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Characterization of fiber reinforced concrete for classification based on strength and ductility

Caracterizarea betonului armat dispers în vederea clasificării pe baza rezistenței și ductilității

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Abstract. *Fiber reinforced concrete is a solution whereby some of the conventional steel reinforcement can be replaced by adding fibers to the concrete mass. Steel fiber reinforced concrete is classified based on strength and ductility. Depending on the amount of fiber, the behavior can be softening or hardening. In the present paper, individual results show a specific hardening behavior. However, this fiber reinforced concrete is classified into a class with weakening behavior due to the variability of experimental results.*

Key words: *fiber reinfored concrete, softening, hardening, strength, ductility*

Rezumat. *Betonul armate dispers reprezintă o soluție prin care se pot înlocui o parte din armăturile convenționale din oțel prin adăugarea de fibre în masa betonului. Betoanele armate dispers cu fibre de oțel sunt clasificate pe baza rezistenței și a ductilității. În funcție de cantitatea de fibre, comportarea poate fi de slăbire sau întărire. În articolul de față, rezultatele individuale arată o comportare specifică de întărire. Cu toate acestea, betonul armat dispers este încadrat într-o clasă cu comportament de slăbire, din cauza variabilității rezultatelor experimentale.*

Cuvinte cheie: beton armat dispers, slăbire, întărire, rezistență, ductilitate

1. Introduction

Fiber reinforced concrete is the result of incorporating a variable amount of discontinuous fibers into the concrete mass. Fiber reinforced concrete is defined as "the material obtained by mixing cement, aggregates, fibers, additives, mineral additions and water during preparation, in predetermined proportions, whose properties develop through the hydration and hardening of the cement and the interaction between the fibers and the matrix".

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Fiber reinforced concrete cannot completely replace conventional reinforced concrete. However, there are scopes of use in which fiber-reinforced concrete can be used as an alternative or in addition to conventional reinforced concrete, offering technical and economic advantages. It has been found that fibers, of any nature, improve the properties of plain concrete. The basic requirements of fibers, when it is necessary to improve the mechanical resistance of concrete and delay the cracking process, are: high tensile strength and adequate modulus of elasticity, increased adhesion to the matrix, chemical stability.

The improvement of the properties of steel fibers influences the increase in the tensile strength of concrete reinforced with such fibers. In practice, the increase in the bending strength of the concrete element reinforced with steel fibers is observed, due to the fact that the distribution of stresses in the tension area is almost constant.

After cracking occurs, if the fibers are perpendicular to the direction of crack propagation, they act as bridges between the crack walls, limiting its development. The preferred areas of use are elements with limited thicknesses (or cast in successive layers of limited thickness). For these types of elements, it is possible to obtain an orientation of the fibers perpendicular to the cracks, and an increased effectiveness of them. The main applications are: floors and slabs for industrial buildings, prefabricated beams, foundation piles, continuous foundations, bridge decks, tunnel linings, explosion-proof structures, facade elements, etc.

2. Fresh properties of fiber concrete

The rheological properties of fiber reinforced concrete depend on the consistency of the matrix as well as the fiber nature, dosage and geometry. The use of fiber contents typical for structural applications, reduces the workability of the mix, especially for fibers with a complex shape and large aspect ratios. Appropriate modifications of the mix composition may be carried out where necessary:

- by increasing the fine aggregate fraction and/or by reducing the maximum aggregate size;
- by using an appropriate type and amount of superplasticizer.

Fiber distribution in the mix should be uniform. In order to achieve this condition, particular attention must be paid to avoid fiber agglomeration (balling). Even though the amount of these agglomerations is limited, their presence can cause some obstructions and make pumping difficult. The more diffused the regions with heterogeneous distributions of fibers, the more diverse the properties of the fiber reinforced concrete are from the nominal ones.

The addition of fibers to concrete may reduce the slump and/or increase the cohesiveness of the mix. This has to be compensated either by using plasticizers or by adjusting the mix proportions.

Pumping fiber concrete does not require special equipment. However, it is useful to have a vibrator on the grid of the pump. Concrete containing short fibers of any type will not cause problems. However, longer steel fibers with an aspect ratio of more than about 60 may require careful attention to mix design, particularly at high dosages (typically, more than 25 kg/m³ of steel fibers. This is very much dependent on the type of fiber being used and the fiber supplier should be able to advise on these aspects. It is recommended that the diameter of the pump pipeline should not be less than one and a half times the length of the fibers used, as they exhibit some flexibility in the pipeline.

It is recognized that plastic shrinkage and cracking are related to bleeding and/or autogenous/chemical shrinkage. Polymer micro-fibers may therefore have beneficial effects, while steel and macro-polymer fibers have little influence. This is one of the main reasons for the use of polymer micro-fibers, particularly in horizontal elements. If fibers of this type are used for this purpose, typical addition rates range between 600 g/m³ and 900 g/m³.

3. Hardened properties of fiber concrete

Fibers are mainly added to influence the hardened concrete properties. Many of the hardened properties which are affected are rarely specified, and are unlikely to be familiar to ready-mixed concrete producers. Fibers significantly affect hardened properties in the following ways:

- increasing post-crack flexural tensile strength;
- increasing shear strength;
- increasing impact resistance;
- reducing crack widths (Design in Serviceability Limit State);
- increasing fatigue resistance.

3.1. Tensile strength

The ability of fibers to transfer stresses across cracks is one of the most important properties of fibers in concrete. This allows a fiber reinforced element to take on a substantial load even after the first crack appears. Fiber reinforced concrete exhibits a specific behavior in axial tension. The fibers improve the tensile stress behavior (tensile strength) of the cracked matrix.

The post-cracking strength may be defined on the basis of point values, f_i, corresponding to specified nominal value of crack opening, or on mean values, f_{eqi}, calculated for assigned intervals of crack opening. When a notched specimen is considered, the crack opening may be conventionally assumed equal to the displacement between two points at the notch tip, $CTOD$ (Fig. 1) .

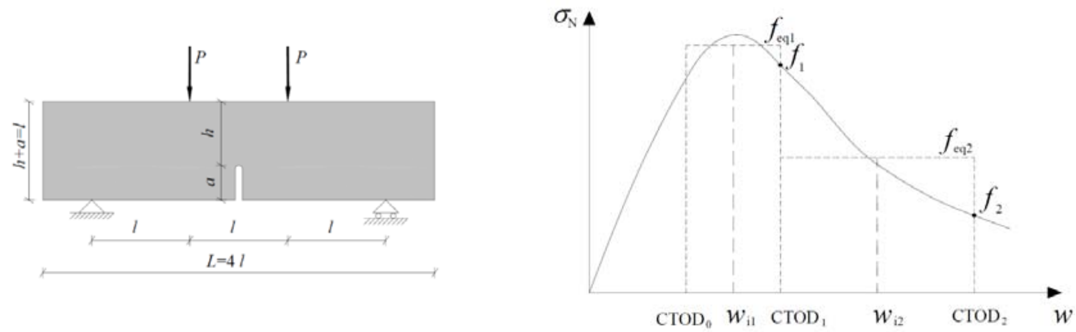


Fig. 1 Definition of point and mean residual strength depending on crack opening values [1]

3.2. Compressive strength

The addition of fibers usually does not affect compressive strength except where the air content is increased, for example by the fiber coating. Fibers generally reduce the brittleness of the matrix, but they do not have significant effect on the compressive behavior. In practice, the constitutive law of fiber reinforced concrete can be assumed equal to that of ordinary concrete.

3.3 Fire resistance

The fire resistance of concrete structures is generally considered not to be influenced by the addition of steel fibers, though the fibers may reduce the degree of spalling somewhat by bridging areas of spalled concrete.

3.4. Impact resistance

Impact resistance, ductility and toughness are generally increased by the addition of any fibers. When impact resistance is required, design is usually determined by testing and then the concrete is specified by type and fiber content.

3.5. Shear strength

The addition of steel fibers to concrete will enhance the shear strength of structural elements. A ductile failure mode is induced, in the same way as by the use of reinforcement stirrups.

3.6. Durability

While steel fibers may reduce the risk of spalling due to corrosion of reinforcement, they do not reduce the rate of corrosion or the rate of loss of cross section. Corrosion of steel fibers themselves at the surface does not cause any spalling.

3.7. Fiber orientation

Orientation of individual steel fibers immersed in fiber reinforced concrete origins from a combination of several basic phenomena of which the most important ones are the so-called wall effect, shear induced orientation and tension stress induced orientation.

The wall effect is caused by the interaction of the immersed steel fibers with the surrounding rigid obstacles such as the formwork. It is geometrically impossible to have a rigid fiber located normal to the formwork at a distance less than half-length of the fiber (red rectangle). Hence, the rigid fiber tends to orientate according to the surrounding flow with a restriction imposed by the wall (blue rectangle).

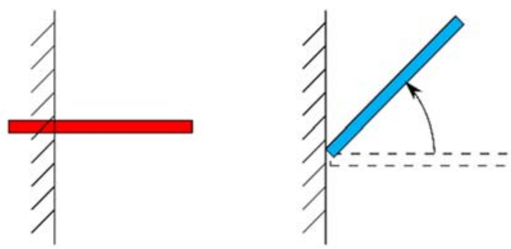


Fig. 2 Wall effect: Blue and red bars represent the possible and impossible orientation of the rigid fiber [2]

4. Mechanical behavior of hardened fiber reinforced concrete

The mechanical behavior of hardened fiber reinforced concrete, the main peculiarity is its tensile behavior. Depending on the tensile strength in the cracked state, fiber reinforced concrete can be classified into concrete with softening or hardening behavior. For low fiber content (with volume fractions approximatively lower than 2%), the behavior is softening. For high fiber content (with volume fractions higher than 2%), the strength can be higher than the matrix one, since a hardening behavior related to multi-cracking phenomenon may occur (Fig. 3).

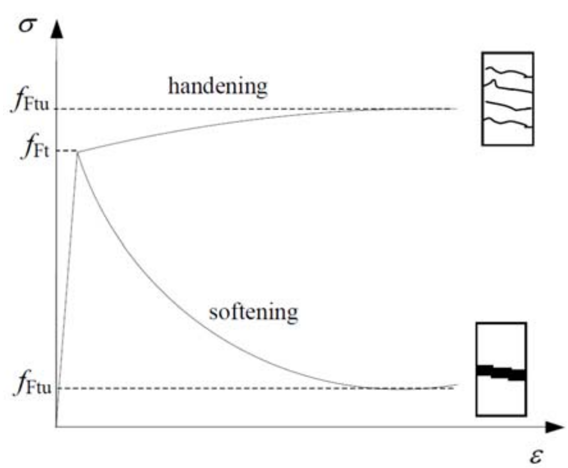


Fig. 3 Fiber reinforced concrete behavior in uniaxial tension depending on fiber content [1]

The properties of the fibers have a direct effect on the behavior of the fiber reinforced concrete. One of these properties is the aspect ratio, defined as the ratio of the total length of the fiber to its "diameter". The aspect ratio has an important effect on the tensile strength of cracked concrete. The tensile strength is higher in concrete containing fibers with a high aspect ratio (Fig. 4).

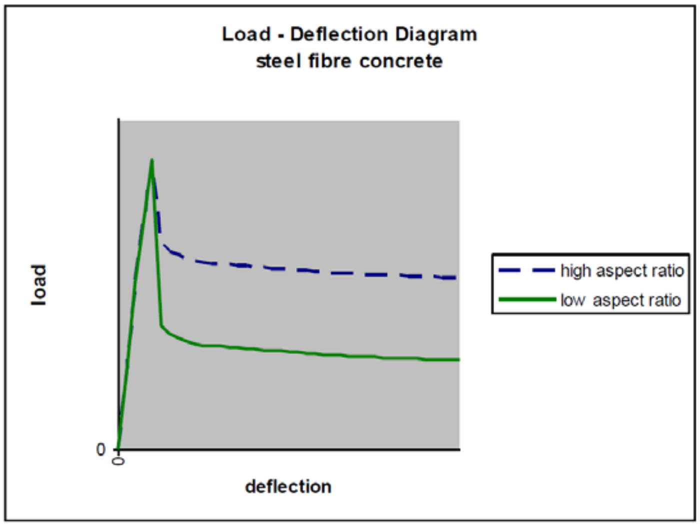


Fig. 4 Post-crack flexural tensile strength of concrete with fibers of different aspect ratios, the same length and the same fiber content (kg/m³) [3]

Correct fiber tensile strength and bond to the concrete matrix are important to obtain a proper pull-out response. Steel fibers usually have hooked ends or other means to transmit stresses from the matrix to the fiber. The anchorage of the fiber must be good enough to attract enough stress to give a high performance while not so high that it results in fiber rupture. In an ideal situation the fiber is slowly deformed and pulled-out from the concrete matrix (Fig. 5).

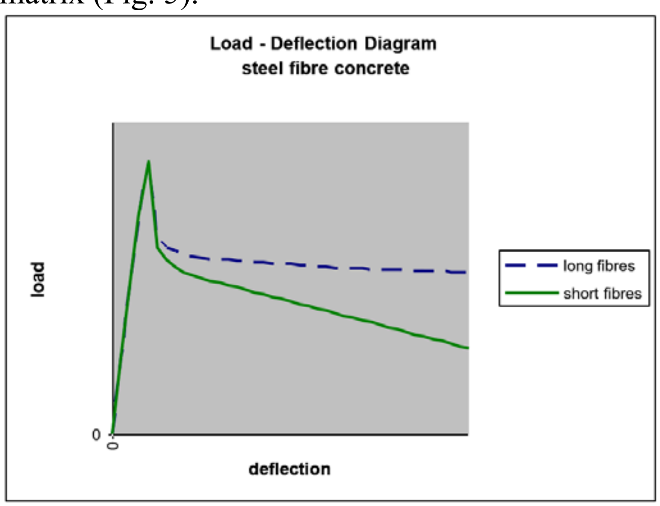


Fig. 5 Post-crack flexural tensile strength of concrete with fibers of different length, the same aspect ratio and the same fiber content. [3]

In addition to the characteristics of the fibers presented above, their shape can also generate different behaviors of fiber reinforced concrete. In Fig. 6, the characteristic load/deflection curves for bending of two concretes with similar compositions, but with different fiber shapes, are presented. If in the case of fiber reinforced concrete with waved fibers, consolidation can be observed after the appearance of cracking, in the case of hooked-end fibers, this phenomenon does not occur, but the ductility is higher and the decrease in strength is slower.

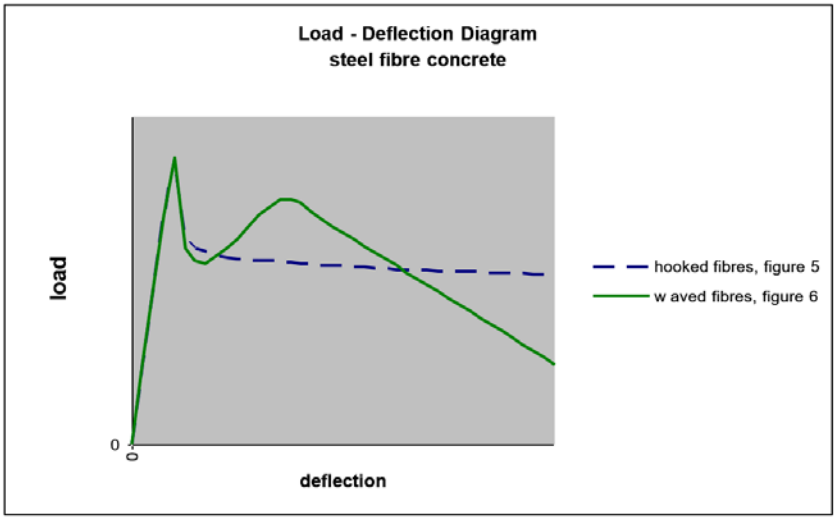


Fig. 6 Post-crack flexural tensile strength of concrete with fibers of different designs and same fiber content [3]

5. Test method for fiber reinforced concrete in tension

This European Standard specifies a method of measuring the flexural tensile strength of metallic fibered concrete on molded test specimen. The method provides for the determination of the limit of proportionality (*LOP*) and of a set of residual flexural tensile strength values.

This testing method is intended for metallic fibers no longer than 60 mm. The method can also be used for a combination of metallic fibers and, a combination of metallic fibers with other fibers.

The tensile behavior of metallic fiber concrete is evaluated in terms of residual flexural tensile strength values determined from the load - Crack Mouth Opening Displacement (CMOD) curve (Fig. 7) or load-deflection curve obtained by applying a center-point load on a simply supported notched prism. (Fig. 8)

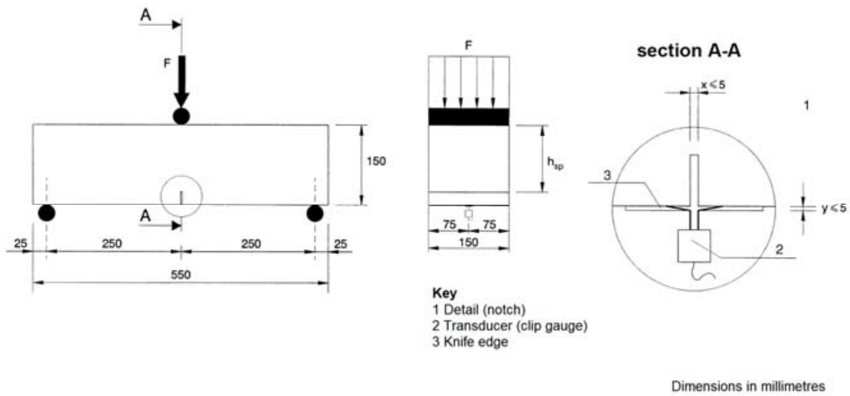


Fig. 7 Typical arrangement for measuring CMOD [4]

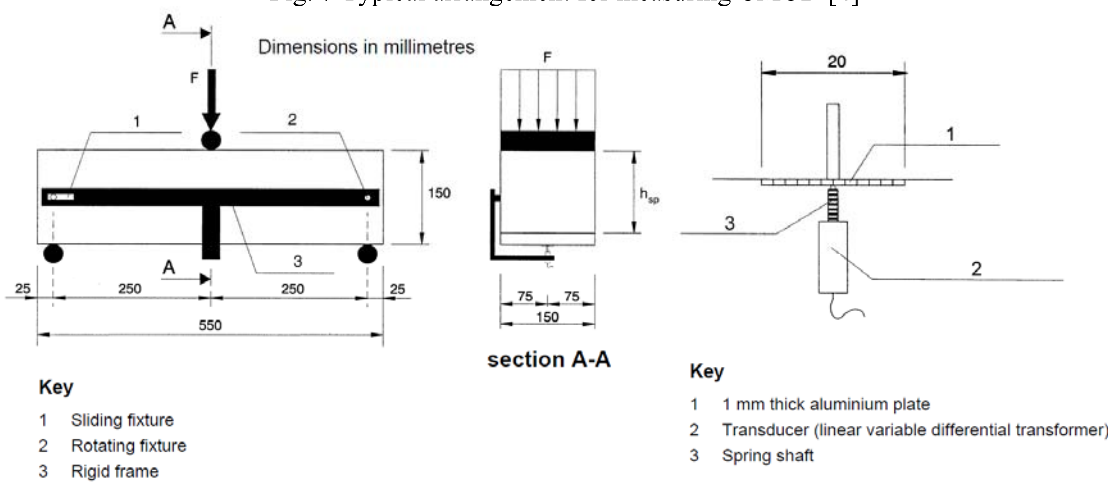


Fig. 8 Typical arrangement for measuring deflection [4]

5.1. Test procedure

In the test procedure for measuring CMOD (Fig. 77) the following terms and definitions apply:

- crack mouth opening displacement - linear displacement measured by a transducer installed on a prism subjected to a center-point load *F* (Fig.7);
- deflection - linear displacement measured by a transducer installed on a prism subjected to a center-point load *F* (Fig. 8);
- limit of proportionality - stress at the tip of the notch which is assumed to act in an untracked mid-span section, with linear stress distribution, of a prism subjected to the center-point load F_L;
- residual flexural tensile strength - fictitious stress at the tip of the notch which is assumed to act in an untracked mid-span section, with linear stress distribution, of a prism subjected to the center-point load

F_j corresponding to $CMOD_j$ where $CMOD_j > CMOD_{FL}$ or to δ_j where $\delta_j > \delta_{FL} (j = 1,2,3,4)$.

The experimental device used to construct the stress/CMOD curve, necessary for classifying dispersed reinforced concrete is schematically shown in Fig. 7. The following relations are used for the stress $f_{ct\,L}^{f}$ at *LOP* and for the residual strengths $f_{R,j}$:

$$f_{ct\,L}^{f} = \frac{3F_L l}{2bh_{sp}^2} \quad (1)$$

$$f_{ct\,L}^{f} = \frac{3F_L l}{2bh_{sp}^2} \quad (2)$$

where

$f_{ct\,L}^{f}$ is the *LOP*, in N/mm^2;
F_L is the load corresponding to the *LOP*, in N;
l is the span length, in mm;
b is the width of the specimen, in mm;
h_{sp} is the distance between the tip of the notch and the top of the specimen, in mm.

$$f_{R,j} = \frac{3Fjl}{2bh_{sp}^2} \quad (2)$$

where

$f_{R,j}$ is the residual flexural tensile strength corresponding with $CMOD = CMODj$ or $\delta = \delta j$ $(j = 1,2,3,4)$, in N/mm^2;
F_j is the load corresponding with $CMOD = CMODj$ or $\delta = \delta j$ $(j = 1,2,3,4)$, in N;
l is the span length, in mm;
b is the width of the specimen, in mm;
h_{sp} is the distance between the tip of the notch and the top of the specimen, in mm.

The material class is obtained from two distinct points of the $\sigma_N - CMOD$ curve (Fig.9) that refer, respectively, to the Service Limit State (SLS; $w = 0.5\,mm$; $f_{r1,k}$) and Ultimate Limit State (ULS, $w = 2.5\,mm$; $f_{r3,k}$). The material class is defined by a numerical value between 1 and 8, obtained from the characteristic value of f_{r1k}, followed by a letter of the Roman alphabet, from "a" to "e". The letter determines FRC behaviour in the post-cracking phase (hardening or softening) from the ratio f_{r3k} / f_{r1k}, as shown in Table 1.

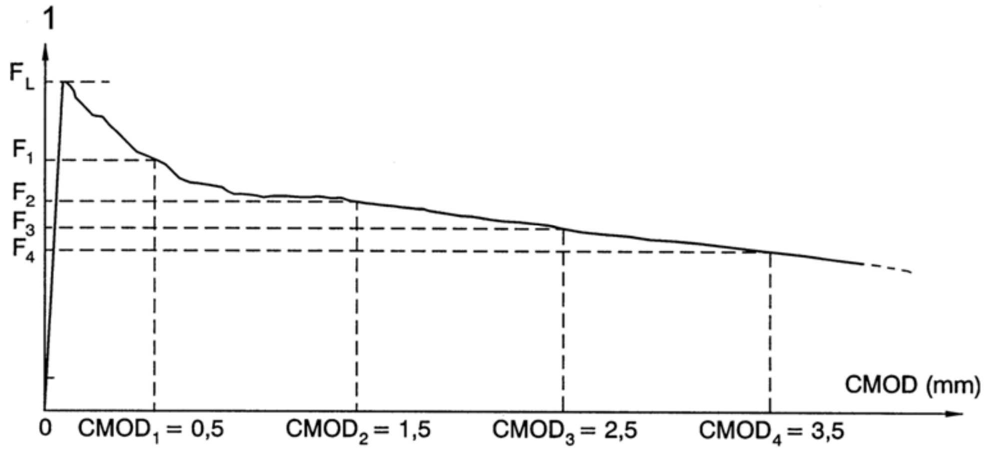


Fig. 8 Load $-CMOD$ diagram and F_j $(j = 1, 2, 3, 4)$ [4]

Fiber reinforced concrete is classified according to its strength and ductility according to Tab. 1. Ductility classes a, b, c, correspond to softening behavior, and classes d and e correspond to hardening behavior.

Table 1

Strength and ductility classes of fiber reinforced concrete [5]

Ductility classes	Characteristic residual flexural strength $f_{R,1k}$												Analytical formulae
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	
a	0.5	0.8	1.0	1.3	1.5	1.8	2.0	2.3	2.5	3.0	3.5	4.0	$f_{R,3k}= 0.5 f_{R,1k}$
b	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.2	3.5	4.2	4.9	5.6	$f_{R,3k}=0.7 f_{R,1k}$
c	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5	5.4	6.3	7.2	$f_{R,3k}=0.9 f_{R,1k}$
d	1.1	1.7	2.2	2.8	3.3	3.9	4.4	5.0	5.5	6.6	7.7	8.8	$f_{R,3k}=1.1 f_{R,1k}$
e	1.3	2.0	2.6	3.3	3.9	4.6	5.2	5.9	6.5	7.8	9.1	10.4	$f_{R,3k}=1.3 f_{R,1k}$

6. Experimental tests on fiber reinforced concrete prisms

Based on the test procedure and the classification into strength and ductility classes, an experimental study was carried out at the TUCEB (Technical University of Construction Bucharest) in which 6 notched prisms were tested. The experimental device is illustrated in Fig. 10. To plot the curves, the applied force and CMOD were measured.


Fig. 9 Experimental device used for 3-point bending test

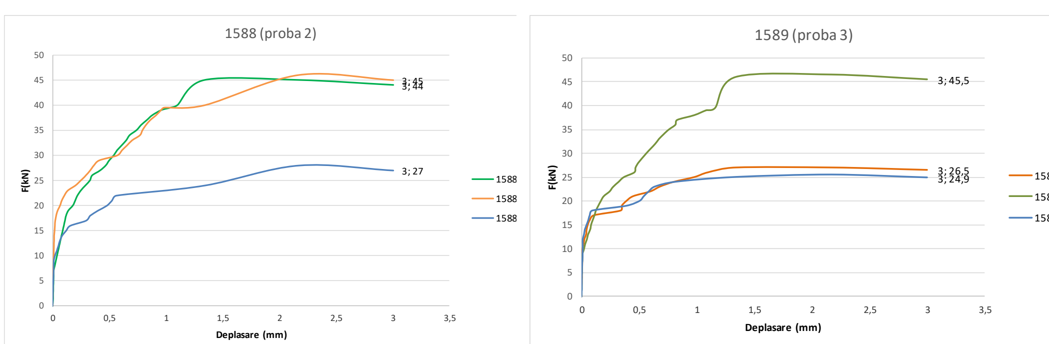
The failure mode of these specimens after the test is illustrated in Fig. 11. This figure shows an irregular crack propagation, which although has a direction induced by the type and configuration of the load, also follows the defects of the material. For this reason, there is also a significant variability in the results, both in terms of the failure mode and the experimental curves. In the bottom view, the presence of fibers crossing the crack is also observed, generating the bridging effect, ensuring resistance in the cracked area. As can be seen, their arrangement is random. Some of them break before failure, or are torn off, but it is observed that some of them remain anchored on both sides of the crack.

a) b)

Fig. 10 Failure mode of the specimen. Side view (a) and bottom view (b)

7. Processing the results and determining the class of fiber reinforced concrete

The experimental Force/CMOD curves are presented in Fig. 11. In these diagrams, which present the 6 tests, a significant dispersion of the results is observed, especially in the cracked area. A significant increase in strength is observed, even after the appearance of the crack, but the differences between the stresses that occur in this area are large, compared to the stress values. From these curves, the values F_L and F_j are extracted, based on which the limit of proportionality $f^f_{ct\,L}$ and the residual strengths $f_{R,j}$ can be determined.



a) b)

Fig. 11 Experimental Force/CMOD plots obtained through 3-pont bending tests

The experimental results for the limit of proportionality $f_{ct\,L}^{f}$ and the residual strengths $f_{R,j}$ are presented in Tab. 2 For each of the 5 strengths, the average and the coefficient of variation were calculated. An increasing dispersion of the results is observed, with the increase of CMOD, which reaches approximately 30% for $f_{R,4}$. Such behavior is specific to this type of material.

Table 2

Three-point bending test results

Residual strength	Specimen						Mean	Coefficient of variation
	1	2	3	4	5	6		
$f_{ct\,L}^{f}$	4.5	6.7	4.5	4.5	4.5	5.6	5.0	18.6%
$f_{R,1}$	9.0	9.6	6.7	6.7	8.6	6.4	7.8	17.7%
$f_{R,2}$	14.4	12.8	7.7	8.6	14.7	8.0	11.0	29.8%
$f_{R,3}$	14.4	14.7	9.0	8.6	14.9	8.2	11.6	28.7%
$f_{R,4}$	14.1	14.4	8.6	8.5	14.6	8.0	11.4	29.0%

Based on these results, to determine the characteristic values X_k of the resistances, the following relationship is used, according to Eurocode 0 [6].

$X_k = X_m \cdot (1 - K_m \cdot V_X)$ (4)

where X_k is the characteristic value of the generic property, X_m is the mean stress, K_m is a parameter dependent on the number of specimens tested and the previously knowledge of V_X, and V_X is the coefficient of variation. The value of the parameter K_m for 6 specimens tested and inexistent previous knowledge is 2,18.

Thus, the values $f_{R,1k} = 4{,}82MPa$ și $f_{R,3k} = 4{,}35MPa$. strength class for $f_{R,1}$ is 4,5 and the ratio of $f_{R,3k}/f_{R1,k} = 0{,}9$ the fiber reinforced concrete goes into class of 4,5. It is observed that the ductility class c is specific to a softening behavior, even if individually, the specimens show hardening behaviors, fact also highlighted by the higher average value for $f_{R,3}$ than for $f_{R,1}$. The result is justified by the fact that the greater dispersion of the results for $f_{R,3}$ than for $f_{R,1}$ led to lower characteristic values.

8. Conclusions

This study presents the main influencing factors and properties necessary to ensure the final properties. To exemplify their behavior, a case study was carried out to determine the strength and ductility class according to current standards.

Fiber reinforced concrete is classified by its tensile behavior in a cracked state, following a three-points bending test, its behavior being either softening or hardening, depending on the amount of fibers added to the mix.

The random nature of the position and orientation of the fibers causes the experimental values of the residual strengths in the cracked state to present an increasingly greater dispersion of the results as the crack mouth opening increases.

In the case of the present experimental study, even if the experimental curves present a typical hardening behavior, the strength and ductility class is specific to a softening behavior. This result is justified by the fact that the high dispersion led to a lower characteristic value for a larger crack mouth opening.

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