Tensile behaviour of high performance hybrid fibre concrete

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ABSTRACT: Hybrid Fibre Concretes (HFC) are newly developed cement composites, whose main characteristic is utilization of different types of steel fibres in high-strength mortar mixtures. Although the flexural behaviour was very superiour, the determination of uniaxial tensile behaviour is necessary to provide a basis for design. In this paper, results of uniaxial tensile tests on HFCs will be presented, followed by the analysis of fibre dispersion in the specimens and its influence on tensile behaviour.

Keywords: hybrid fibre concrete, high performance concrete, tensile strength, ductility, fibre dispersion

1 INTRODUCTION

Very low tensile strength and no ductility are the biggest disadvantages of concrete. Fibres can bridge cracks in concrete, and in this way, the uniaxial tensile and flexural response may be improved. However, application of fibres usually did not give expected results in the past. In most cases, no improvement of flexural and uniaxial tensile strength was obtained, softening started imediately after reaching the maximum tensile stress, so that actually only the fracture energy was improved [1].

Recently developed mixtures of Hybrid-Fibre Concrete (HFC) contain short and long steel fibres combined in a high-strength fine mortar. Flexural responses of all tested mixtures are very good [2]: the obtained flexural strengths range up to 45 MPa with obvious strain hardening up to crack openings of 2-3 mm, and the values of fracture energy ranged up to 45.0 N/mm.

Mixed fibre composition follows exactly the tensile fracture processes of concrete. Short thin fibres efficiently bridge microcracks, which develop in the first phases of tensile loading. Namely, if applied in appropriate volume content, the number of these fibres in a structural element is large, while the distances between them are small, which corresponds exactly with the arrangement of the microcracks [3]. The result of the coalescence of microcracks is usually the formation of one larger macrocrack. Long and stiff steel fibres, additionally strengthened by hooks at their ends, can optimally bridge such cracks. Short fibres also contribute partly in bridging of macrocracks, as similarily long fibres took part at bridging of microcracks up to some extent (Fig. 1).

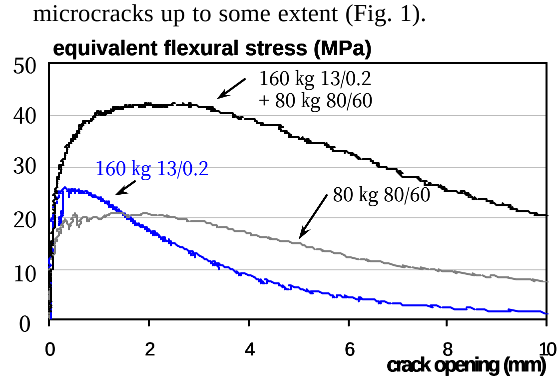

Fig. 1: Influence of short (13/0.2) and long (80/60) fibre types on flexural behaviour (from [2])

Some most characteristic results of 3-point bending tests on mono- and hybrid-fibre concrete are given in Fig 1. It is clear from this figure that one can achieve both high flexural strength and high ductility by combining different fibre types. These improvements are not caused by higher fibre content only in hybrid-fibre mixtures, but also synergetic effects appear to develop if different fibre types are used together.

Flexural loading creates however a combination of tensile and compressive stresses in concrete specimens, and the pure tensile capacity of concrete remains therefore unknown. Furthermore, the σ-w-curves necessary for any application of concrete may theoretically be created using inverse analysis, but with a high level of uncertainity. The most realistic characterization of tensile behaviour of concrete can be obtained only by uniaxial tensile tests [3].

In this paper, the results of uniaxial tensile tests on Hybrid-Fibre Concretes with different types and amounts of steel fibres will be presented and discussed, followed by the analysis of dispersion and deformability of fibres in HFC specimens.

2 UNIAXIAL TENSILE TESTS

2.1 *Research goals*

The basic research goal is the determination of tensile behaviour for different types of Hybrid-Fibre Concrete. Of special interest is also the influence of different fibre types on tensile behaviour. Practical outcome of the tests should consist of σ–w-relations for different types of HFC. A recommendation on how many of which fibre type is needed to achieve appropriate tensile strength, ductility and crack pattern is necessary as well.

2.2 *Mixture compositions*

Compositions of the applied concrete mixtures, together with some basic workability and strength properties, are given in Tab. 1. The basic criterion is the applied fibre volume content. The demand was to produce and test practically applicable mixtures, regarding their costs in engineering practice. According to an initial analysis from [4], the applied fibre amount should be up to 1.5 - 2 vol.-%, in order to be able to compensate high costs of fibre concrete mixtures with smaller cross-sections of appropriate structural elements. The maximum applied fibre content was therefore set at 2 vol.-% (160 kg/m^3).

Tab.1: Mix composition and basic properties

	fibres (vol.%) straight	hooked ends		w/b	slump flow	fcc	fspl
	13/0.2	80/40	80/60		(cm)	(MPa)	(MPa)
1				0.2	82 / 85	119.7	9.6
2			1	0.2	57 / 61	124.4	11.6
3	2			0.2	81 / 76	133.0	14.3
4	1		0.5	0.2	84 / 88	125.0	15.7
5	1	1		0.2	73 / 75	113.0	15.3

The mixtures were developed in steps, and the complete development procedure is given in [2]. Utilization of low water-binder ratio of 0.20 is essential to obtain optimum bond properties between fibres and surrounding concrete matrix, which exist in that case [5]. Another very important requirement was the self-compactability of fresh mixtures. This property is of importance especially for fibre concrete, due to more regular orientation and dispersion of fibres in a structural elements [6]. As fibres, especially those with higher length/diameter ratio (aspect-ratio), usually have negative impact on the workability, somewhat higher amounts of blast furnace slag cement (up to 1100 kg/m^3) and finer grain composition (D_{max}=1 mm) had to be applied in order to produce viscous and stable mixtures, without clustering or segregation of fibres.

2.3 *Testing samples*

After non-linear finite element simulations, the so-called "dog-bone"- shape of the specimens was chosen (Fig. 2a). According to those analysis, one could expect multiple cracking in the middle zone of the specimen, where the highest tensile stress exists. With this shape of specimen, no notches were needed to create stress concentrations. This shape also fitted best into the relatively small available space for the specimen in the testing machine. Taking into account also the available tensile capacity of the testing machine of 100 kN, the dimensions of the smallest cross section were set at 70X70 mm, so that the maximum achievable tensile stress was limited to 20 MPa.

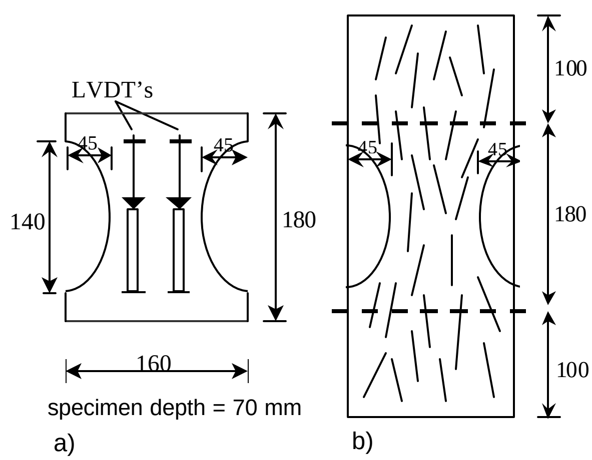

Fig. 2: a) Dimensions of the specimens with LVDTs positions, b) initial shape of the specimens with schematized fibre dispersion

The final dimensions of the samples may still seem rather small, taking into account that the biggest fibre length was 60 mm. However, the dimensions of the structural elements of HFC can also be very small, due to large compressive and (flexural) tensile capacity of this material [7]. Alignment of long fibres along the walls can therefore certainly be expected in the structures as well. It is therefore possible to correlate the results of these tensile tests with the behaviour on structural level.

It was moreover decided to perform these tests on specimens without notch. This was motivated by the practical application as well, because real structures do not possess any notches. In potential structural elements made of HFC, tensile fracture may occur in zones with maximum tensile stresses, but also in zones with lower fibre concentration, independent on stress level. Another reason to refrain from notched specimens was the registration of the specific cracking patterns, such as multiple cracking [8]. Such cracking property may assure good durability of Hybrid-Fibre Concrete, which would be another potential advantage of this material. Notched samples were used only for testing of plain concrete, and for a number of samples of mixture 5, in order to compare the results with those from un-notched samples.

2.4 *Preparation of specimens*

Dispersion of fibres in a sample is of crucial importance for the tensile response of any type of fibre concrete. One must therefore assure constant casting process, not only in order to achieve good mechanical properties, but also in order to minimize scatter of the results. Due to the specific shape of the samples, an optimum fibre alignment not only in the middle, but also at the end zones of the sample must be assured. This is especially important for long fibres. The initial samples were therefore cast in moulds, which were about 10 cm longer at both sides then the final sample, and which already had 2 half-circled parts in order to obtain directly the specific "dog-bone" shape of the specimens (Fig. 2b). The end-parts of initial specimens were cut off 3 weeks after casting. One day before testing, the upper and lower side of each sample were sand-blasted. Due to the unpredictable fibre dispersion, there was the possibility of glue failure at the end zones. In order to stiffen the end-zones additionally, four thin steel strips were applied, two of them were glued latherally outside, and another two in grooves inside the sample.

The curing regime was the same for all specimens: 26 days at 20ºC and with a relative humidity of 95-100%. After the preparation, each specimen was glued to the upper and lower platen under small compression (1-2 MPa). Tests were performed with fixed boundaries, i.e. no rotation of the plates was allowed.

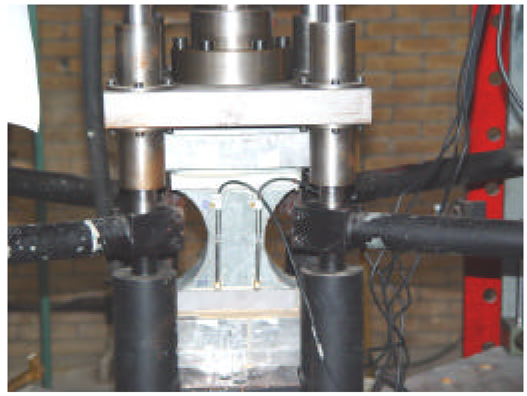

Fig. 3: Specimen with LVDT's glued in the testing frame, both ends were additionally stiffened by steel stripes outside and inside the specimen.

Minimum three samples were tested for each mixture composition, at an age of 28 days, under deformation-control. The crack opening was registered by 4 LVDTs ("Schlumberger", linear stroke +/- 1 mm), attached at the front and back of the specimen (Fig. 3). Measuring length of 110 mm for fibre reinforced, and of 35 mm for plain concrete specimens was used. Two displacement rates were used: 2 μm/s up to a displacement of 10 mm, and after that 20 μm/s until the end of the test.

3 RESULTS

3.1 *General overview*

An overview of all the obtained values of tensile strength in relation to applied fibre volume content is given in Fig. 4. As expected, the use of fibres increased the values of tensile strength. Values of fracture energy ranged from 0.1 N/mm for plain concrete, over 28.5 N/mm for concrete No. 2 (2 vol.-% of 13/0.2 fibres), up to about 50 N/mm for concrete No. 5 (hybrid fibre composition). These values are quite high, and they are also rather similar with those calculated from 3-point bending tests in [2].

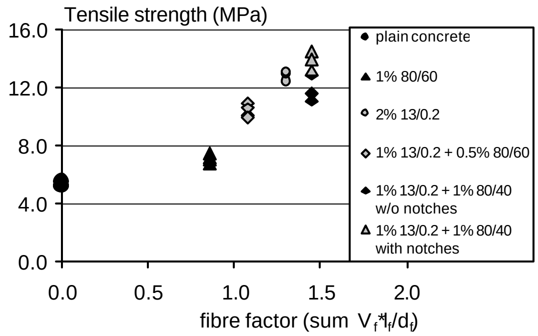

Fig. 4: Tensile strengths for different types of Hybrid-Fibre Concrete

All specimens exhibited elastic deformation up to very small displacements (0.003 to 0.010 mm, depending on the applied fibre type). After that, the plastic hardening was registered for all types of fibre concrete, up to the crack openings of 0.2 to 0.5 mm, depending on the applied fibre type. After that, strain softening began, followed by formation of one dominant crack. At the crack opening which corresponds approximately to 1/3 of the fibre length (for all fibre types), no tensile capacity could be registered, i.e. the stress was equal to zero. Concerning the testing itself, almost no bending of specimens was observed, and the scatter in results was very low. The applied testing method showed itself as very efficient: there were no un-successful tests.

3.2 *Tensile behaviour of plain concrete and of concrete reinforced with a single fibre type*

Taking into account that the same composition of the concrete matrix as for mixtures with fibres was applied, the test results of the plain mixtures served as a reference for other results. Almost the same values of tensile strength were observed in all performed tests, while the full softening behaviour could be registered in only one case, due to the slight bending of the specimen. The obtained tensile strength ranged from 4.5 to 5.0 MPa (Fig. 4).

The addition of 1 vol.-% (80 kg) of long hooked-end fibres (RC-80/60-BP) caused the increase of tensile strength of about 20%, and a very large improvement of ductility. Strain hardening began after the elastic phase, at a tensile stress of about 5 MPa, which corresponds to the tensile strength of reference plain concrete. The corresponding displacement is about 0.0025 mm. Plastic hardening was present up to a stress of about 6-7 MPa, and a crack opening of about 0.3-0.4 mm, after which softening started (Fig. 5).

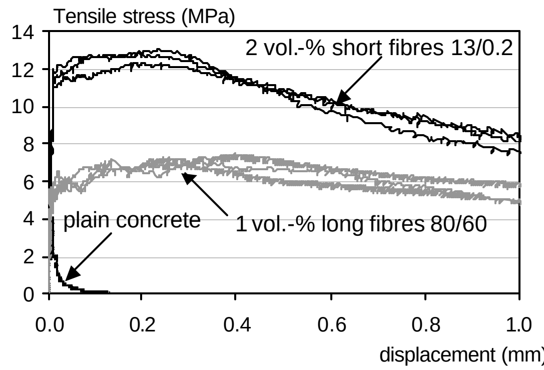

Fig. 5: Tensile behaviour of plain concrete and concrete's with a single fi bre type (short or long fibres)

The application of 2 vol.% (160 kg) of short straight fibres OL 13/0.2 caused a tremendous increase of tensile strength up to 13 MPa, with obvious strain hardening as well. Plastic hardening began after the elastic phase, at a tensile stress of about 11 MPa, and at crack opening of about 0.01 mm, and it was present up to a crack opening of about 0.2 mm, after which strain softening began (Fig. 5). This shows that the application of short fibres has a very positive influence on the improvement of first of all the tensile strength, and of the ductility as well.

3.3 *Tensile behaviour of hybrid-fibre concrete*

Concrete No. 4 contains lower fibre amount than concrete No. 3, but in this case 1 vol.-% of short straight fibres was exchanged with 0.5 vol.-% of longer hooked-end fibres RC-80/60-BP. The idea was to try to achieve the similar tensile strength and fracture energy with a lower fibre content. This was partially achieved, with tensile strength ranging between 10.5-12.0 MPa, which was quite similar to the values obtained with 40 kg more of short fibres (concrete No. 3). Somewhat higher ductility and fracture energy were registered, see also Fig. 6.

Concrete No. 6 contains the same fibre volume content as mixture No.3, the only difference is that 80 kg of short straight fibres are exchanged with 80 kg of long hooked-end fibres RC-80/40-BP. The goal was to try to increase both the tensile strength and the ductility, with the same fibre volume content. In addition, for this mixture three un-notched and three notched specimen were tested.

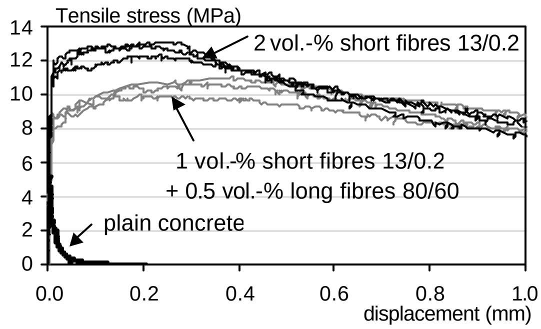

Fig. 6: Comparison of tensile response of concrete with only short fibres and with somewhat lower amount of short and long fibres

As it can be observed (Fig. 7), very similar tensile behaviour could be reached with applied fibre combinations. The tensile strength was however a little bit lower for the concrete with short and long fibres. This can be explained by irregular cracking patterns and by disability of fibre hooks to deform fully due to such patterns. The total fracture energy was, however, higher for hybrid-fibre concrete.

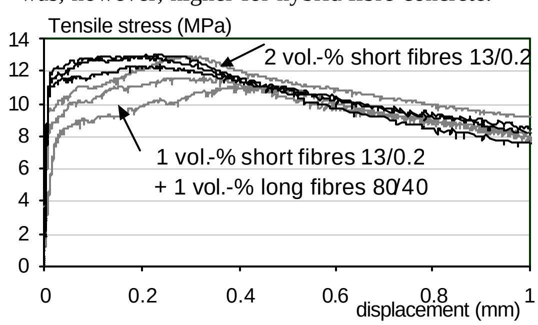

Fig. 7: Comparison of tensile responses of concrete with only short fibres, and concrete with the same amount of short and long fibres

3.4 *Cracking pattern and influence of notches on it*

The "dog-bone" shape of the specimens was chosen in order to generate cracking in the narrow zone in the middle of the specimen. In spite of that, the cracking patterns of un-notched specimens were very different (Fig. 8), and it is therefore not possible to draw any generalized conclusions. For specimens, which contained short fibres or both short and long fibres, the cracking started with the formation of numerous microcracks, after which one dominant crack formed. The formation of this crack corresponds approximately to the beginning of the softening branch in the tensile diagram. As it was observed on the fractured specimens after the tests, the dominant crack followed the easiest path to propagate through the fibre concrete. This was very often near the ends of the long hooked-end fibres, so that in many cases only the fibre hook was visible at the crack surface (Fig. 8). In some cases, even a failure along the fibres was observed. That caused that fibre hooks could not deform fully, which can have an impact on the tensile strength.

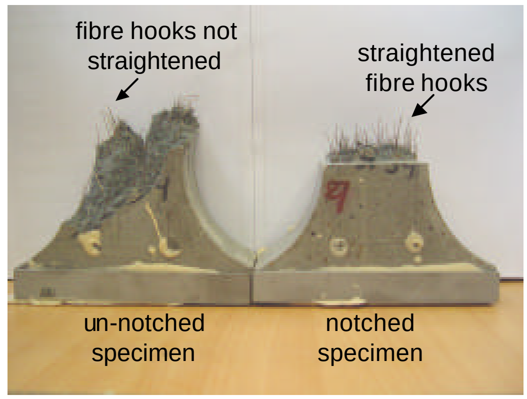

Fig. 8: Cracking patterns, position of fibres and deformation of fibre hooks in the cracking plane for un-notched and notched specimen.

The presence of notch causes larger stress concentrations, and results in the "controlled" development of a crack in one appropriate direction (Fig. 8). In this case, fracture is not directed by fibre distribution, but mostly by high stresses in weakened cross-section. The chance that the hooks of long fibres may be fully deformed becomes higher in this case, and therefore also the tensile strength and ductility will be improved. These were the reasons for performing tests with notch, and this has been done only for mixture No.5. Notches were introduced at all 4 sides of the specimens, and their depth was 5.0±0.5 mm. A comparison of tensile behaviour is given in Fig. 9.

Notched specimens had larger tensile strength and higher ductility than un-notched ones. The elastic limit for both types of specimens is approximately the same. One may conclude that the elastic limit is a material property, i.e. it is not dependent on the test set-up. After the elastic limit was reached, notched specimens showed a more pronounced plastic hardening than un-notched specimens. The scatter in the tensile behaviour was smaller for notched specimen as well. These differences are a consequence of different efficiencies of fibres in the cracked cross-sections of notched and un-notched specimens.

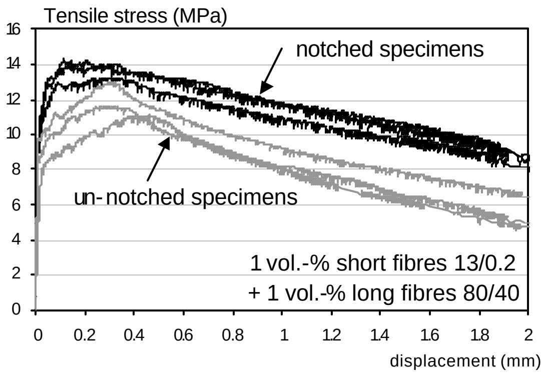

Fig. 9: Comparison of tensile response of notched and un-notched specimens of concrete No. 5 (contains both short and long fibres)

3.5 *Comparisons with other results*

Uniaxial tensile tests on traditional fibre concrete with 1 vol.-% (80 kg/m3) of long hooked-end fibres RC-80/60-BP were recently performed in [8]. Some comparisons of the results with the present HFC No. 2 (which possesses the same fibre content, and therefore will have a similar price) are given in Fig. 10.

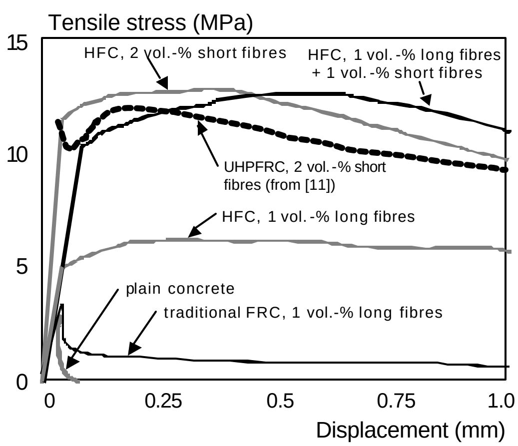

Fig. 10: A schematic comparison of tensile response for different types of traditional and high-performance fibre concrete

Traditional FRC possesses no plastic hardening, the stress decreases suddenly, right after it reached the limit of elasticity, which is a result of crack formation and of in-ability of fibres to bridge it adequately. Traditional FRC is therefore not able to assure stable tensile response. High performance concrete from this research with the same type and content of fibres (concrete No. 2) shows 2 times higher tensile strength, a very pronounced strain hardening and therefore much more stable tensile response.

A comparison of the tensile response of here present concretes No. 3 and No. 5 with some results of ultra-high-performance fibre concrete's (UHPFRC) from [10], [11], is presented in Fig. 10 as well. Somewhat higher values of tensile strength were registered for HFC, than with Ductal - UHPFRC, for the same fibre type and content of 2 vol.-%, taking into account that the tests were performed on un-notched specimens in both cases. Although no data about the fracture energy of UHPFRC's were available, one may expect that it will be somewhat higher in the case of HFC, due to the presence of long hooked-end fibres. Although the same fibre content was used in both cases, a somewhat higher price may be expected in the case of UHPFRC, due to the application of large amounts of expensive fine fillers, such as microsilica.

The same raw materials and testing machine were used in previous uniaxial tensile tests on Multi-Modal FRC [12, 13]. In that case, only the notched specimens were used, and they were much smaller than in this research (the narrowest cross section was only 30X20 mm). Rather high values of tensile strength could be reached (up to 30 MPa), but with much higher fibre contents (up to 8 vol.-%).

4 ANALYSIS OF FIBRE DISPERSION AND FIBRE DEFORMABILITY

4.1 *Goals and methods of the analysis*

Dispersion and orientation of fibres have a decisive influence on the tensile response of any fibre concrete, no matter how big the fibre volume fraction is [1, 14]. Counting of long fibres was performed in order to observe fibre dispersion, and its influence on the tensile strength, ductility and crack pattern. Similar analysis was already performed for the HFC-beams, which were tested in 3-point bending tests [9]. Firstly, all visible long fibres present on the crack surfaces were counted. After that, a distinction between fully deformed fibres (straightened fibre hook), and partially deformed fibres (fibre hook not straightened) has been made, and the number of both fibre types was estimated. Moreover, the visible lengths of long fibres were measured. This allowed for the creation of 2 probability functions: *p(l)*, which is the probability that a fibre with a visible length *l* can be found in a cross-section, and *p(d)*, which is the probability that a fibre with a visible length *l* will have deformed, i.e. straightened hook.

All these analysis were performed because of observed differences between pullout tests on individual fibres given in [5], and the response of fibres as a group in a composite. In pullout tests the plastic deformation of fibre hooks was always present in the first, and thus the most important part of the pullout process. One may therefore expect that efficient hook deformation may assure the reaching of high tensile strength of the fibre composites. However, in some cases, no hook deformation occurred, which means that fibres do not act with full efficiency. These phenomena will be explained in the next section.

4.2 *Fibre dispersion – results*

Generally, it was observed that the probability of hook deformation depends mostly on the visible length of fibres: if this length is shorter, the probability that the hook will be deformed decreases. This is also dependent on other factors, such as the presence of short fibres, which have a role of secondary reinforcement and which enhance the hook deformation (i.e. the efficiency) of long fibres.

The values of probability functions *p(l)* and *p(d)* for concrete No. 2 (only long fibres), and No. 4 (long and short fibres), are given in Fig. 12. The dominant visible length of fibres is 0-10 mm in concrete No. 2, and 20-30 mm in concrete No. 4. It should also be noted that about 20% of fibres have visible lengths larger than a half of the fibre length (30 mm = 60 mm / 2), which means that the fibre pullout process does not follow only the shorter embedded length, but also the inner structure of the concrete.

Probability *p(d)* that the hooks will be deformed is much higher for concrete No. 4, which is reinforced with both fibre types. In this case, a visible fibre length of e.g. 15 mm guarantees a full hook deformation in all cases. For mixture No. 2, the hook deformation for the same visible length is only 10%, i.e. about 10 times smaller.

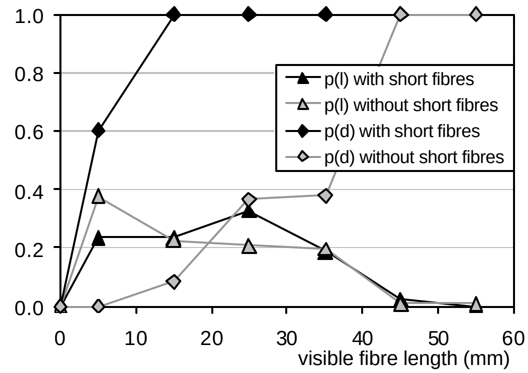

Fig. 12: Probabilities *p(l)* that a fibre with visible length *l* may be found in cracked cross-section and *p(d)* that fibre hooks will be deformed, for concretes with long fibres only and with long and short fibres

Of special interest was also the determination of functions *p(l)* and *p(d)* for notched and un-notched specimens of concrete No. 5, due to the rather large differences in tensile behaviour (see Fig. 13).

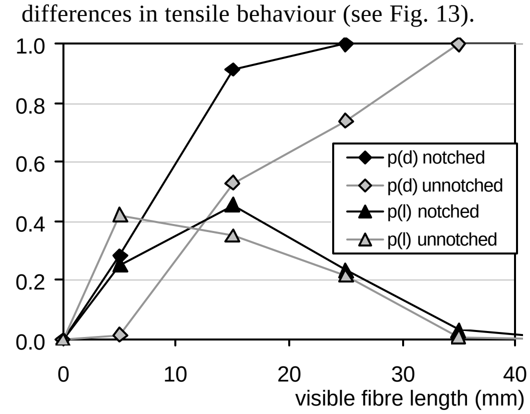

Fig. 13: Probabilities *p(l)* that a fibre with visible length *l* may be found in cracked cross-section and *p(d)* that fibre hooks will be deformed, for notched and un-notched specimens of the same type of Hybrid-Fibre Concrete

The distribution of visible fibre lengths is rather different for these types of specimens. More than 40% of fibres in cracked cross-section of un-notched specimens possess a length smaller than 10 mm, i.e. they have rather low efficiency. In notched specimen, only 20% of lengths under 10 mm was observed, while the visible length of most fibres is between 10-20 mm. The probability of hook deformation is higher in the case of notched specimens, which is an explanation for better tensile behaviour. For example, almost all fibres in notched specimens with visible length from 10-20 mm will be deformed. The situation is different in un-notched specimens, where for the same visible length, only 50% of fibre hooks will be deformed, i.e. only those fibres will be fully active.

5 CONCLUSIONS

The uniaxial tensile behaviour of a number of mono- and hybrid-fibre reinforced concretes was estimated. Maximum applied fibre volume was 2 vol.-% (160 kg/m^3). Tensile tests were performed on unnotched and on a couple of notched "dog-bone" specimens. From the obtained results, the following may be concluded:

1. High tensile strengths up to 14 MPa were obtained, and the plastic hardening was very pronounced in all types of concrete, up to the crack openings of 0.3 to 0.5 mm. Applied fibre amounts were relatively low (up to 2 vol.% or 160 kg/m^3). All this makes these concrete types very attractive for possible practical applications.

2. Cracking in most of the un-notched specimens began with formation of many fine cracks, and after hardening, one dominant crack formed, which marked the beginning of the strain softening. At a crack opening of about 1/3 of fibre length, the tensile stress was equal to zero.

3. For un-notched specimens, the highest tensile strength of about 13 MPa is obtained with mixture with 2 vol.-% of short fibres. Concrete types with fibre combinations showed similar tensile performance: tensile strengths were similar with tensile strength of concrete with short fibres only, while the ductility and the fracture energy were higher.

4. Rather large differences in tensile behaviour were observed when un-notched and notched specimens of the same type of concrete were used. The maximum value of tensile strength of more than 14 MPa was obtained with notched specimens. Ductility and fracture energy were also higher in tests with notched specimens.

5. These differences are consequence of different crack patterns, which are dependent on the dispersion of long fibres. In un-notched specimens, crack followed the easiest way of propagation, often near the ends of fibres. Many of fibre hooks did not deform, which has an impact on both the tensile strength and ductility. Deformation of hooks was also more pronounced when short fibres were present in the concrete.

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