Three-fibre-type hybrid fibre concrete

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ABSTRACT: Rheological and fracture investigations on hybrid fibre concrete were performed to develop a material with improved tensile strength. The hybrid fibre concrete that was used in this investigation contained fibre mixtures of three different types of fibres. In order to optimise such a material, a four point bending test with continuously justified external loads ('pendulum-bars four-point-bending test') was developed. This paper presents results of four-point bending test on cut and moulded specimens and three-point bending tests on moulded specimens. Also, comparisons of results of different bending tests from different authors, mixtures, test arrangement and boundary conditions are presented.

1 INTRODUCTION

The principal aims of this work are first to balance the ratio between tensile and compressive strength of cementitious materials. In the past several approaches with different kinds of materials were made to develop ultra-high strength concrete, such as RPC (Richard & Cherezy 1995), Ductal (Orange et al. 2000) and multimodal FRC (Rossi & Renwez 1996). In all the above mentioned cases a ultra-high compressive strength was produced, but this increase has not lead to the improvement of the compressive vs. tensile strength ratio (c/t-ratio). Since in most applications, not such a high compressive strength is needed, it is much more appropriate to develop a cementitious material with a "ultra-high" tensile strength and to balance the c/t-ratio. The c/t-ratio should be decreased from 10:1, which is typical for an ordinary FRC, to ideally, as close as possible to 1:1. This may lead to possibility to obtain material with shear cracks. The results of a double punch shear test, in which shear cracks were observed, will be presented in further paper [Stähli et al. 2004].
In this paper investigations of hybrid fibre concrete (HFC) with three types of fibres were made in order to obtain these improved characteristics. HFC is a material that contains different types of fibres, e.g. different material as steel or PVA, or shapes and geometry of fibres. Three types of steel fibres of different geometry and shape were used in this paper.

In order to investigate fresh concrete properties slump flow tests were carried out. The mechanical experiments included maximal compression, three- and four-point bending tests. In order to assess the properties of these new types of HFC a four-point bending test with pendulum bars has been developed. The pendulum-bar four-point bending test has several advantages over the more conventional four-point bending test. In this paper the new test set up will be discussed, the followed mixing procedure for HFC and results of recent experiments will be presented.

2 RHEOLOGICAL INVESTIGATIONS

Markovic et al. (2003) showed that the mechanical properties of self-compacting HFCs are much better than those of ordinary FRCs in particular the bending strength. Self compacting mixtures are considered essential in order to obtain good fibre and particle distributions throughout the volume. In order to assess whether a mixture is self-compacting, two types of slump flow tests, i.e. a small one with the Hagermann cone or mortar flow

test and a large one with the inverted Abrams cone, were performed. In some series both the large and the small test were carried out. The aim was to determine the correlation between the results obtained from these tests. The small cone is originally a mortar flow test. The geometries of the two cones are quite different (Fig. 1). The small cone was used to find self-compacting mixtures which were used for the mechanical tests. The test with the small cone was performed the same way as the large slump flow test with the inverted Abrams cone but upright. Two perpendicular diameters were measured after 10 to 20 seconds, when the concrete stopped flowing and the average value of these measurements were calculated.

A mixture is considered self-compacting when the values of the large slump flow test are larger than 650mm (Markovic et al. (2003) and Ramsburg (2003). The latter one also reports that the difference between the inverted and upright Abrams cone SCC test is less than 1%. The criterion for self compactness with the small cone was an average diameter of a minimum of 230mm .

To develop self-compacting HFCs the small slump test was carried out because of its easier handling. As soon as the mixtures which were used for further investigations were found with the small cone, rheological test with both the inverted Abrams cone and the small cone were performed.
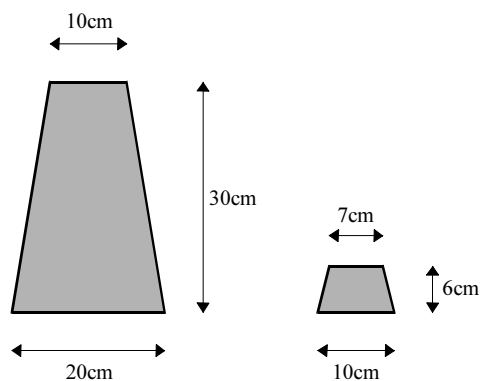

Figure 1. Geometry of the slump flow cones

2.1 Rheology and testing fresh HFC

It is necessary to assure that the mixing and testing procedure is optimised and kept uniform for all the samples.

A recommended procedure for mixing and rheological testing of HFC yielded good results is the following:

Step 1: All the tools needed should be prepared in advance before the start of the mixing. It is important to wet all the equipment, i.e. slump flow cones and table, trowels and mixer.

Step 2: The microsilica slurry (1:1) is prepared.

Step 3: Aggregates are weighted in a different vessel than binder (i.e. as fly ash and cement).

Step 4: Water and plasticizer are weighed in a separate vessel.

Step 5: Binders (including microsilica slurry) are weighed in one vessel.

Step 6: Water-plasticizer mixture is poured into the cement-binder mixture and is mixed for four minutes.

Step 7: It is ensured that the material is well mixed and no residue sticks to a wall of the mixing vessel or to the mixing blades.

Step 8: All the aggregates are added into the mixture and mixed for 1½ min.

Step 9: The mixture consistency is checked by a trowel. Should there be any material which is not properly mixed, the mixing is continued for another minute.

Step 10: All the fibres are added and mixing proceeds for another two minutes. At the end the consistency of the mixture is again controlled by a trowel. The criterion to decide whether to mix for another minute or not are: (i) no fibres stick together (hedgehog) or they are not well distributed and (ii) no fibres stick to the mixer blades or the wall of the mixing vessel.

Step 11: Fresh concrete properties are tested using the slump flow tests. It is important that all the tools needed for these tests are damp but not wet, and that the test is made within one minute after the end of the mixing process. It is recommended to dispose all the concrete that was needed for the slump flow test.

Step 12: The oiled formworks for specimens for mechanical testing are filled immediately after the end of the fresh properties testing procedure.

3 MECHANICAL TESTS

3.1 Sample preparation

The specimens in formworks were placed into a room with controlled environment (R.H. = 75%, T = 20°C) immediately after casting. There the specimens were demoulded 24 hours after casting and left in the room for another 25 days. In order to achieve a plain surface on the top sides, the specimens were (dry) ground at the age of 26 days. The grinding was performed two days before testing and the grinding depth was never more than

one millimetre. After grinding, the specimens were stored in the testing room, so that the internal specimen humidity could equilibrate with the humidity of the testing room. All tests were performed on specimens of the age of 28 days.

3.2 Pendulum bending test (PBT)

3.2.1 Operational principle

The rationale for using pendulum bars is based on the idea that during a four-point bending test the forces which act on the specimen should remain perpendicular to the specimen, the symmetry should be maintained throughout the whole test, there should be no friction between the supports and the specimen, and it should be possible to measure the forces at supports and load-points. These issues become important especially when a material of increased ductility, such as HFC, is tested. Figure 2 shows the principal difference between ordinary four-point bending test and the pendulum-bars four-point bending test. In order to achieve the mentioned objectives, the forces are transferred onto the specimen by means of a set of long pendulum bars. During the test between pendulum bars the directions of the external forces continuously changes in the same way as the geometry of the specimen changes, so that they remain at right angles to the surface of the specimen. The symmetrical setup of the test
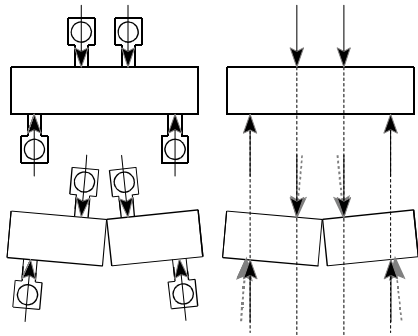

Figure 2. Comparison of load setups in ordinary and the pendulum bars four point bending tests. On the left side of the figure the force setup of a pendulum bar test is shown and on the right side the one of an ordinary four point bending test. The grey arrows represent the forces from the pendulum bars test on the left side of this figure.

arrangement is maintained during the test. This is also achieved by the fact that the pendulum bars and the whole test arrangement has many degrees of freedom of movement. Thus, the supports are free to move in lateral directions and the forces in

the individual bars can be easily measured with strain gages. In the ordinary four-point bending test
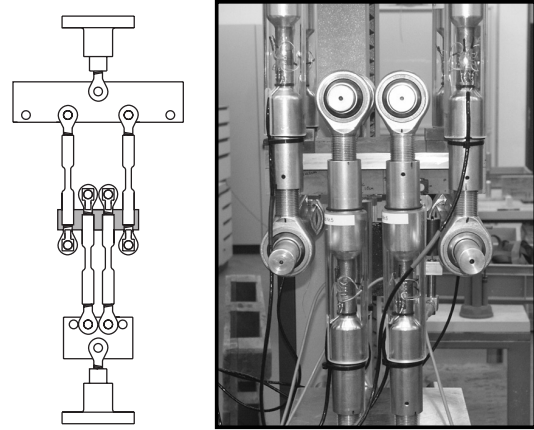

Figure 3. Sketch and photograph of the pendulum-bars four-point bending test

the forces remain vertical and the angle between force and surface of the specimen change continuously as shown in Figure 2. By raising the angle, friction between the supports and the specimens grows and the symmetry changes (Gjørv et al 1977).
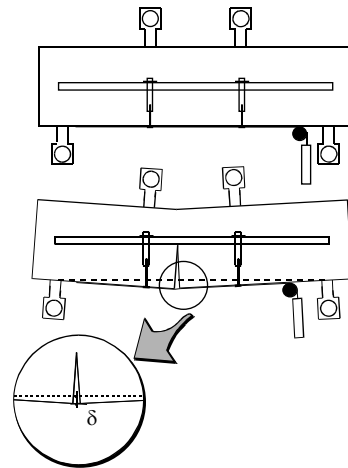

Figure 4. Deflection measurements

A sketch of the test arrangement and a photograph of the whole test setup is shown in Figure 3.

3.2.2 Measurements

The deflection of the beam is derived from readings of two pairs of LVDTs in the arrangement

as shown in Figure 4. The 'maximum' deflection of the beam has been calculated as the intersection of the two straight lines given by de displacement of the LVDT and the geometry of the setup. This method assures that no sensor is in the zone where cracks are expected. In most cases the deflection derived provides an upper bound value.
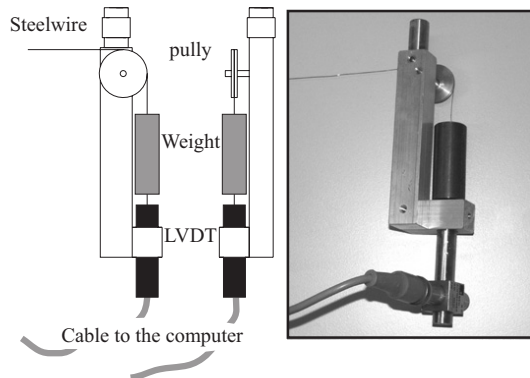

Figure 5. CMOD sensor

The crack mouth opening was measured using a steel wire that was fixed along the bottom side of the specimen. A sketch and a photograph of the CMOD sensor are displayed in Figure 5. The CMOD includes all deformations in the measuring rate and no correction has been made.

Two computers were needed to carry out the test. As shown in Figure 6, one computer controlled the test, whereas the other was used for logging the data.
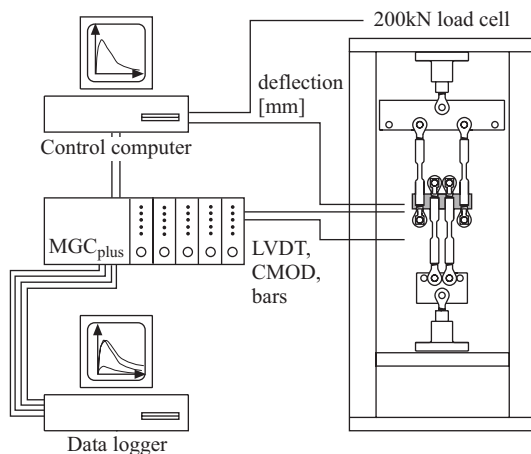

Figure 6. Measuring and control equipment

The test was carried out in displacement-control. The control displacement was an internal displacement sensor of the Zwick loading machine.

The displacement rate was kept constant in 0.002mm/s. for all the experiments.

The forces in the pendulum bars were also measured. Having the results of the loads in the bars, the symmetry of the load setup could be assessed as shown in Figure 7. In all tests the difference between the most loaded and the least loaded bar was less than 6%. This result corroborates the fact that with pendulum bars the test setup remains continuously symmetric.
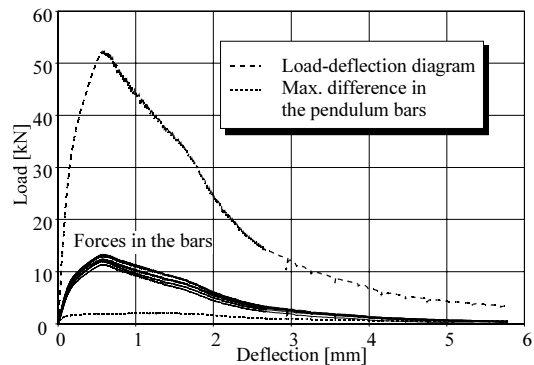

Figure 7. Load-deflection-diagram in the pendulum bars

3.3 Moulded and cut

All the four-point bending tests were carried out on specimens of 280/70/70 mm in size (Fig. 8).

In order to investigate the wall effect in hybrid fibre concrete, tests on specimens with both cut and moulded walls were carried out. Three moulded specimens and one concrete block for the cut specimens were produced in the same batch. The size of the large concrete block was chosen to ensure that a layer of 30mm thickness could be removed from each Side and three specimens were
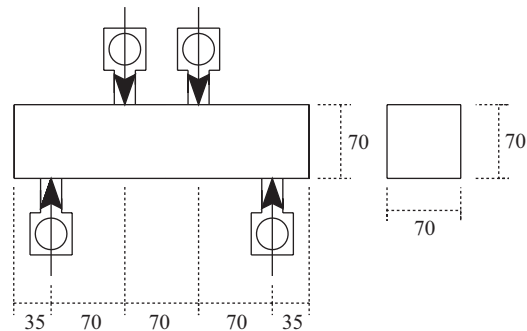

Figure 8. Geometry of the specimens and the test setup

obtained with the same dimension as the moulded specimens (Fig. 9). As the cover length corresponds to the length of the longest fibre used

in the specimens, the wall effect should be negligible. The disadvantage is, of course, that the individual fibres are cut which results in a different type of wall effect.
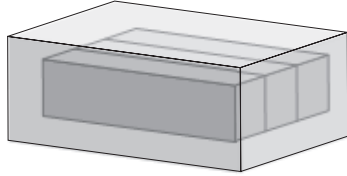

Figure 9. Concrete block for the cut specimens

3.3.1 Materials

Table 1. Mixture compositions

	Steel fibre [vol-%]		
Nr.	0.15/6	0.2/12	0.6/30
1	5.00	-	-
2	-	3.00	-
3	-	-	2.00
4	4.00	0.50	0.25
5	4.25	0.52	0.27
6	4.50	0.56	0.28
7	4.75	0.60	0.30
8	5.00	0.62	0.31

In the first three series single fibre mixtures were made with a maximum amount of fibres, such that the mixture would still have self-compacting properties. In the subsequent series fibre cocktails were used. The mix proportions are given in Table 1. For all the mixtures the same matrix was used. This matrix had a w/b-ratio of 0.2, a maximum aggregate size of 1mm and a sand to binder ratio of 40 to 60%. The cement used was CEM I/52.5 R. All fibres were produced by Stratec and their respective geometries and shapes are listed in Table 2.

Table 2. Fibre geometry

Fibre type	l [mm]	d [mm]	l/d	shape
0.15/6	6	0.15	40	straight
0.2/12	12	0.2	60	straight
0.6/30	30	0.6	50	undulated

4 RESULTS

4.1 Fresh HFC properties

In Table 3 the results of the rheological test are summarised. The ratio between the results of the large and the small slump flow tests varied between 2.4 and 3.0.

Table 3. Fresh concrete behaviours

Nr.	Sf_s* [cm]	Sf_l** [cm]	Ratio [large/small]
1	20	56	2.8
2	30	-	-
3	29	72	2.5
4	29	83	2.9
5	28	68	2.4
6	20	58	2.9
7	26	74	2.8
8	27	81	3.0

* Sf_s: Small slump flow
** Sf_l: Large slump flow

4.2 Compressive strength, density and Young's modulus

Compressive strength, density and Young's modulus were determined for all the specimens. The results are given in Table 4. These properties were determined in standard tests used cylinders and cubes. The results are averages of at least three specimens except the Young's modulus, for which only one cylinder was tested.

4.3 Results of bending tests

The new four-point bending tests between pendulum bars has been used for all 8 mixtures on both moulded and cut specimens. Also, standard

Table 4. Mechanical properties of the materials

Nr.	Density [kg/m³]	Compressive strength [MPa]	Young's modulus [GPa]
1	2550	153.50	38.86
2	2470	156.30	39.16
3	2359	123.23	36.56
4	2534	147.18	37.81
5	2515	148.31	37.84
6	2520	161.30	37.51
7	2532	153.70	38.23
8	2581	158.17	38.00

three point bending tests were carried out for all 8 mixtures. Three samples were tested for each parameter combination.
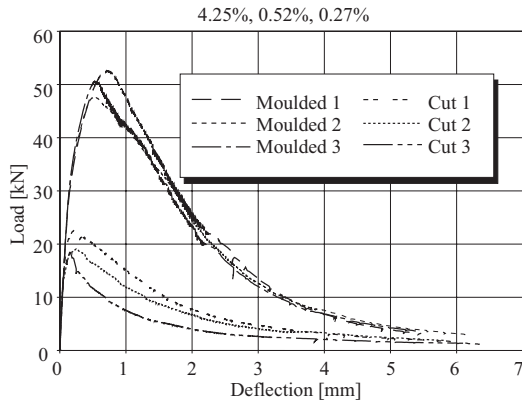

Figure 10. Load-deflection-diagram of HFC with three types of fibres (Total fibre volume is 5.04%, Batch Nr. 5)
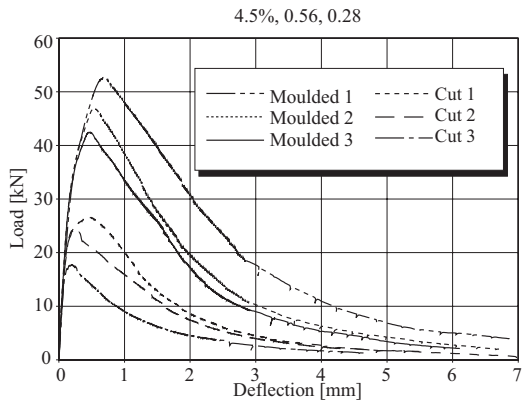

Figure 11. Load-deflection-diagram of HFC with three types of fibres (Total fibre volume is 5.34%, Batch Nr. 6)
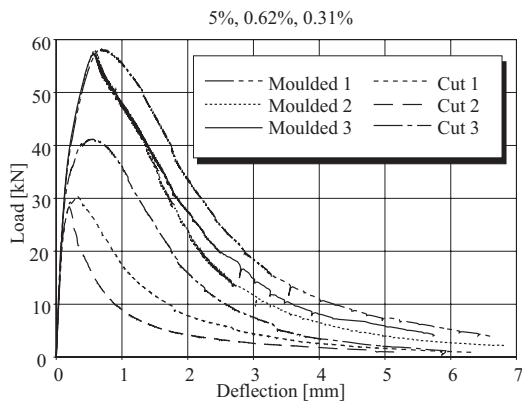

Figure 12. Load-deflection-diagram of HFC with three types of fibres (Total fibre volume is 5.93%, Batch Nr. 5)

Figures 10 to 12 show the load-deflection diagrams for some of the mixtures. It shows clear and substantial differences between the behaviour of cut and moulded specimens.

All the strength results are summarised in Figure 13 and the respective coefficients of variation are given in Table 5.
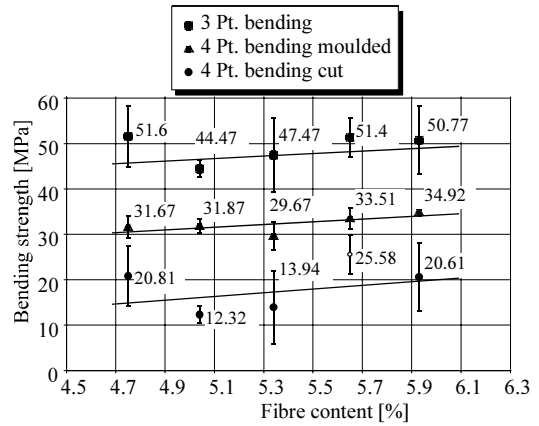

Figure 13. Overview of bending strength results for various mixtures

Table 5. Summary of average bending strength and coefficients of variation

N r.	4 Pt. (moulded)		4 Pt. (cut)		3 Pt.	
4	31.7	(7.48)*	20.81	(15.62)	51.6	(12.91)
5	31.9	(4.93)	12.3	(11.36)	44.5	(4.27)
6	29.7	(10.62)	13.9	(20.44)	47.5	(17.08)
7	33.5	(6.62)	25.6	(14.50)	51.4	(8.31)
8	34.9	(1.06)	20.6	(19.12)	50.8	(14.81)

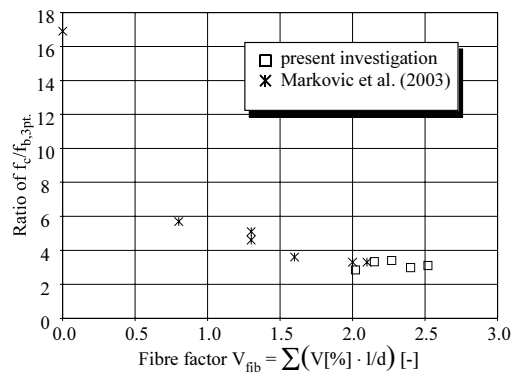* maximum bending strength [MPa] and in brackets coefficient of variation [-]

Figure 14. Overview of the ratio of $f_c/f_{b,3pt.}$ vs. fibre factor (not the uniaxial tensile strength is used, but the values computed from the results of three-point bending tests.)

In Table 6 and Figure 14 it is shown that the ratio of $f_c/f_{b,3pt}$ decreases with increasing fibre factor. It

also seems to have a limitation of a ratio of $f_c/f_{b,3pt}$ at a value of 3.0.

Table 6. Ratio of $f_c/f_{b,3pt}$ for various mixtures

Nr.	4 Pt. (moulded)	4 Pt. (cut)	3 Pt.
4	4.64	7.07	2.85
5	4.65)	12.06	3.33
6	5.43	11.60	3.40
7	4.59	6.00	2.99
8	4.53	7.68	3.11

5 DISCUSSION OF RESULTS

5.1 Relation between fibre factor and slump flow

Figure 15 shows the relation between slump flow and fibre factor. It is apparent that - for the fibres and matrix used in this investigation - the fibre factor must be lower than 2.2 in order to keep the mixture self-compacting.
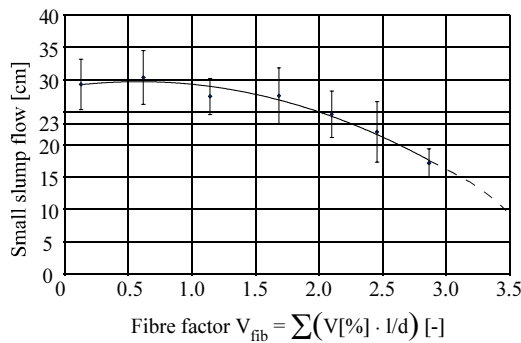

Figure 15. Fibre factor vs. small slump flow

Another important property of fresh concrete is the degree of segregation. It was observed that segregation appears only when long fibres, such as the 6/30 fibres, were used. For the small fibres, such as the 0.15/6 fibres, segregation was not apparent.

5.2 Comparison between different bending tests

Three-point and pendulum-bar four-point bending tests were carried out with mixtures, for which the fibre to fibre volume ratio was kept constant at 16:2:1 for short, medium and long fibres and the maximum fibre volume was increased up to 6% (by volume).

It is obvious from Figure 13 that the bending strength increases with increasing fibre content for all types of bending tests. It also shows that the

increase in strength is nearly the same for each different test.

From the results it can be inferred that for the moulded specimens the scatter in the four-point bending test between pendulum bars is smaller than the scatter for the three-point bending test. Again, this fact justifies the development of such a test.

Moreover the results showed that the scatter of the moulded specimens is smaller than the scatter for the cut specimens.

A comparison between different investigations on hybrid fibre concrete is given in Figure 16. The Figure compares the data presented with the results of three-point bending tests made in Zürich by Van Gunsteren (2003) and in Delft by Markovic et al. (2003). This diagram also shows that the strength increases, while the fibre factor is similar in the tests by Markovic et al. (2003) and the current experiments. The strength increase is a little larger than in tests done by van Gunsteren (2003)
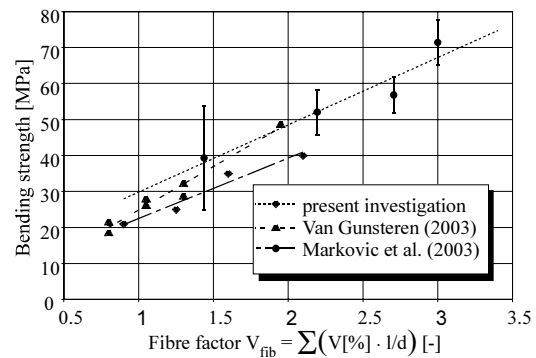

Figure 16. Comparison between three point bending tests

In this diagram it can be also seen that the results of Van Gunsteren (2003) and Markovic et al. (2003) are at a lower level than the results reported here. An explanation for this could be that the authors were working with three types of fibres, whereas Van Gunsteren (2003) and Markovic et al. (2003) used two types of fibres only. Quite likely the limits of possible mixtures have not been explored to full extent, and it is expected that even better results can be achieved.

5.3 Crack patterns

Different failure modes were observed for different mixtures. This could also be the reason for the relatively large scatter some of the results. Examples of different fracture modes are: a single crack right in the middle of the specimen (Fig. 17a), typical 'shear-like' cracks (Fig. 17b) and in a single case - batch Nr.2 - multiple cracking was observed

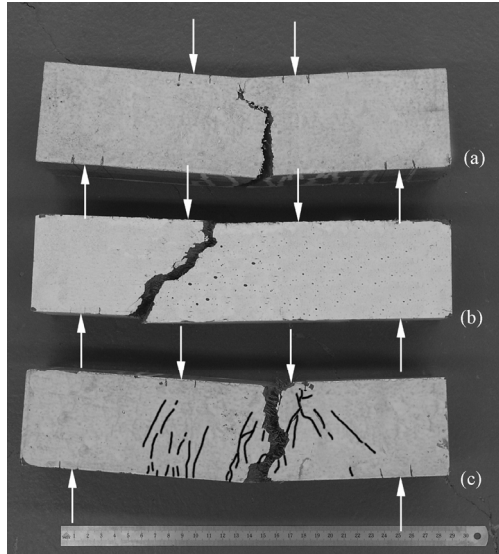(Fig. 17c). It is obvious that for different crack modes different stress-strain curves were obtained.

Figure 17. Example of crack patterns. (a). bending crack, (b). shear-like crack, (c). multiple cracking.

6 CONCLUSIONS

On the basis of the present experimental results the following conclusions can be drawn:
1. The use of a small slump flow test cone is a fast method, which allows carrying out sufficient number of slump flow tests in relatively short time. It is also possible to compare these results with those of the larger Abrams cone. The ratio between these two tests lies between 2.4 and 3.
2. Pendulum bars are the solution to overcome inherent problems of ordinary four-point bending tests, such as continuously changing angles between load and specimen surface, asymmetry during a bending test, friction in the supports. Moreover in the pendulum-bars it is possible to measure the forces in supports and load-points.
3. The influence of the walls in moulded specimens can not be neglected. The differences in the maximum bending strength and the scatter of specimens with moulded and cut walls are rather large. This effect could have less influence with the increase in the size of the specimen because the ratio between total volume and wall area decreases with increasing size.
4. The results show that HFC mixtures containing three types of fibres are more efficient than mixtures with two or even one type of fibres only.
5. The ratio of $f_c/f_{b,3pt}$ could be decreased to a minimum of 2.85, which is as far a the authors knowledge is, the lowest value for HFC obtained to date.

7 ACKNOWLEDGEMENT

8 REFERENCES

Gjørv, O.E. & Sørenson, S.I. & Arnesen A. 1977. Notch sensitive and fracture toughness of concrete. In Cement and Concrete Research. Vol 7. 333-344, Norway

Markovic, I. & Walraven, J.C. & Van Mier, J.G.M. 2003. Development oh high performance hybrid fibre concrete In *A.E. Naaman & H.W. Reinhardt (eds.),* RILEM Publication. s.a.r.l.,. 277-300. Delft

Orange, G., Dugat, J. and Acker, P. (2000), Ductal®: New ultra-high performance concretes - Damage resistance and micromechanical analysis, *in Proceedings BEFIB-V, Lyon 2000,* RILEM Publications s.a.r.l., Cachan, 781-790.

Ramsburg, P. 2003. The SCC Test: Inverted or upright?. In Hanley-Wood LLC *The concrete Producer*, July 2003. 1-5. USA

Rossi, P. and Renwez, S. (1996), High performance multi-modal fibre reinforced cement composites (HPMFRCC), *Proc. 4th Int'l. Symposium on High Strength/High Performance Concrete, Paris*, 1996, pp. 687-694.

Van Gunsteren, E.M. 2003. Entwicklung eines hochwertigen selbstverdichtenden hybriden Faserbetons mit Bezug zum Versagen unter Zug und Schub, diplomawork at the IBWK. ETH Zurich. Zurich