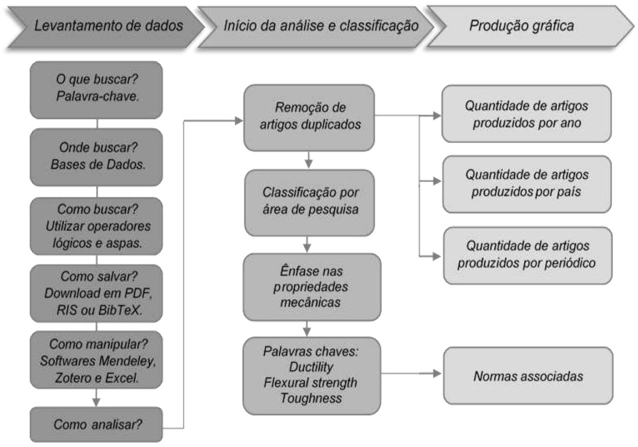

Fig. 1. Sequence of Sistematic Literacture Mapping processes. Source: The authors

A. *Bibliometric analysis*

From the total number of articles without duplicates (1,263) it was possible to quantify the production per year in the period determined for the search, from 2016 to 2020, which revealed that the UHPC research area has grown since then. The quantification of articles per country by origin revealed that China has the largest number of publications on UHPC. Following are the United States and Germany. The articles were also quantified according to the journals in which they were published. It was noted that ten journals were stood out in publications on UHPC, as they published approximately half of the available data. The other half was in charge of another 226 journals. Among the ten largest journals with publications on UHPC, three deserve mention due to the number of published contents: Construction and Building Materials, Engineering Materials and Cement and Concrete Composites, all from Elsevier.

In order to provide a broad view of the themes that have been researched about this concrete, the articles found were classified into eight researches area, as can be seen in Fig.2. The research was carried out using keywords in the abstracts. The highlighted slice will be detailed in the sequence.

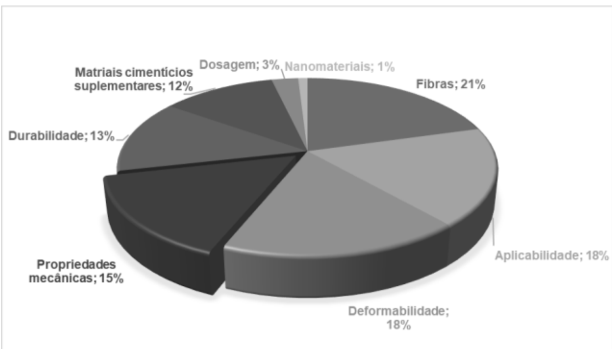

Fig. 2. Classification of articles in research area, with emphasis on the portion corresponeding to mechanical properties. Source: Authors.

B. *Specified analysis*

The percentage of articles corresponding to mechanical properties (15%) represents studies that contain the keyword "mechanical properties" in the abstract. Within the 221 articles related to this research area, three concomitant Keywords were determined: ductility, flexural and toughness, which accounted 12 articles (Fig.3).

The articles about mechanical properties of the UHPC that had these three keywords defined were analyzed in search of standards that specified the flexural tensile strength and toughness. The analysis showed that the ASTM C1609 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) has been the most used among the researchers.

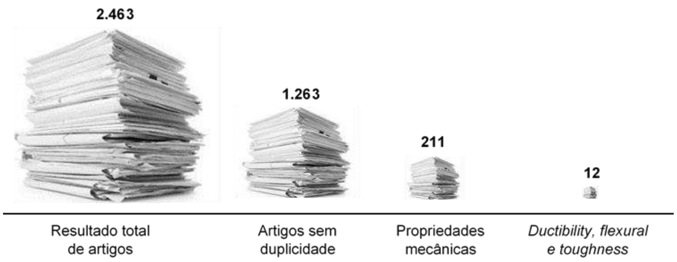

Fig. 3. Number of results. Font: Adapted from J.Ruiz. (2013)

III. Comparative Study Between the Different Test Methods Used

The French standard for characterization of the UHPC is one of the oldest, presenting specification recommendations since 2003, undergoing revisions to result in a normative publication in 2016. Therefore, it is being used as a reference for this research. Based on the literature systemic review, 11 articles that investigated the tensile strength and toughness of UHPC were separated [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

The French standard NF P18-470 presents recommendations for the structural application of UHPC, defining specifications of its properties, production and control. Among them, there are two test methods for the determination of tensile behavior of UHPC: 3-points and 4-points bending strength tests.

The 3-point flexural test consists in utilize prismatic specimens with dimensions of a x a x 4a with a notch located on the lower face, with a depth of half the length of the longest fiber used. Supported on two supports, having a test span of 3a, a displacement sensor is fixed in the region of the notch in order to obtain the crack mouth opening displacement (CMOD). A load with constant speed is applied on the center of specimen, in line with the notch. From this test, a load-CMOD curve is obtained. Through an inverse analysis, it's possible to determine an equivalent curve for the material under direct tension after cracking [7].

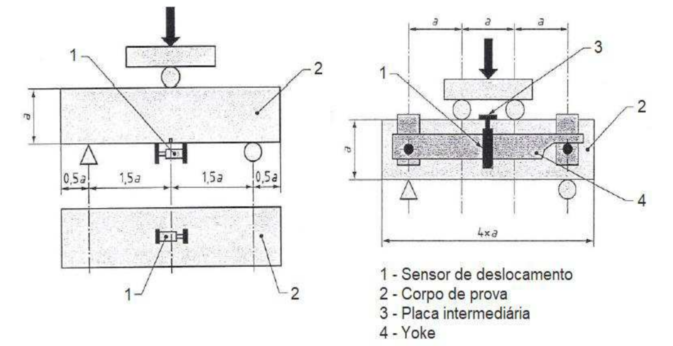

Fig. 4. Settings of 3-points (left) and 4-points (right) tensile strength tests. Font: Adapted of NF P18-470 (2016).

The 4-point bending test consists in utilize prismatic specimens with dimensions a x a x 4a without presenting a notch on the lower face. Supported on two supports, having a test span of 3a, a displacement sensor is fixed in the center of specimen by a Yoke. A load applied on the Middle third of specimen at a constant speed. From this test a load-displacement curve is obtained that allows the determination of the elasticity limit under tensile and the tensile strength after cracking [7].

Table I presents for each article related to the test standard used to the determination of tensile strength and toughness of material.

The American standards ASTM C1609, ASTM C78 and ASTM C1018 present specifications and test procedures to determine the behavior of concrete subjected to bending tensile stresses. The test procedure for these standards is quite similar: the tensile strength is made by 4-points bending test, where the test span is 3a (where a is the height of the specimen) as well as [7]. However, there are some differences between these standards regarding the dimensions of specimens and the calculation of results.

The ASTM C78 standard doesn't specify the width value, and may present specimens with rectangular transversal cross-section, differently of ASTM C1018 and ASTM C1609 which recommend a square transversal cross-section. Despite this, the three standards specify the width being three times the height value + 50mm, managing to meet the dimensions ratio a x a x 4a, the same required by [7]

TABLE I. STANDARDS OF TENSILE STRENGTH AND THOUGHNESS

NORMAS MENCIONADAS	TÍTULO DA NORMA
ASTM C1609/C1609M [8]	Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-point Loading), American Society for Testing and Materials, West Conshohocken, Pennsylvania, 2012.
ASTM C78 [9]	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).
ASTM C1018 [10]	Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading).
UNI11039 [11]	Test Method for the Determination of First Cracking Strength and Ductility Indexes. 2003. (Four-point bending tests)
EN14651 [12]	Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality 2005)
GB/T 31387 [13]	National Standard of the People's Republic of China, Reactive Powder Concrete
RILEM TC 162-TDF [14]	RILEM TC 162-TDF: Test and design methods for steel fibre reinforced concrete; bending test. Final Recommendation

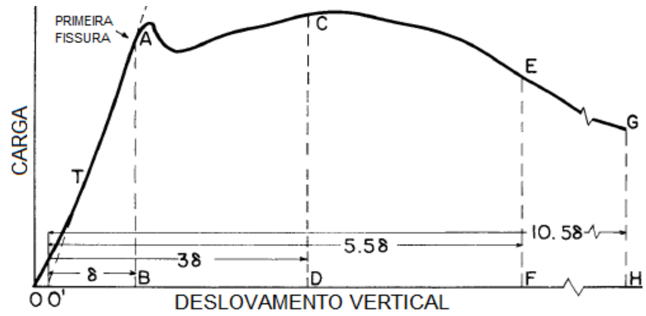

Fig. 5. Load-Vertical displacement standard curve and definition of áreas under the curve for ASTM C1018. Font: Adapted from ASTM C1018 (1997).

With respect to the test calculations, ASTM C78 is a test performed for concrete in general (not necessarily fiber reinforced) determining only the flexural tensile strength using the maximum applied load. Differently of this case, the ASTM C1018 and ASTM C1609 standards are specific for fiber reinforced concrete. Using a displacement sensor, a load-vertical displacement curve is obtained in the test, where it's possible to obtain the value of the tensile strength at the moment of the appearance of the first crack and the toughness of the composite by calculating the area under the curve (Fig. 5).

With respect to toughness, ASTM C1018 determines curve points for specifics displacements (δ, 3δ, 5,5δ e 10,5δ, where δ is the vertical displacement from the start point of the curve to the vertical displacement at the moment of the appearance of the first crack) for the calculation of toughness from the beginning of the test to the specified displacement point so that it can then determine the residual strength factor. For ASTM C1609, the toughness is the area under the curve for vertical displacement ranging from 0 to L/150, where L is equal the length of the test span. In addition to, the ASTM C1609 standard determines two residual resistance points, located where the vertical displacement is equal to L/600 and L/150 (Fig. 6).

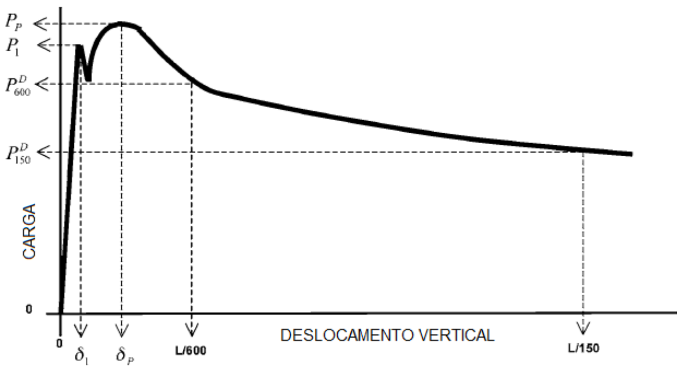

Fig. 6. Load-Vertical displacement standard curve for ASTM C1069. Source: Adapted from ASTM C1069 (2012).

Based on [11], the UNI 11039 standard presents the 4-points bending test utilizing specimens with dimensions of 150x150x600 mm and test span of 450 mm, respecting the same standard used by [7]. However, unlike the other standards that perform the 4-points bending test, the specimen has a notch in the center of the lower face, and during the test the crack top opening displacement (CTOD) and the load applied at this instant are measured, getting a load-CTOD curve as a response.

In this case, two areas under the curve are considered: the first being the are under the curve between the CTOD points equal to 0 mm (at the moment of formation of the first crack) and 0,6 mm and the second being the area between the points CTOD equal to 0,6 mm and 3,0 mm. With these values, it's possible to determine the parameter feq(0-0,6) and feq(0,6-3,0) (Fig. 7) being respectively the nominal tension for CTOD between 0 mm and 0,6 mm and nominal tension for CTOD between 0,6 mm and 3,0 mm. These nominal tensions are actually the post-cracking strengths utilized for, respectively, service limit state and ultimate limit state.

Standards EN 14651 and RILEM TC 162-TDF present very similar test procedures, evaluating the tensile behavior in terms of residual strength through the graphic load-CMOD (Fig. 8) through the 3-points bending test using prismatic specimens, with a square cross-transversal section of 150mm of side and length varying between 550 mm and 700mm for EN 14651 and for RILEM TC 162-TDF, 550 mm.

The GB/T 31387 standard specifies test methods for UPHC, which to determine the tensile strength is used the same procedure provide in GB/T 50081 with some adaptations, such as changing the speed in the load rate and use of prismatic specimens of dimensions 100x100x400 mm. According with [15], the type of bending test used is 4-point bending test.

Among of the articles selected for studies, [19] and [22] used the 3-points bending test to characterize the UHPC in tensile. The articles [18, 20, 21, 23, 24, 25] used the 4-point bending test in their experimental studies. The three remaining works weren't considered in this work because they don't use bending test for the characterization of UHPC. In the work [16] they analyze the behavior of UHPC wall panels under explosion loads. In the case of the authors [17], they carry out a literature review of the state of the art of the UHPC, not performing experimental work. Finally, [26] was not included, because in their study it evaluates the behavior on a positive tensile moment of a slab reinforced with an overlay of UHPC and carbon fiber reinforced polymer.

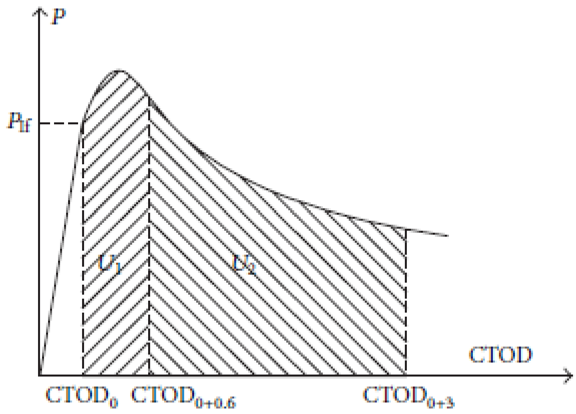

Fig. 7. Load-CTOD standard curve for UNI 11039. Source: F. Bencardino (2013)

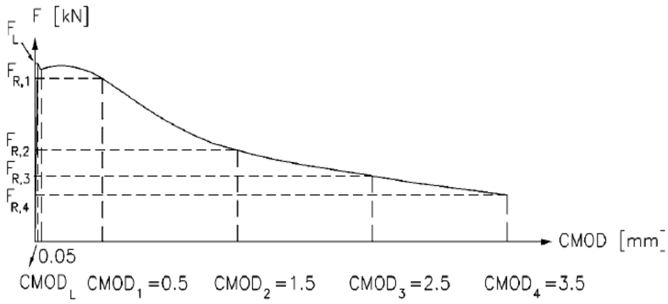

Fig. 8. Load-CMOD standard curve for EN 14651 and RILEM TC 162-TDF. Source: RILEM TC 162-TDF (2003)

Reference [18] studied the mechanical properties of UHPC with steel fiber and steel wool. Among these properties, they characterized its tensile behavior using both the 4-points bending test to determine the tensile strength based on the procedures present in ASTM C1609 and the 3-point bending test to determine the fracture toughness of the material through of the ASTM E399 standard. In both cases, they used prismatic specimens with dimensions of 304 mm x 762 mm x 38,1 mm, not following the standard of dimensions a x a x 4a.

Reference [19] compared the bending behavior characteristics of beams composed of high-strength concrete (HSC) with and without use of fibers, with compressive strength between 100 MPa and 120 MPa. To determine the tensile strength of concrete, a 3-point bending test was performed on prismatic specimens (100x100x400 mm) under the RILEM TC 162-TDF recommendations. With the results obtained, an inverse analysis was performed to estimate the tensile strength.

Reference [20] analyzed the tensile behavior and toughness of UHPC using fibers with two different lengths. For this, the authors performed two procedures of different standards on prismatic specimens (40 mm x 40 mm x 160 mm): ASTM C1609 to perform the 4-point bending test and ASTM C1018 to determination of toughness through the area under the curve.

Reference [21] used different types of fiber in UHPC to provide an insight into the energy dissipation mechanisms. Among the tests performed, ASTM C1609 was used to determine the flexural tensile strength in specimens with dimensions 101,6 mm x 101,6 mm x 457,2 mm.

Reference [22] compared the tensile behavior of UHPC and HSC using prismatic specimens (100 mm x 100 mm x 400 mm) with a notch on the lower face. Through a load-CMOD graph resulting from a 3-point bending test, a inverse analysis was performed to determine its post-cracking behavior. Although not referring to the UHPC material, the toughness of reinforced beams was determined through the area under the load-vertical displacement curve in response to 4-points bending test.

Reference [23] performed a 4-points bending test to determine the flexural tensile strength of UHPC, however, they don't bring any additional information about the test. The UHPC was used later in columns that were subjected to tests with explosive load.

Reference [24] analyzed the effects that high temperatures cause on mechanical properties of UHPC with polypropylene fibers. The flexural tensile strength was performed based on the ASTM C78 standard (4-points bending) on specimens with dimensions 40 mm x 40 mm x 160 mm.

Reference [25] performs a analysis on the mechanical properties of UHPC. Based on GB/T 31387 standard, using specimens with dimensions 100 mm x 100 mm x 400 mm, the flexural tensile strength is determined by the 4-points bending test.

IV. Conclusion

In view of the systematic literature mapping and the comparative study, the following conclusions were made:

The 4-points bending test is the most used test to determine the tensile behavior of the UHPC, which in all cases is possible to use the same dimension standard a x a x 4a for prismatic specimens presented by the French standard. In the case of 3-points bending test, only [14] didn't meet this standard.

Specimens with a x a x 4a dimension ratio (width, height and length), as well as in NF P18-470, were adopted in most of cases for the performance of flexural tests, with only [18] that deviated from this standard.

The necessity of create a normative standard to determine the tensile behavior of UHPC is remarkable, considering the number of standards used and the variations in test procedures present in the works presented, especially in determining the toughness of the material under study.

Acknowledgment

The authors thank CAPES (Coordination for the Improvement of Higher Education Personnel) and CNPQ (National Council for Scientific and Technological Development) for their support.

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