The wedge splitting test – a test method for assessment of fracture parameters of FRC?

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ABSTRACT: In the presented paper, the applicability of the wedge splitting test for determining fracture properties of fiber-reinforced concrete is discussed and results obtained when using different specimen geometries are compared. This is based on experiments on steel fiber-reinforced concrete, with different mix proportions and fiber geometries, and non-linear fracture mechanics analyses. Furthermore, a general discussion of the wedge split test method when applied to FRC is presented, e.g. requirements on the test set-up, specimen geometry, data analysis techniques to determine the tension softening relationship, etc.

Keywords: Wedge-splitting test, fiber-reinforced concrete, fracture mechanics.

1 INTRODUCTION

Knowledge of the physical nature of the fracture processes of cementitious composites, such as concrete and fiber-reinforced concrete, are becoming central for design of concrete structures and development of new high performance materials. The most significant difference between regular concrete and fiber-reinforced concrete (FRC) is the energy absorption capacity. Accordingly, FRC are used in structures because of this energy absorption capability, which in turn motivates the attempts to determine the most proper test procedure for FRC toughness characterization. In spite of this, there is yet no agreed standard test method for conformity assessment of these fundamental fracture properties, which are needed if FRC are to be used in structural applications.

This endorse the views that there is need for a simple and robust test method, for determining the fracture properties of fiber-reinforced cementitious composites, that can be used by small and medium large companies in their daily production without having to invest in expensive testing equipment. A test method should, in order to be accepted and widely used in the industry, preferably make use of small specimens that are easy to handle, should not require advanced, close-loped, testing systems, and, above all, produce reliable test results. The wedge splitting test (WST), originally proposed by Linsbauer & Tschegg (1986) and later developed by Brühwiler & Wittmann (1990), fulfils these basic requirement: the wedge-split test method has the advantage of using a relatively small and compact specimen; furthermore, the test method does not require sophisticated test equipment, the test is stable and a closed loop system is not required. The method has proved reliable for fracture testing of ordinary concrete, at early age and later, see Østegaard (2003) and de Place Hansen *et al.* (1998), for autoclaved aerated concrete, see Trunk *et al.* (1999), and for light-weight aggregate concrete, see Faust & Voigt (1999). However, regarding the wedge splitting test and steel fiber-reinforced concrete not much information can be found.

Fiber reinforced concrete, with low and moderate volumes of fibers, exhibit softening and the tensile softening relationship (the so-called stress-crack opening relationship) is a fundamental relationship that may be used to describe the toughness. In the fictitious crack model, originally suggested by Hillerborg, see Hillerborg *et al.* (1976) and Hillerborg (1980), the main parameters are: the tensile strength, the fracture energy, and the shape of the softening curve. Knowledge of these parameters is crucial for a complete characterization of the material behavior and, consequently, for a computational fracture analysis. Since the fictitious crack model was introduced to describe the fracture processes of quasibrittle materials, considerable research has been carried out in attempting to quantify its associated softening law. For regular concrete, the shape of the softening curve does not vary too much, see Stang (1992) and Cornelissen *et al.* (1986), and for most practical applications it is usually sufficient to determine the fracture energy and select an appropriate softening relationship. For FRC, on the other hand, the shape of the softening curves varies considerably (depending on the type and amount of fibers used, the quality of the concrete, etc.) and the complete fracture energy is not of interest since the critical crack opening, w_c, (defined as the crack opening when the traction becomes zero) occurs for very large crack openings for most fibers, while it for most concretes seldom is larger than 0.2 mm. There are also other differences between the fracture behavior of regular concrete and fiber-reinforced: the size of the characteristic dimension of the microstructure; the length and the width of the fracture process zone, which for concrete has been shown to be dependent on the specimen size, see Otsuka & Date (2000); the fiber bridging mechanisms; and critical crack opening, w_c. In view of these differences there are questions that need to be investigated regarding the wedge splitting test before it can be used as a standardized test method for fiber reinforced concrete.

2 TEST PROGRAM

A test program was set up in order to investigate the applicability of the WST-method for steel fiber reinforced concrete. Different specimen geometries were used in the investigation; see Figure 1 and Table 1 for geometry. In total six different concrete mixes were used (the volume fraction of fibers, V_f, the fiber geometry, and the water cement ratio was changed), see Table 1. The fibers used were of the type hooked end, from Dramix: RC-80/50-BN (fiber, length 50 mm, diameter 0.62 mm, tensile strength 1050 MPa); and RC-80/30-BP (length 30 mm, diameter 0.38 mm, tensile strength 2300 MPa). To avoid any wall effects, the notches were sawed and the specimens were casted with a depth of 150 mm and then 25 mm were cut on each face to produce a specimen with a thickness of 100 mm. The specimens were water cured until testing.

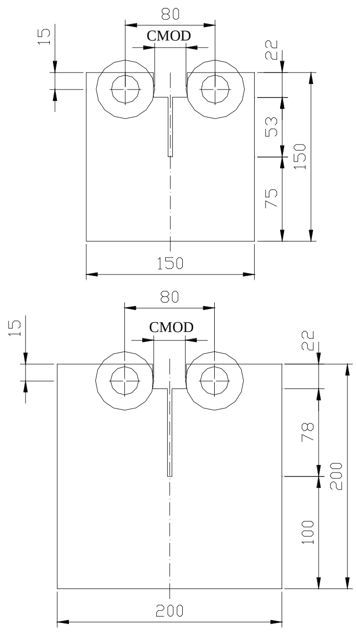

Figure 1. The geometry of the wedge splitting specimens used in the experiments, specimen thickness 100 mm.

Table 1. Materials used in test program and specimen sizes and the number of specimens.

Concrete	Type of fiber	V_f [%]	Spec. size [mm]	No. of Spec.
Mix 1:	RC-80/50-BN	0.50	150	4
w/c 0.55			-	
Mix 2:	RC-80/50-BN	0.75	150	4
w/c 0.55			-	
Mix 3:	RC-80/50-BN	0.50	150	5
w/c 0.45			200	5
Mix 4:	RC-80/50-BN	0.75	150	5
w/c 0.45			200	4
Mix 5:	RC-80/30-BP	0.50	150	5
w/c 0.45			200	4
Mix 6:	RC-80/30-BP	0.75	150	4
w/c 0.45			200	5

The tests were performed in a deformation controlled testing machine (screw driven), see Figure 2. The rate of the vertical displacement was approximately 0.15 mm/min, which resulted in a CMOD-rate of 0.08 mm/min. The crack mouth opening (CMOD) was measured with a clip gauge, placed in the groove (as indicated in Figure 1), the horizontal deformation at the center of the roller bearings was measured with two LVDT-gauges and the vertical deformation was measured with a LVDT-gauge. In the tests, a wedge angle of 15° was used and the roller bearings used was of the type double row deep groove from SKF (designation 4205 ATN9).

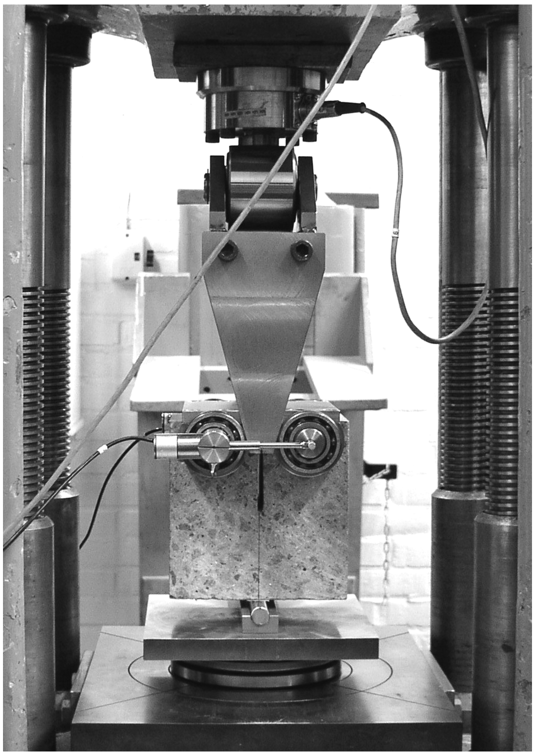

Figure 2. Test set-up with a 150 mm specimen in the machine.

3 TEST RESULTS

Figure 3 to 7 shows the test results for the tested specimens. As can be seen, the scatter of the result is quite large, primarily due to the variations in the number of fibers crossing the fracture plane. Generally, with the lower fiber addition, V_f = 0.5 %, the peak-load occurs at a CMOD of 0.1 to 0.2 mm and the load levels out or decreases after that. While with the higher fiber addition, V_f = 0.75 %, the peak-load occurs for a CMOD between 0.5 and 3.0 mm, the load levels out or increases after a CMOD of 0.2 mm. Furthermore, with a higher fiber addition the peak-load increases.

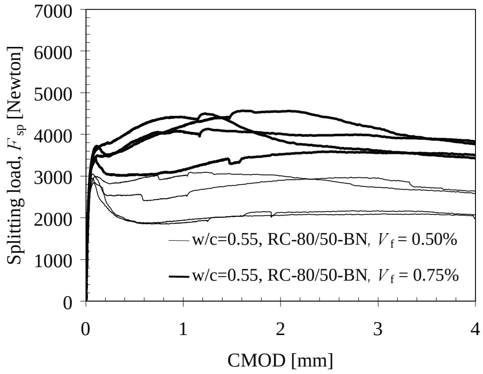

Figure 3. Splitting load-CMOD curves for specimens from Mix 1 and 2, specimen size 150 mm.

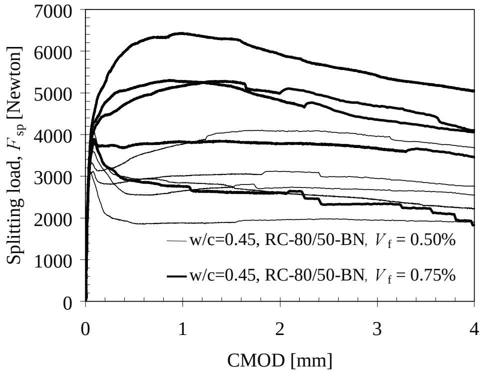

Figure 4. Splitting load-CMOD curves for specimens from Mix 3 and 4, specimen size 150 mm.

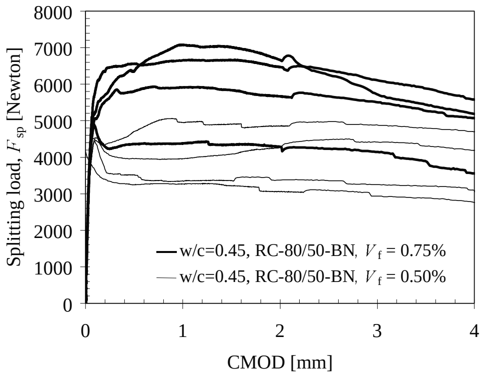

Figure 5. Splitting load-CMOD curves for specimens from Mix 3 and 4, specimen size 200 mm.

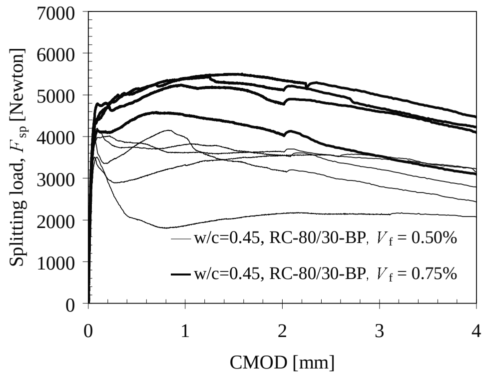

Figure 6. Splitting load-CMOD curves for specimens from Mix 5 and 6, specimen size 150 mm.

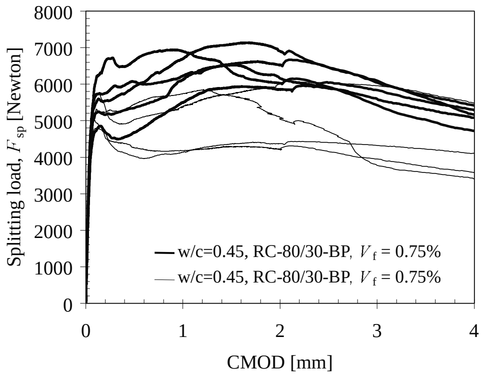

Figure 7. Splitting load-CMOD curves for specimens from Mix 5 and 6, specimen size 200 mm.

The work of fracture can be calculated from the area under the splitting force CMOD diagram, the contribution from the vertical force component is neglected. The fracture energy, G_F, is the work of fracture divided by the ligament area, A_{lig}. The ligament area, A_{lig}, is the projected area on a plane parallel to the ideal crack direction. In Figure 8 and 9 the fracture energy has been calculated for CMOD values between 0.25 and 4.0 mm. As can be seen in Figure 8 and 9, the fracture energy increase as the fiber volume is increased. Furthermore, the qualities of the matrix and the fiber geometry also have an influence on the fracture energy; a denser matrix (lower w/c-ratio) increases the fracture toughness and the shorter fibers seems to provide the higher fracture toughness than the longer fibers. When comparing the results from the two specimen sizes it can be concluded that there is no significant difference in the fracture energy.

To investigate the scatter in the test results the coefficient of variance (COV) has been calculated, this can bee seen in Figure 10 and 11. The coefficient of variance varies between 5 % and 28 % for the 150 mm specimen and between 5 % and 20 % for the 200 mm specimen. Hence, it seems that the scatter is smaller for the larger specimen. This is probably related to the distribution and orientation of the fibers, which get more uniform in a larger body, and to the fact that the larger specimen has a larger ligament.

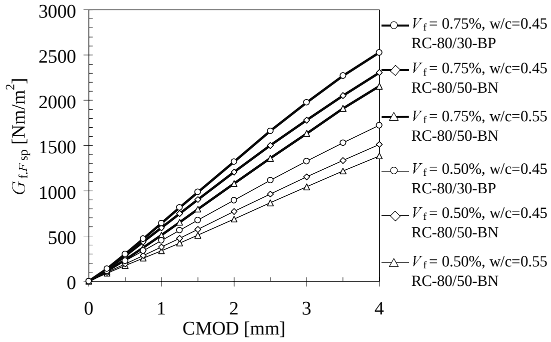

Figure 8. Evolution of fracture energy, for specimens from Mix 1 to 6, specimen size 150 mm.

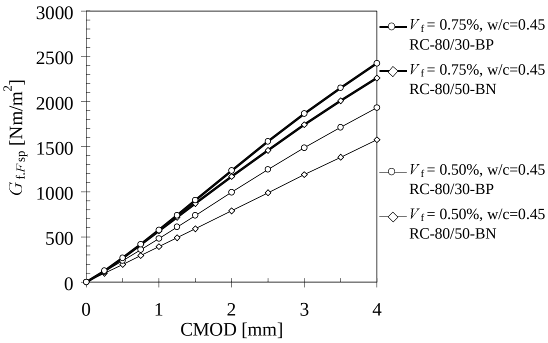

Figure 9. Evolution of fracture energy, for specimens from Mix 3 to 6, specimen size 200 mm.

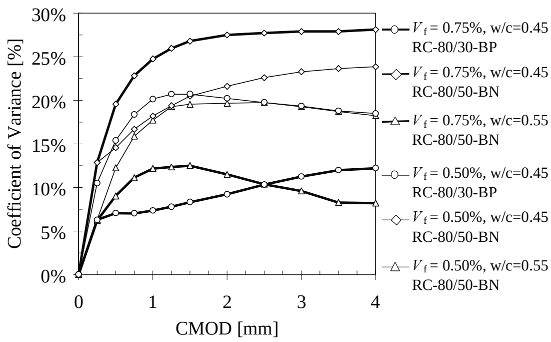

Figure 10. The coefficient of variance for the fracture energy. For Mix 1 to Mix 6, specimen size 150 mm.

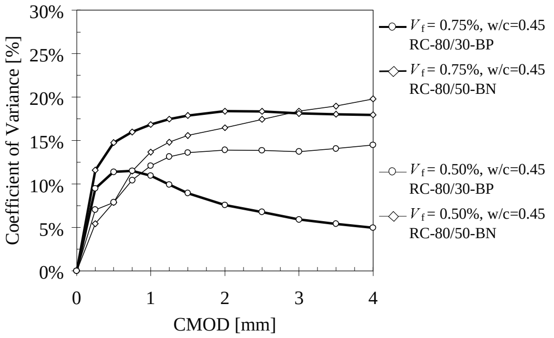

Figure 11. The coefficient of variance for the fracture energy. For Mix 3 to Mix 6, specimen size 200 mm.

During the tests it was observed that for some of the tested specimens horizontal cracks developed, see Figure 12 and 13. The cracks were most frequent on the specimens showing a hardening behavior, but it also occurred on some of the other specimens.

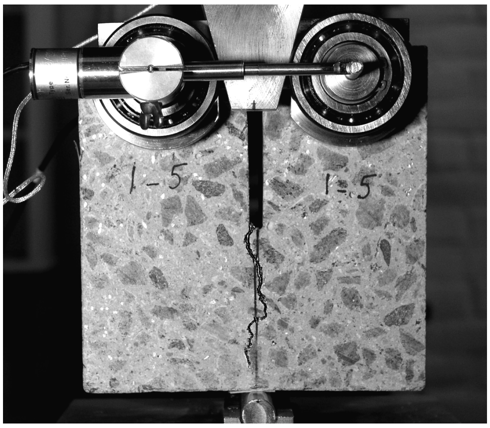

Figure 12. Specimen with only vertical crack.

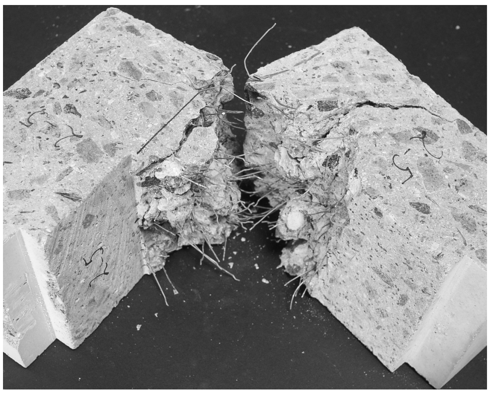

Figure 13. Fractured specimen with both vertical and horizontal crack.

4 INVERSE ANALYSIS

For ordinary concrete the wedge splitting test can be used to determine the fracture energy, G_F, and as the shape of the stress-crack opening relationship does not vary to much inverse analysis can be used to determine the non-linear fracture mechanics parameters from the experimental result; see Roelfstra & Wittmann (1986), Que & Tin-Loi 2002, Østergaard (2003). For fiber-reinforced concrete, on the other hand, the shape of the stress-crack opening relationship is more important than the fracture energy and an appropriate evaluation method, that allows an interpretation of the test result in form of a stress-crack opening relationship, is required.

In this study, analyses of the tested specimens from Mix 1 and Mix 2 were carried out using the commercial available program package DIANA, version 8.1. In the analysis all elements outside the crack are linear elastic and isotropic and the crack was modeled with a discrete crack, using so-called non-linear interface elements. The interface elements can be considered as non-linear springs describing the Mode I fracture properties.

As the shape of the stress-crack opening relationship is quite complex, the following procedure was followed: (1) the initial slope of the softening relationship should be steep, close to what could be expected for a conventional concrete; (2) the tensile strength were then changed until the first part of the splitting load- CMOD curve fitted the experimental data; (3) then the following points of the stress-crack opening relationship were determined in additional steps. This approach is similar to the poly-linear approximation method suggested by Kitsutaka (1997). No optimization procedure has been used to minimize the error, as at this stage the objective has been to see if it is possible to get a general agreement.

The result of the FE-analyses can be seen in Figure 14 and 16 were it is compared with the experimental result. The overall agreement is acceptable for Mix 2 and quite good for Mix 1. This, however, does not imply that the correct stress-crack opening relationship has been determined. The stress crack-opening relationships in Figure 15 and 17 are characterized by an initial steep drop followed by a section with increasing stress before the stress starts do reduce again. Generally, the experimental result for the specimens from Mix 2 is harder to fit as they show a hardening behavior.

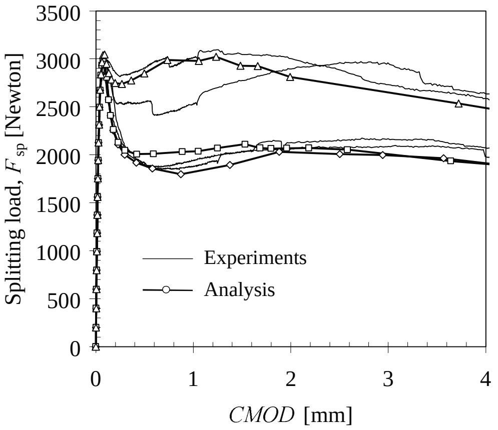

Figure 14. Comparison between analyses and tests for Mix 1, specimen size 150 mm.

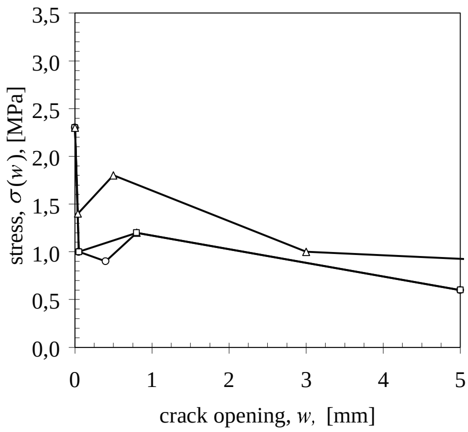

Figure 15. Stress-crack opening relationship to fit the test result for specimens from Mix 1.

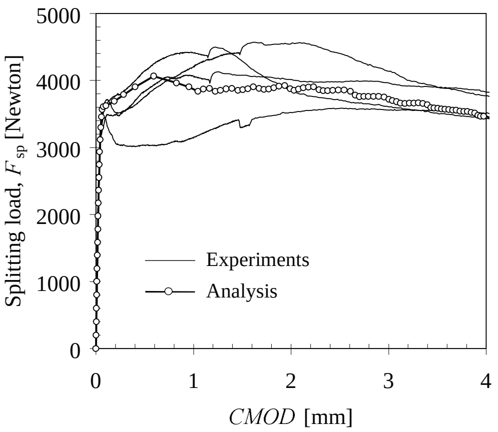

Figure 16. Comparison between analyses and tests for Mix 2, specimen size 150 mm.

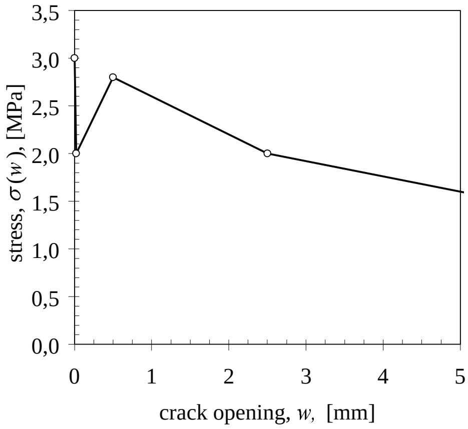

Figure 17. Stress-crack opening relationship to fit the test result for specimens from Mix 2.

The stress distribution at peak-load, for specimen from Mix 2, is presented in Figure 18. As can be seen, there exists a region outside the assumed fracture plane with tensile stresses as high as the tensile strength of 3.0 MPa. This is both perpendicular and parallel to the crack. In fact, the principal stresses, close to the crack plane, are actually parallel to the crack. Similar results, from FE-analysis, have also been shown for notched beams, by Planas *et. al.*, (1992) and by Olson (1994).

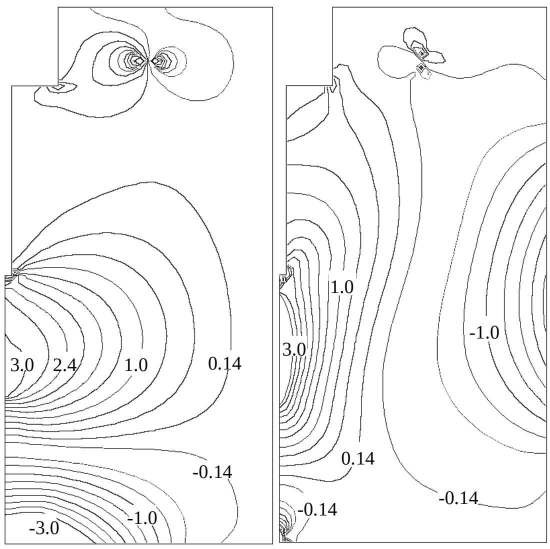

Figure 18. Result from analysis of specimen from Mix 2. (a) Stresses perpendicular to the crack. (b) Stresses parallel to the crack.

5 CONCLUDING REMARKS

The results from this study suggest that the wedge splitting test method could be used as a fracture test for steel fiber reinforced concrete. The test method does not require any sophisticated testing equipment. The only requirement on the testing machine is that it must have a constant crosshead displacement with a rate of about 0.1 to 0.2 mm/min.

The size of the specimen, 150 or 200 mm, does not seem to have any influence on the fracture energy as evaluated here, see Figure 19. On the other hand, the specimen size seems to have an effect on the scatter of the test result, see Figure 20. The conclusion, from this limited test series, is that for shorter fibers, maximum length of 30 mm, a 150 mm specimen could be sufficient. However, the specimen size seems to have an effect on the scatter. The scatter is smaller for the 200 mm specimen. The reasons for this is that the smaller the specimen is the larger the influence of wall-effects are on the fiber distribution. Furthermore, a larger fracture ligament also has a positive effect on the scatter.

The variability (coefficient of variance, COV) of the results is of the same magnitude as for other test methods for FRC. In these tests the COV varied between 5 % and 28 % for the 150 mm specimen and 5 % and 20 % for the 200 mm specimen. Similar values have been reported by others, e.g.: Kooiman (2000), COV from 10 to 30 % for three-point bending test on notched beam; Barragán *et al.* (2003), COV 20 to 30 % for uni-axial tension test; and Lee & Barr, COV in the order of 20 % for three-point bending test on notched beam.

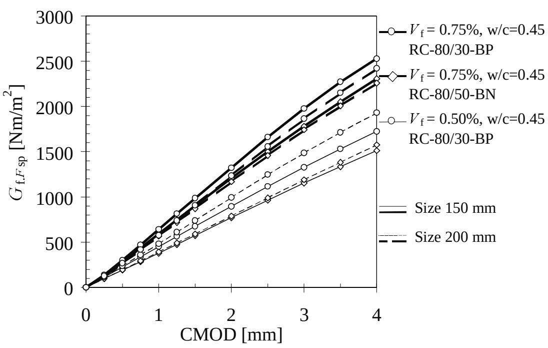

Figure 19. Comparison of the fracture energy evaluated from the two specimen sizes. For specimens from Mix 3 to 6, dashed line indicates the specimens with a size of 200 mm.

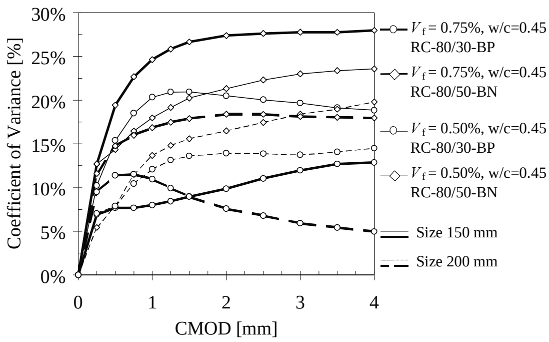

Figure 20. Comparison of the coefficient of variance for the two specimen sizes; dashed line indicates the specimens with a size of 200 mm.

As mentioned, the wedge splitting method requires an appropriate evaluation method that allows an interpretation of the test result in form of a stress-crack opening relationship, as this is the purpose of the test method. The analyses that have been carried out so far indicate that it is possible to determine a stress-crack opening relationship. However, for fiber reinforced concrete, the inverse analysis is more complicated than for ordinary concrete. The main problem with the inverse analysis is that there exists no unique solution, and it is possible to fit the experimental data with different stress-crack opening relationships. In addition, the poly-linear stress-crack opening relationship is not suited for a finite element analysis as convergence problems arise. Furthermore, for FRC it is difficult to distinguish between the tensile strength and the first part of the softening curve. The stress-crack opening relationship may have a steep drop which is followed by a phase where the stress increase until it starts to decrease again, see Figure 15 and 17.

The finite element analysis indicates that parallel to the crack high tensile stresses may develop. This may be an explanation to why horizontal cracks developed on some of the tested specimens.

6 FURTHER RESEARCH NEEDS

To verify that the test method can be used to determine the stress-crack opening relationship a comparison should be made with uni-axial tension tests. Furthermore, the mechanisms and effects of horizontal cracks needs to be investigated and also if they should be avoided, for example by a guide notch.

For the finite element analysis, the assumption of a discrete crack is perhaps not suitable as horizontal cracks developed in some of the tested specimens and other approaches should be investigated. One interesting method is the non-local damage approach with which it would be possible to investigate the evolution of damage and the size of the fracture process zone, see di Prisco & Mazars (1996), Ferrara & di Prisco (2001), and Bažant & Jirásek (2002). Furthermore, if the test method is to be used as a standardized test method a simple and robust program for inverse analysis needs to be developed. For this, standard methods for interpretation and analytical representation need to be agreed upon.

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