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MECHANICS OF CRACKING IN FIBER REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT

Fiber Reinforced Cementitious Composites (FRCC) technology is nowadays aiming at the development of materials with exceptional energy dissipation ability and extreme tensile performance. The objective is to mitigate the limitations of conventional concrete deriving from its quasi-brittle nature, which have negative consequences for the structural performance at particularly severe loading and serviceability conditions. The formation and further development of cracks under tensile loading strongly influence the mechanical behavior of FRCC in tension, therefore the assessment of the tensile stress-crack opening behavior of these materials is of great significance. The work presented in this paper describes the crack formation in FRCC and other cementitious composites in tension, as well as the experimental procedure and test setup used to evaluate the tensile performance of these materials at the level of the stress-crack opening behavior. The results obtained with a few different types of FRCC are utilized to analyze and compare the effect of various composite parameters including fiber reinforcement, cementitious matrix and interfacial bond properties on the resulting tensile behavior.

The fracture process zone encloses relevant mechanisms that explain the quasi-brittle nature of concrete as a structural material. It is an important concept in non-linear fracture mechanics and in the simulation of cracking processes. A better understanding of the micro-cracking mechanisms taking place at the level of the fracture process zone is therefore relevant for an optimized design of FRCC, as well as for the simulation of its mechanical behavior. In this study a digital image analysis procedure was used to capture the crack initiation and propagation process in concrete and other cementitious composites. The formed cracks are observed at a small scale, allowing the investigation and analysis of propagating cracks near the crack tip. The information obtained is used to further understand the mechanics of fracture in cement based materials and especially the ones containing fiber reinforcement.

1. INTRODUCTION

The recent technological development of a wide variety of fibers has been creating new opportunities for the improvement of FRCC as a structural material. Their design nowadays aims at the development of materials with exceptional energy dissipation ability and extreme tensile performance. The intention is to mitigate the limitations of conventional concrete deriving from its quasi-brittle nature, often revealed by the catastrophic collapse of structures during extreme loading events or the early loss of functional properties of structures due to insufficient durability. These are two of the main motivations of technological development of FRCC.

1.1. Fiber Reinforced Cementitious Composites

In the past few decades the research carried out in the FRCC field has suggested different approaches for the design of these materials (Brandt 2008). In particular, when the FRCC is designed to develop strain-hardening in tension and multiple cracking, the so-called Strain-hardening Cementitious Composites (SHCC) are obtained. Engineered Cementitious Composites (ECC), a class of cement based materials typically reinforced with Polyvinyl Alcohol (PVA) fibers, is one of the examples of SHCC showing relatively high tensile strain hardening ability (between 3% and 7% of ultimate tensile strain) and average tensile strength of 5 MPa (Li 2003).

In the perspective of structural design, strain-hardening ability in tension is often referred to as the most relevant feature of SHCC. The structural problems that can be effectively solved by using these materials are numerous and diverse. Strain-hardening in tension results in the ability of the material to develop multiple cracks. This relevant material property represents a dual advantage in engineering applications: while more cracking develops at the same tensile deformation level, the individual crack openings are much smaller, often invisible to the naked eye. The resulting benefits in terms of durability and preservation of functional properties of the structural elements are evident. Conversely, higher energy dissipation ability exists at the level of a single crack, which is multiplied by the large number of cracks typically developed. The result is a material that can be designed to exhibit high toughness, among other beneficial material features.

The mechanical behavior of FRCC is the result of a delicate balance of multiple factors. The interfacial bonding and fiber pull-out properties, the material parameters of the fibers and of the matrix, the distribution of material flaw sizes in the matrix, the fiber orientation and their dispersion in the matrix play an important role in the resulting composite mechanical behavior. The study of the influence of all these parameters separately is cumbersome, given that they perform in a highly coupled manner. At a smaller scale the fiber pull-out tests are often performed to study the interaction between the single fiber and the matrix. However the reliability of the results obtained is often questioned mainly because the mechanical behavior exhibited by the isolated fiber while being pulled out is seldom comparable to the mechanics of the same fiber embedded in the FRCC. Alternatively, the most commonly used type of test, either to characterize or to design SHCC, is the direct tension test to assess the stress-strain behavior, using dumbbell-shaped (Figure 1 and Figure 2) or coupon specimens (Kanda and Li 2006; Naaman and Reinhardt 2006). The material tensile stress – strain law is thereby assessed, as well as the potential of the material to develop multiple cracks. Although with additional uncertainty, inverse analysis may alternatively be used to derive indirectly the stress - separation law from bending or diametric compression tests, like the Compact Tension Test (CT), the Wedge Splitting Test (WST), the Four Point Bending Test among others (see for example Shah et al. 1995).

The assessment of the constitutive behavior of FRCC in terms of the stress – crack opening behavior is often seen as the most advantageous approach to assess the tensile performance of FRCC. The main obstacle to this strategy is the difficulty associated with the isolation of a single crack when the material is especially designed to develop multiple cracks and demonstrates high tolerance to damage. In order to produce the adequate mechanical conditions for the initiation and evolution of a single crack, the stress fields generated on test specimens under tension need to be locally intensified. This may be achieved by introducing constrictions or notches at predetermined sections (Fischer et al. 2007, RILEM TC TDF-162 2001, Shah et al. 1996). In the present work the SCTT setup was used to assess the tensile stress – crack opening behavior of seven different FRCC. The formation of a single crack during testing was confirmed in previous studies (Pereira et al. 2009).

Figure 1: Test-setup to assess tensile stress-strain behavior.

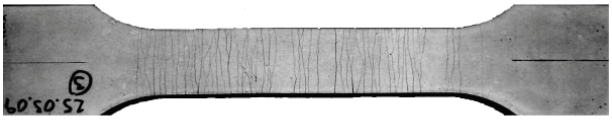


Figure 2: Example of ECC specimen showing multiple cracks after direct tension test (Lárusson et al. 2010).

1.2. Digital Image Analysis of Fracture Process

The transition zone between the fully developed crack and the intact bulk material ahead of the crack tip of propagating cracks encloses relevant mechanisms that determine the quasi-brittle behavior of cementitious composites and concrete. The moderate tensile hardening prior to the attainment of the ultimate tensile capacity and the subsequent rapid tensile softening that characterize the quasi-brittle behavior of concrete are explained by a diffuse micro-cracking area forming ahead of the crack tip known as the fracture process zone (Karihaloo et al. 1993, Landis and Shah 1995). The great attention that the scientific community devotes to the fracture process zone derives from its importance in non-linear fracture mechanics and in the simulation of cracking processes in cementitious composites. When fibers are used to restrain crack propagation, the immediate outcome is additional closing stresses that develop in the region of the macro-crack forming behind the propagating crack tip. However, the presence of the fibers may also have an effect in the region of the fracture process zone ahead of the crack tip, and therefore it may affect the mechanics of crack initiation and propagation. A better understanding of the micro-cracking mechanisms taking place at the level of the fracture process zone is therefore relevant for an optimal design of fiber reinforced cementitious composites (FRCC).

The research described in the literature towards a better understanding of the fracture process zone led to the development of special techniques of analysis of cracking. The very fine cracks to be detected require high resolution equipments (Hornain et al. 1996, Otsuka and Date 2000). In addition, most of the intrusive characterization techniques used in other materials potentially induce preliminary cracks in concrete, either due to direct mechanical action, induced drying, or the alteration of other physical variables important for the delicate balance of the microstructure of concrete. Many different techniques have been especially developed for the analysis of the fracture process zone and cracking in concrete and other cement based materials. Radiography (x-rays, neutrons, or others), impregnation, acoustic emission, ultrasound, laser holography and interferometry are examples of techniques which have successfully revealed quantitative information about the fracture process zone (Otsuka and Date 2000, He et al. 1995, Knab et al. 1984, Shah 1990). Although most of the macroscopic features of cracking processes in concrete are well understood, the micro-mechanisms of cracking and the essence of the fracture process zone still preserve some uncertainties. More qualitative and quantitative information about the fracture process zone is still required, as it can help improving the design of cement based materials, and in particular the design of more efficient FRCC.

Recent developments in digital photography technology have reached significant improvements in the quality of digital acquisition of images for scientific research. In particular, the digital image correlation technique has been developed to obtain full field surface displacements and strains of objects under load, based on the comparison of two digitized images of the surface of an object before and after deformation (Chu et al. 1985). In this study the cracking behavior of four cementitious composites was investigated. The purpose was to identify the potential of this technique to reveal the important features of the cracking process in each of the four types of cementitious composites investigated. The contribution of the results obtained for a better understanding of cracking process in cementitious composites and of the effect of fiber reinforcement at the level of the fracture process zone was assessed.

2. TENSILE STRESS – CRACK OPENING BEHAVIOR OF FRCC

2.1. Materials and Test Methods

In the present work, the tensile behavior of seven different fiber reinforced cementitious composites was assessed. The materials used in the composition of the cementitious matrix were the same for all composites, and the type and volume fraction of fiber reinforcement was varied. The matrix composition in terms of the weight of each ingredient for a total volume of 1 dm^3 is presented in Table 1.

Table 1: Weight of the materials used for 1 dm^3 of cementitious matrix.

Cement	Fly ash	Fine sand (0.17 mm)	Quartz powder	Water
428 g	856 g	150 g	150 g	100 cm^3

Fibers of three different natures were used: PVA (polyvinyl alcohol), PAN (polyacrylnitrile) and PP (polypropylene). The main properties of these fibers are presented in Table 2.

Table 2: Main properties of the fibers used.

Abbrev.	Tensile strength	Length	Diameter
	MPa	mm	µm
PVA	1600	8	40.0
PP	900	12	40.0
PAN 1.5	826	6	12.7
PAN 3.0	767	6	18.0
PAN 6.7	413	6	26.8
PAN 30	295	6	57.0

Considering the PP and the PAN fibers all composites contained 2% of fibers by volume, while for PVA fibers the percentages of 1% and 2% by volume of the composite were used.

2.2. Single Crack Tension Test (SCTT)

The assessment of the mechanical parameters of a planar crack during the initiation and propagation stages requires the isolation of a single crack during the entire test sequence. SHCC materials are designed to develop multiple cracks in tension, consequently the formation of only a single planar crack is naturally prevented by the material. To meet this requirement, different geometries of notched specimens were previously investigated, and their ability to promote the initiation and full development of a single crack was explored.

The dimensions and final geometry adopted for the specimen are presented in Figure 3. The length of the specimen was 120 mm and the free distance between the fixed edges during testing was 70 mm. The testing sequence consisted of subjecting the specimens to a constant axial displacement rate of 5 µm/s. This deformation rate was imposed by the hydraulic actuator to the specimen by means of two hydraulic grips, providing fixed support conditions to both ends of the specimen (rotations and transverse displacements were restrained). During testing the opening of the notch was evaluated by means of two clip gages positioned in opposite sides, as shown in Figure 4.

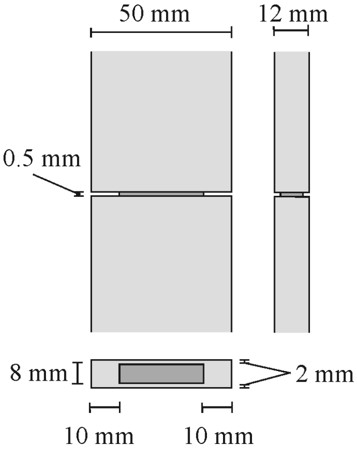


Figure 3: Geometry of the SCTT specimen.

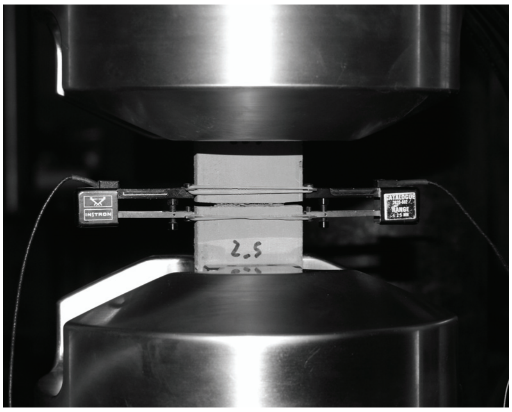


Figure 4: Tensile test-setup including supports and clip gages.

An example of a ruptured specimen with the final geometry proposed in this study is presented in Figure 5, where a single crack was obtained and characterized in tension. After adopting this geometry the formation of a single crack was consistently obtained in the tests conducted subsequently.

2.3. Tensile Stress – Crack Opening Results

The results obtained after testing the FRCC specimens in direct tension are presented in Figure 6 to Figure 9. The values of the tensile stress (nominal tensile stress) were obtained by computing the ratio between the experimental tensile load and the net area of the notched cross-section (8×30 mm^2). The crack mouth opening displacements (CMOD) were obtained by averaging the displacements measured in the two opposite clip gages, although these were typically very approximate. For each composite, the results of three of the six specimens tested are shown. Excluding anomalous results, the upper and lower limit results obtained are presented to show an envelope of the obtained behavior.

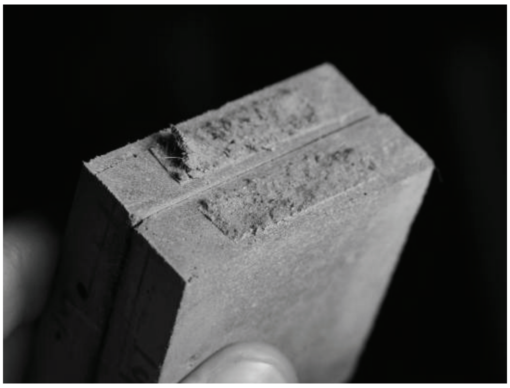


Figure 5: Single crack obtained with the adopted specimen geometry.

As shown in Figure 6 to Figure 9, the results obtained are consistent and reasonable, revealing the intrinsic mechanics of each composite system. The influence of the geometrical and mechanical parameters of each fiber reinforcing system can be traced and studied effectively. The activation of fibers with different diameters occurs at different stages of the cracking processes. The PAN fibers, with a smaller diameter, were activated even before the first cracking strength was reached, and have contributed effectively to the increase of the cracking peak stress. Their premature effective activation was followed by an also premature exhaustion of their contribution to the post-cracking tensile behavior. The contribution of PVA and PP fibers to increase the first cracking strength was insignificant. Instead, their full mobilization became apparent in the post-cracking stage, with the pronounced increase of the tensile bridging stress. The main difference between the SCTT results observed for PVA and PP fibers was in the region of the tensile stress – crack opening curves where the peak bridging stress is reached. While for the PVA reinforced composites the experimental curves exhibited an inverted v-shape, for the PP reinforced composites the experimental curves exhibited a smooth inverted u-shape curve. The well known superior interfacial bonding of the PVA fibers with the matrix may justify these results, as opposed to the poorer bonding of the PP fibers due to their hydrophobic nature (Li et al. 2002; Wei et al. 2002).

The obtained results seem to reveal distinct generic stages of a typical tensile stress – crack opening behavior. At the onset of tensile testing, the evolution starts with what can be assumed as a predominantly elastic behavior, with a steep increase in the applied load while tensile deformation increases. This first stage ends when the nominal matrix cracking strength is achieved with a rapid transition of the tensile stresses from the cracked matrix to the fibers and the subsequent tensile stress decay. Preliminary stages of micro-cracking and micro-defect propagation may affect the shape of this transition stage, governed by fracture mechanisms and dependent on the shape and size of pores and micro defects.

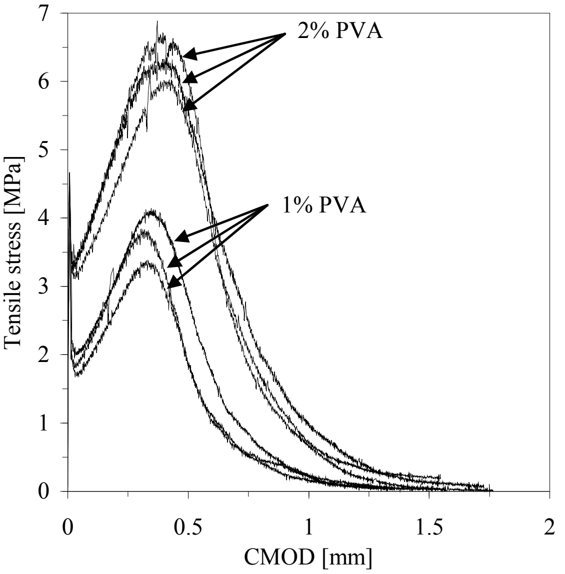


Figure 6: Tensile stress – CMOD for the composites reinforced with PVA fibers.

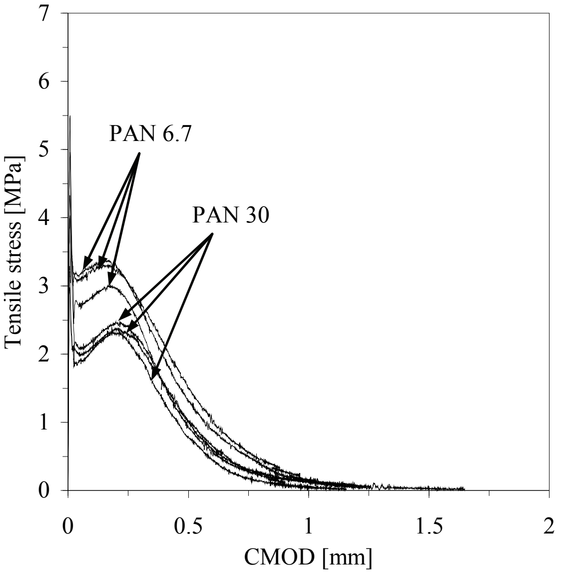


Figure 7: Tensile stress – CMOD for the composites reinforced with PAN6.7 and PAN30 fibers.

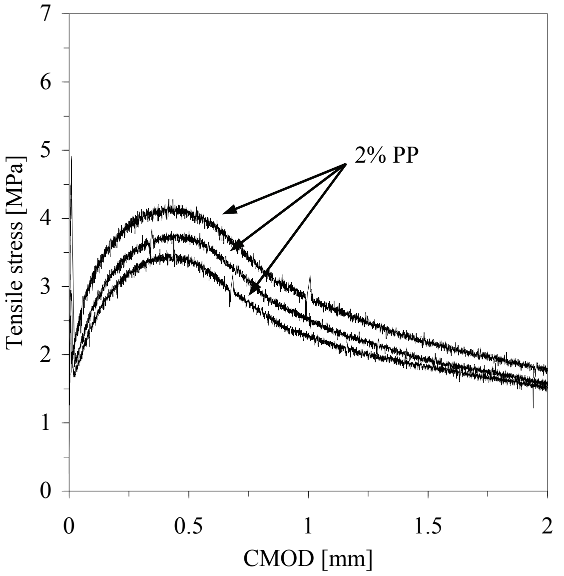


Figure 8: Tensile stress – CMOD for the composites reinforced with PP fibers.

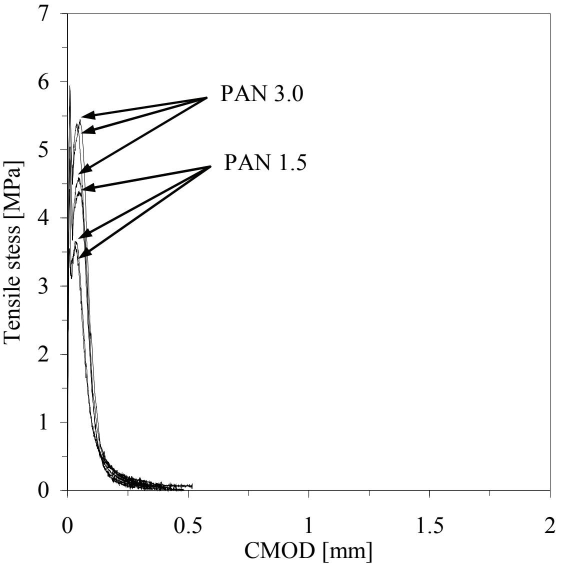


Figure 9: Tensile stress – CMOD for the composites reinforced with PAN1.5 and PAN3.0 fibers.

After the rapid load decay caused by the transfer of the tensile stresses from the matrix to the fibers, a new hardening stage supported by the full mobilization of the fiber-matrix bonding mechanisms is initiated. While the fibers stretch, hardening occurs until the peak stress is reached. In this third stage the stiffening effect provided by the fiber reinforcement is exhausted either due to fiber debonding and slip-softening pull out mechanisms or fiber rupture. The result is respectively an inverted ‘u’ or ‘v’ shape in the region of the tensile stress – crack opening curve where the peak bridging stress is reached.

The fourth stage consists of the post-peak softening stage observed in all curves. It coincides with the gradual neutralization of the remaining links between opposite crack faces. This stage may be divided into two different branches with different inclinations, one steeper and other mostly horizontal, depending of the geometry and the mechanical properties of the aggregates and the fibers.

The sequence of stages previously described consists of an interpretation of complex mechanisms taking place at the level of a single crack in the bulk composite, which summarize in a rational way the tensile behavior of FRCC, useful from a design perspective. In Figure 10 this systematic approach of the tensile stress – crack opening behavior is summarized in the shape of a constitutive design law.

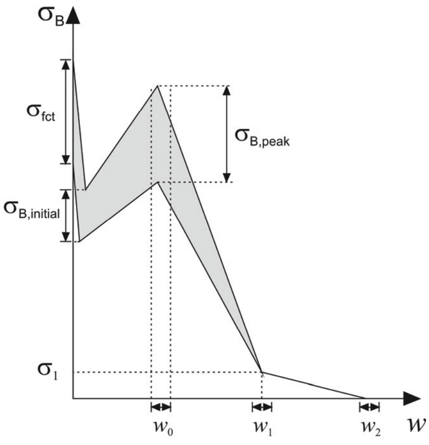


Figure 10: Tensile stress – crack opening design law for FRCC (Yang and Fischer 2006).

The resulting data, and the scatter associated to each of the parameters represented in the generic tensile stress – crack opening curve, may be used to support the structural design and to define reliability factors for each mechanical parameter. Material and structural design may be integrated with this approach.

3. INVESTIGATION OF FRACTURE USING DIGITAL IMAGE-BASED ANALYSIS

3.1. Materials and Test Methods

The testing procedure consisted of applying an eccentric tensile load to a single-edge notched specimen at a constant displacement rate of 5 μm/s, inducing the formation and subsequent propagation of a single crack in a controlled manner (Figure 11). Further details about the testing procedure may be found elsewhere (Pereira et al. 2011).

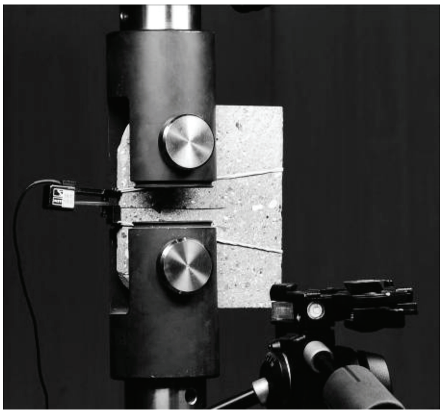


Figure 11: Eccentric load tensile test setup.

Four specimens with different compositions were tested: cement paste, mortar, concrete and FRCC. The composition of the cement paste consisted of cement and water only. The concrete composition consisted of the addition of aggregates with a maximum size of 4 mm to the cement and water paste. The composition of the mortar and the FRCC consisted of cement, fly ash, fine sand (0.170 mm) water and admixtures, and Polyvinyl Alcohol (PVA) fibers as reinforcement in the case of the FRCC.

The formation and propagation of the crack was traced in a portion of 24 mm by 36 mm at the surface of the specimen. Images with resolution of 24 megapixels were captured every second during testing and subsequently used for the continuous interpolation of the strain fields at the inspected surface of the specimen.

3.2. Mechanical Results

The results obtained in terms of load – crack mouth opening displacement (CMOD) during testing are presented in Figure 12. The CMOD was measured using a clip gage, positioned at the edge of the notch (Figure 11).

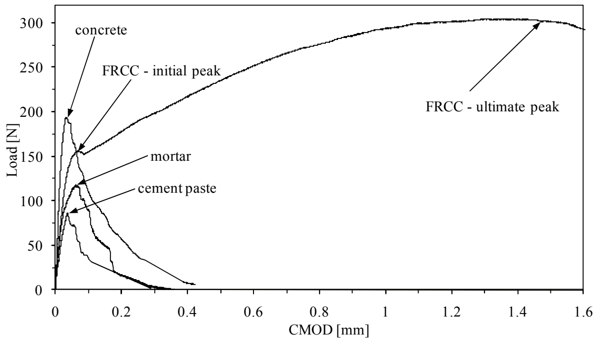


Figure 12: Load – CMOD curves measured during testing. The peak loads are identified with an arrow.

In general, the load-CMOD curves obtained for the three non-reinforced cementitious matrices present similar quasi-brittle behaviors, with the cement paste reaching the lowest tensile load (86 N) and the concrete the highest (192 N). The post-peak softening branch in the concrete specimen showed more gradual load decay compared to the other unreinforced cementitious matrices. The quantity and size of aggregates used in each matrix apparently affected the fracture process, with more and bigger aggregates leading to less sudden energy releases and abrupt load drops during softening. The PVA fibers in the FRCC specimen were responsible for a pronounced tensile hardening stage after the first peak load (initial peak). The maximum tensile load reached was 304 N (global peak) at a CMOD of 1.46 mm.

3.3. Near Tip Full Field Strain Analysis

In Table 3, the results obtained with the image-based monitoring system are shown. The principal strains derived from the interpolated displacement fields at the facets overlay are presented. The color gradients evolve from dark grey (zero strain) to white (maximum strain of 5%). These strain values refer to the displacement gradients derived at the facets overlay, according to the principles of linear elasticity (Chu et al. 1985). To illustrate the obtained results, three representative stages were selected: before the peak load was reached (90% of the peak value), when the peak load was reached and after the peak load (50% of the peak value). In the case of the FRCC specimen, the peak load refers to the first peak load.

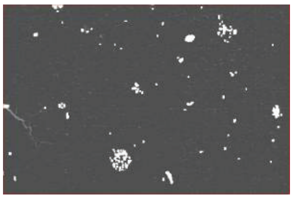
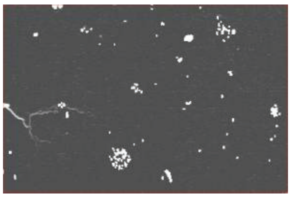
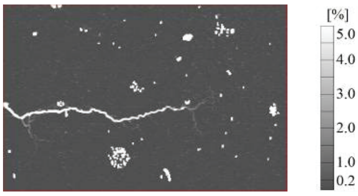
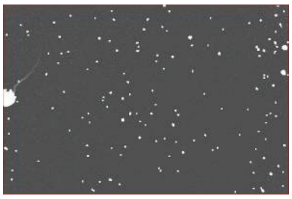
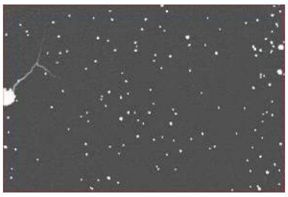
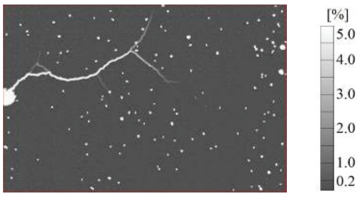
The images in Table 3 show that the technique reveals high sensitivity to detecting very small cracks. When 90% of the peak load was reached the opening at the tip of the notch was 4 μm in the cement paste specimen, 4 μm in the mortar, 5 μm in the concrete and 4 μm in the FRCC. For all specimens the measured deformations revealed the early initiation cracks at the tip of the notch, well before the peak load was reached.

The effect of crack branching was visible in all the specimens tested, although assuming different details. In the mortar specimen the crack branches developed were fewer, longer and more discrete. In the concrete specimen the crack branching occurred more frequently and the branches of the main crack were less visible and more diffuse. A small area of diffuse micro-cracking ahead of the principal crack was visible in some stages as well. The increase of the number of aggregates and their size contributed to the increase of crack smearing. Simultaneously, the smaller and more frequent crack branches formed suggest that the crack smearing near the crack tip contributed to the gradual dissipation of the energy during the fracture process. In the FRCC specimen, branching and crack smearing were less visible, probably due to the contribution of the fibers to arrest the propagation of micro-cracks. Observing the results obtained with the cement paste specimen (Table 3), secondary cracks became visible right from the onset of the testing sequence. These secondary cracks were not connected to the principal crack initiating at the tip of the notch, suggesting that these were shrinkage cracks, activated with the increase of ambient stress. The crack path was influenced by these pre-existing shrinkage cracks, which may explain the lower initial stiffness observed in the load - CMOD.

3.4. Crack Profiles and the Influence of Fiber Reinforcement

The influence of fibers in the fracture process and crack propagation was evaluated by investigating the crack profiles obtained in the mortar and the FRCC

Table 3: Maximum principal strains in the facet overlay for three load levels: before peak load (90% of the peak load); when peak load is reached; after peak load (50% of the peak load).

	90% of peak load (before peak)	peak load	50% of peak load (after peak)
Cement paste			
concrete			
mortar			
FRCC			

specimens. The morphology of the principal crack formed in the mortar specimen is depicted in Figure 13 at five distinct loading stages: before the first peak load when 90% of the load is reached (P-10%), when the peak load is reached (P), and after the peak load is reached for 90% of the peak load (P-10%), 80% of the peak load (P-20%) and 50% of the peak load (P-50%). The crack profiles were obtained by computing the evolution of the distance difference between two points placed in opposite sides of the principal crack. Thirty of these virtual clip gages were placed evenly spaced (1 mm) along an initial portion of the macro-crack measuring 30 mm, starting from the tip of the notch.

In general, the results presented in Figure 13 reveal that the displacements measured in the virtual clip gages follow approximately the shape of a third order polynomial trend line. Significant differences between the general shapes in the mortar and in the FRCC specimens can although be observed. In the case of the mortar specimen, when using the 2 mm virtual clip gages the open crack portion of the displacement profiles seems to gradually change from a single curvature shape to double curvature. When these crack profiles are compared with the ones obtained with the FRCC specimen, the gradual transition from a single to a double curvature shape is no longer observed. For comparison, the five stages selected for the FRCC were the ones in which the crack opening at the tip of the notch (x = 0) was approximately identical to the respective ones observed in the five load stages selected for the mortar specimen, while using the 2 mm virtual clip gages. This comparison allows also to observe that cracks with the same opening at the tip of the notch (x = 0) show a much smaller length in the case of the FRCC than in the mortar specimens. Additionally, in the case of the FRCC specimen the relative displacements in the region ahead of the tip of the crack are negative, which may be a consequence of the bridging stresses provided by the fibers in the region of the open crack. These additional compression strains/stresses in the region ahead of the crack tip affect the propagation of the crack by promoting the rapid transition from the undamaged bulk material to the fully open crack through a smaller length.

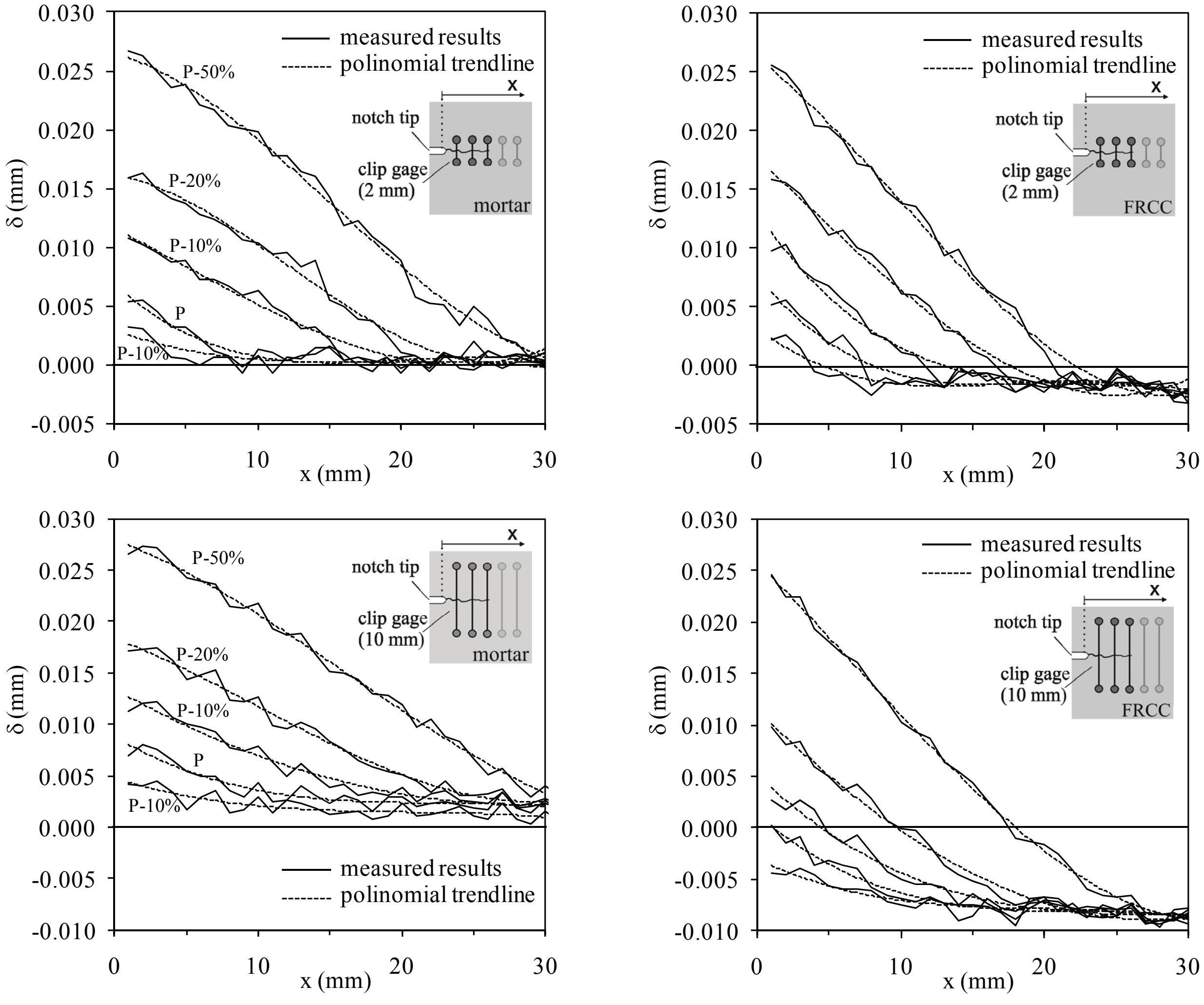


Figure 13: Crack profiles obtained for different loading stages of the mortar and the FRCC specimens using two virtual clip gage lengths (2 mm and 10 mm).

The use of the virtual clip gages with a length of 10 mm instead of the 2 mm aimed at helping to identify the area around the crack predominantly affected by the crack propagation. Figure 13 shows that the differences observed previously regarding the curvature of the displacement profile in the region of the open cracks remain similar but less evident. The compression strains observed ahead of the crack tip became more pronounced in the case of FRCC, contrarily to the mortar specimen where small tensile strains were observed through the whole monitored length, even at the early stages of the cracking process. This suggests that the contribution of the fibers in the case of the FRCC results in the overall increase of the ambient compression stresses surrounding the fracture process zone, which in turn contribute to the reduction of the crack length for the same CMOD and the reduction of the size of the transition region between the open crack and the intact bulk material. Due to the reduced post-peak residual tensile stresses in the mortar, the ambient stresses surrounding the crack tip region are tensile and develop along the full monitored length, even at the early crack stages. As a consequence, the stabilization of the cracking processes and crack propagation resulting from the adoption of the fibers was not only a direct consequence of the fiber contribution for crack bridging but also a result of the alteration of the stress and strain fields surrounding the crack tip. Not only the shape but also the length of the transition zone between the fully open crack and the intact bulk material were changed or affected by the presence of the fibers.

4. CONCLUSIONS

The formation of a single crack in a fiber reinforced cementitious composite during the tensile test is essential for the accurate assessment of the constitutive stress-crack opening behavior.

The activation of fibers with different diameters occurred at different stages of the cracking processes. The fibers of smaller diameter were activated even before the first cracking strength was reached, and they contributed effectively to the increase of the first cracking strength. The enhanced contribution of the fibers with larger diameter for the tensile hardening became more evident in the post-cracking stage instead. The main difference between the tensile stress – crack opening behaviors observed of PVA and PP fibers was in the region where the peak bridging stress is reached. While the PVA reinforced composites exhibited an inverted v-shape curve, the PP reinforced composites exhibited a smooth inverted u-shape curve. Therefore the SCTT revealed to be sensitive to the different interfacial bonding, fiber rupture and pull-out conditions established between the fibers and the matrix.

The constitutive tensile stress – crack opening law comprises very relevant information for the numerical modeling of structures conceived with FRCC. Numerical models of continuum or discrete with the ability to simulate discrete cracks or simulating cracking smearing the crack displacements by representative areas or volumes may benefit from the information extracted with the SCTT and the constitutive tensile stress – crack opening material law. In the perspective of the material design of FRCC itself, the design and optimization procedure may be based on a set of requirements established with respect to the main parameters characterizing the tensile stress – crack opening law. The SCTT setup allows the consistent assessment of the constitutive stress – crack opening law and may be used as an important instrument to guide the process of designing and optimizing the material.

The analysis of propagating cracks in cementitious composites with an image-based monitoring technique presented in this study allowed the interpretation of the relevant micro-mechanical events taking place during the initiation and propagation of the cracks, as well as the investigation of their relation with the observed mechanical behaviors. The influence of shrinkage induced pre-existing cracks on the path of the principal crack was revealed by the images of the cement paste specimen. The pre-existing cracks also explained the smaller initial stiffness observed in the cement paste specimen. Similarly, the presence of different quantities and sizes of aggregates influenced the morphology of the propagating cracks especially near the crack tip. In the cementitious composites containing more and larger aggregates, the observed cracks developed shorter and more smeared crack branches, sometimes even a small, diffusely cracked area ahead of the crack tip was observed. In the FRCC specimen the crack branches were less visible, suggesting that the fibers have contributed effectively to the micro-cracking arrestment.

The investigation of the displacement profiles along the cracks formed in the mortar and in the FRCC specimens led to the conclusion that the shape of the crack was altered by the use of fibers as reinforcement. Also the crack lengths observed at different loading stages at the same crack tip opening displacements (CTOD) were reduced in the case of the FRCC. The presence of the fibers in the FRCC was shown to affect the mechanical behaviour of the composite not only by contributing to the crack bridging in the region of the open crack but also by changing the ambient strains surrounding the crack tip region and in particular altering the size and boundary conditions of the fracture process zone.

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