Postcracking behaviour of hybrid steel fiber reinforced concrete

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ABSTRACT: This papers presents research on the mechanical performance (compressive strength, bending behaviour according to RILEM TC162-TDF) of both normal and hybrid steel fiber reinforced concrete. The investigated parameters were fiber type (shape, length) and fiber dosage. The results show that very short and short fibers affect the cracking process at small crack openings while the longer fibers provide a good ductility at larger deformations. For the mixtures with one type of fiber the absolute scatter on the results of the bending tests is much smaller than for the long fibers. In this research the synergetic effect of the combination of different types of steel fiber is ambiguous.

1 INTRODUCTION

Cementitious composites are typically characterized as brittle, with a low tensile strength and strain capacity. Fibers are incorporated into cementitious materials to overcome this weakness, producing materials with increased tensile strength, ductility and toughness and improved durability (Balaguru and Shah, 1992).

Fibers can differ from each other by size, shape and material (steel, carbon, synthetics, glass, natural fibers, ..). However, for most structural and non-structural purposes, steel fibers are the most used of all fiber types. Synthetic fibers on the other hand are mainly used to control early cracks in slabs on grade and to avoid spalling of high strength concrete during fire.

A more recent development in fiber reinforced cement-based composites is the use of fiber hybridization to optimize material performance based on the intended use. Two or more fiber types are combined so that the material can achieve the beneficial performance characteristics of each fiber. Typically this improvement is attained by using fibers that will affect the cracking process during different stages of loading, which often involves using fibers of varying sizes and moduli (Shah and Kuder, 2004).

The idea is that the short fibers can bridge efficiently the microcracks, which develop in the first phases of the tensile loading (Fig. 1a). When microcracks join with each other into larger cracks, long fibers may be activated as bridging mechanism (Fig. 1b). As a result the ductility enhancement depends mainly on the long fibers (Markovic, 2006).

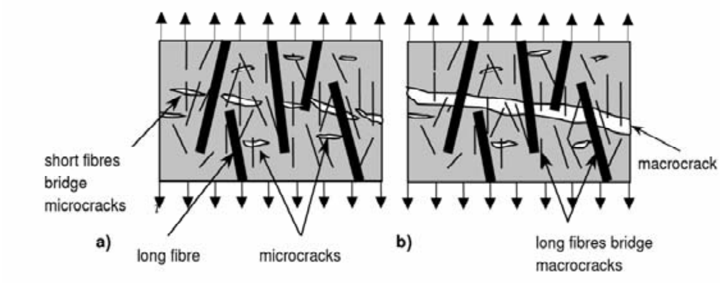

Figure 1. Action of the different fiber types in concrete (Markovic, 2006)

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2 RESEARCH PROGRAM

The test program, executed at the Department of Civil Engineering of the K.U.Leuven, involved RILEM 3-point bending tests (Vandewalle et al, 2002) to measure the postcracking tensile behaviour of fiber concrete. The test set-up is shown in Figure 2. The test specimen is a beam of 550 to 600 mm length and a cross section with a width and depth of 150 mm. The span of the test specimen is equal to 500 mm. In the middle of the span the specimen is notched, the depth of the notch is equal to 25 mm. The test is performed under CMOD (crack mouth opening displacement) control. Besides the CMOD and the load, also the relative deflection at midspan at both sides of the prism can be measured optionally.

The compressive strength ($f_{cm,cube}$) is measured on cubes with side = 150 mm.

Three types of steel fibers are applied, i.e. one very short straight steel fiber (SK : length = 6 mm, diameter = 0.16 mm – OL6/.16), one short straight steel fiber (K : length = 13 mm, diameter = 0.16 mm – OL13/.16) and one long hooked-end steel fiber (L : length = 35 mm, diameter = 0.55 mm – RC65/35BN).

The total fiber content ranges from 0 (reference mix) to 90 kg/m^3. Fifteen mixtures in total were tested as shown in Table 1. LxKySKz means a mixture with a dosage of x kg/m^3 long hooked-end fibers, y kg/m^3 short fibers and z kg/m^3 very short fibers.

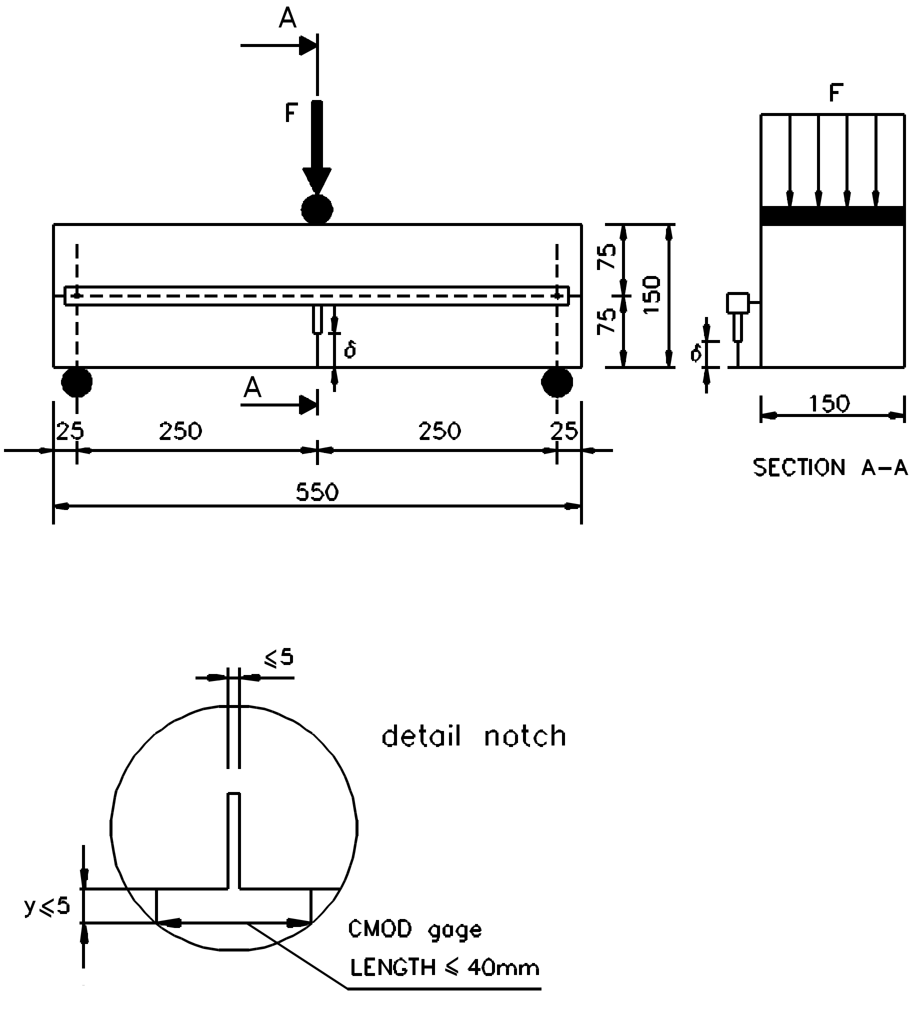

Figure 2. Test set-up (Vandewalle et al., 2004).

Table 1. Overview of test program and mechanical results.

Series	$f_{cm,cube}$ (MPa)	$f_{fct,L}$ (MPa)	$f_{R,1}$ (MPa)	$f_{R,4}$ (MPa)
L00K00SK00	54.5	-	-	-
L00K00SK30	59.6	4.45 (0.33 – 7.42)[(x)]	1.81 (0.30 – 16.57)	0.30 (0.07 – 23.33)
L00K00SK60	62.1	5.45 (0.27 – 4.95)	2.63 (0.28 – 10.65)	0.49 (0.10 – 20.41)
L00K30SK00	62.8	5.19 (0.31 – 5.97)	2.78 (0.29 – 10.43)	1.26 (0.13 – 10.32)
L00K60SK00	66.9	5.98 (0.34 – 5.69)	4.40 (0.38 – 8.64)	1.98 (0.18 – 9.09)
L30K00SK00	55.9	5.11 (0.30 – 5.87)	3.45 (0.92 – 26.67)	2.64 (0.75 – 28.41)
L60K00SK00	57.2	6.15 (0.73 – 11.87)	5.96 (0.76 – 12.75)	4.24 (0.59 – 13.92)
L00K30SK30	76.9	5.34 (0.36 – 6.74)	3.46 (0.53 – 15.32)	0.80 (0.24 – 30.00)
L30K30SK00	65.2	5.37 (0.34 – 6.33)	4.77 (0.39 – 8.18)	2.95 (0.25 – 8.47)
L20K40SK00	67.2	5.69 (0.49 – 8.61)	4.85 (0.70 – 14.43)	2.70 (0.48 – 17.78)
L40K20SK00	61.6	6.06 (0.62 – 10.23)	5.75 (0.72 – 12.52)	3.47 (0.39 – 11.24)
L20K20SK20	64.8	6.10 (0.64 – 10.49)	5.30 (0.82 – 15.47)	3.03 (0.62 – 20.46)
L30K30SK30	69.2	6.63 (0.70 – 10.56)	6.37 (0.72 – 11.30)	3.76 (0.36 – 9.57)
L30K60SK00	67.2	7.07 (0.56 – 7.92)	6.94 (0.53 – 7.64)	4.48 (0.36 – 8.04)
L60K30SK00	58.6	6.36 (0.48 – 7.55)	6.30 (0.46 – 7.30)	4.47 (0.50 – 11.19)

(x) : value (MPa) (absolute scatter (MPa) – relative scatter (%))

The concrete composition is identical for all mixtures (see Table 2). Only the dosage of superplasticizer changed since the presence of steel fibers in concrete decreases its workability.

Table 2. Concrete composition.

	kg/m^3
Gravel 4/16	1012
Sand 0/5	865
Cement CEM I 52,5N	350
Water	175
W/C	0,5

After casting, the specimens were cured at +20°C and 95-100 % relative humidity for 4 weeks.

3 TEST RESULTS

3.1 *Compressive strength*

The mean cube compressive strength of the different mixes is given in Table 1. $f_{cm,cube}$ ranges between 54.5 MPa (reference mix) and 76.9 MPa (L00K30SK30). The addition of steel fibers results in a higher compressive strength. Moreover, the test results show also that very short and short steel fibers provide a higher improvement of $f_{cm,cube}$ than the long hooked-end steel fibers do. The reason for this is probably the fact that the very short and short steel fibers can bridge efficiently the microcracks.

3.2 *Tensile behaviour*

Each fiber concrete mixture consists of 6 prisms for the bending test. The mean value and the scatter (absolute – relative) of the bending test results of all series are mentioned in Table 1. $f_{fct,L}$ is the limit of proportionality while $f_{R,1}$ and $f_{R,4}$ are the residual flexural tensile strength at CMOD = 0.5 mm, CMOD = 3.5 mm respectively.

3.2.1 *Scatter*

The load-CMOD-curves of series L00K00SK60 are shown in Figure 3, of series L00K60SK00 in Figure 4, of series L60K00SK00 in Figure 5 and of the hybrid mixes L60K30SK00 and L30K60SK00 in Figures 6 and 7 respectively. The detailed results of the other mixtures can be found elsewhere (De Smedt and Rolies, 2005, Fevrier and Vangoidsenhoven, 2006).

The absolute scatter of the results of the concrete with only very short steel fibers (L00K00SK60), short steel fibers (L00K60SK00) respectively is much smaller than of the steel fiber concrete with only long hooked-end fibers (L60K00SK00). However, when looking to the relative scatter (see Table 1), the short fibers give the best results if only one type of steel fiber is used.

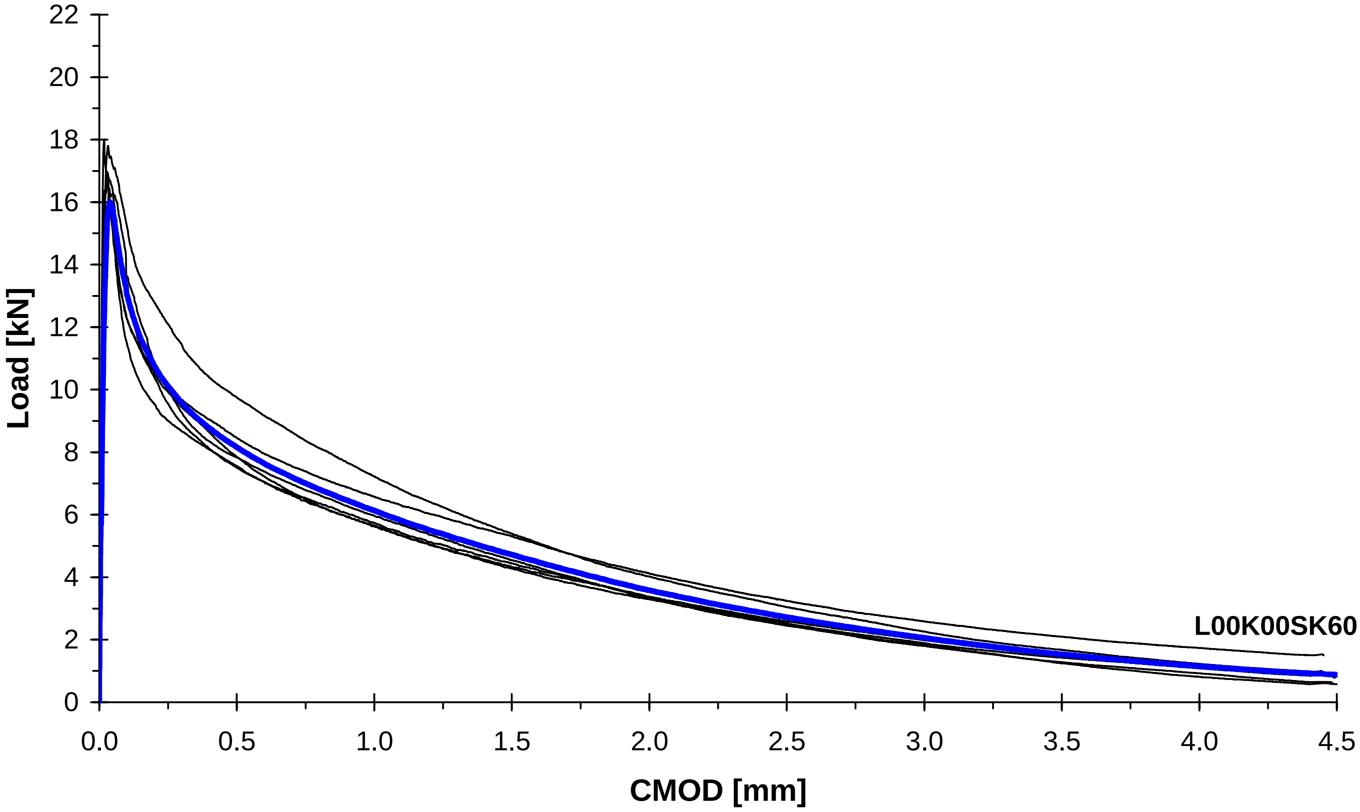

Figure 3. Load-CMOD-curves for L00K00SK60.

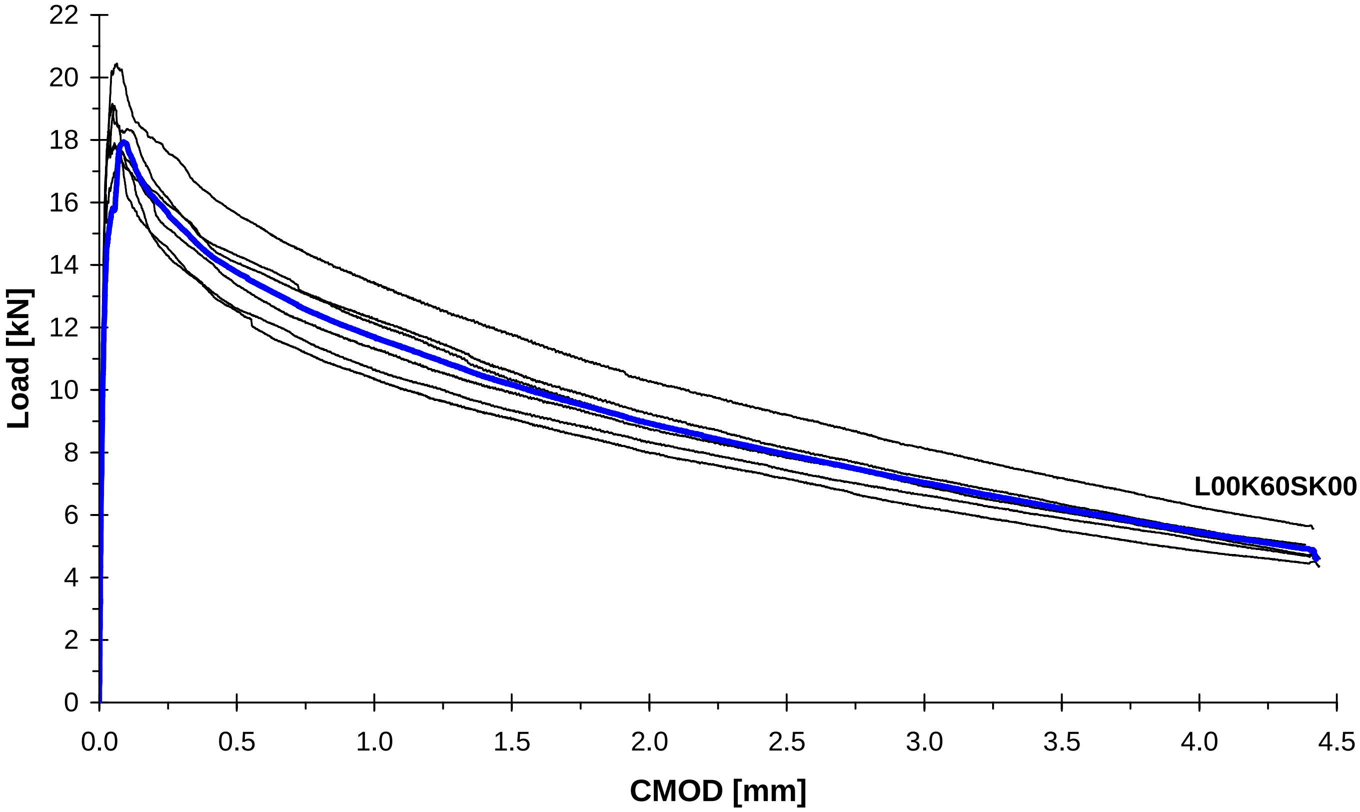

Figure 4. Load-CMOD-curves for L00K60SK00.

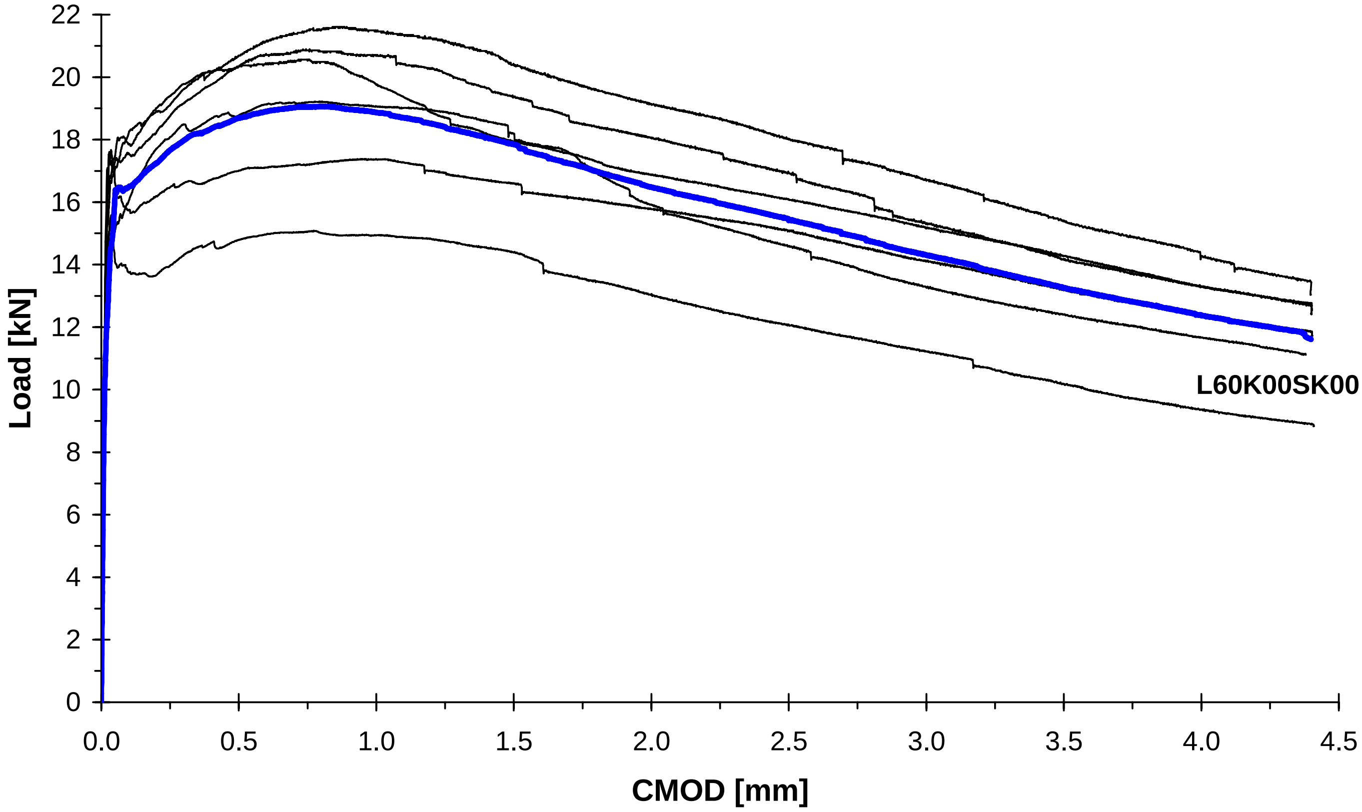

Figure 5. Load-CMOD-curves for L60K00SK00.

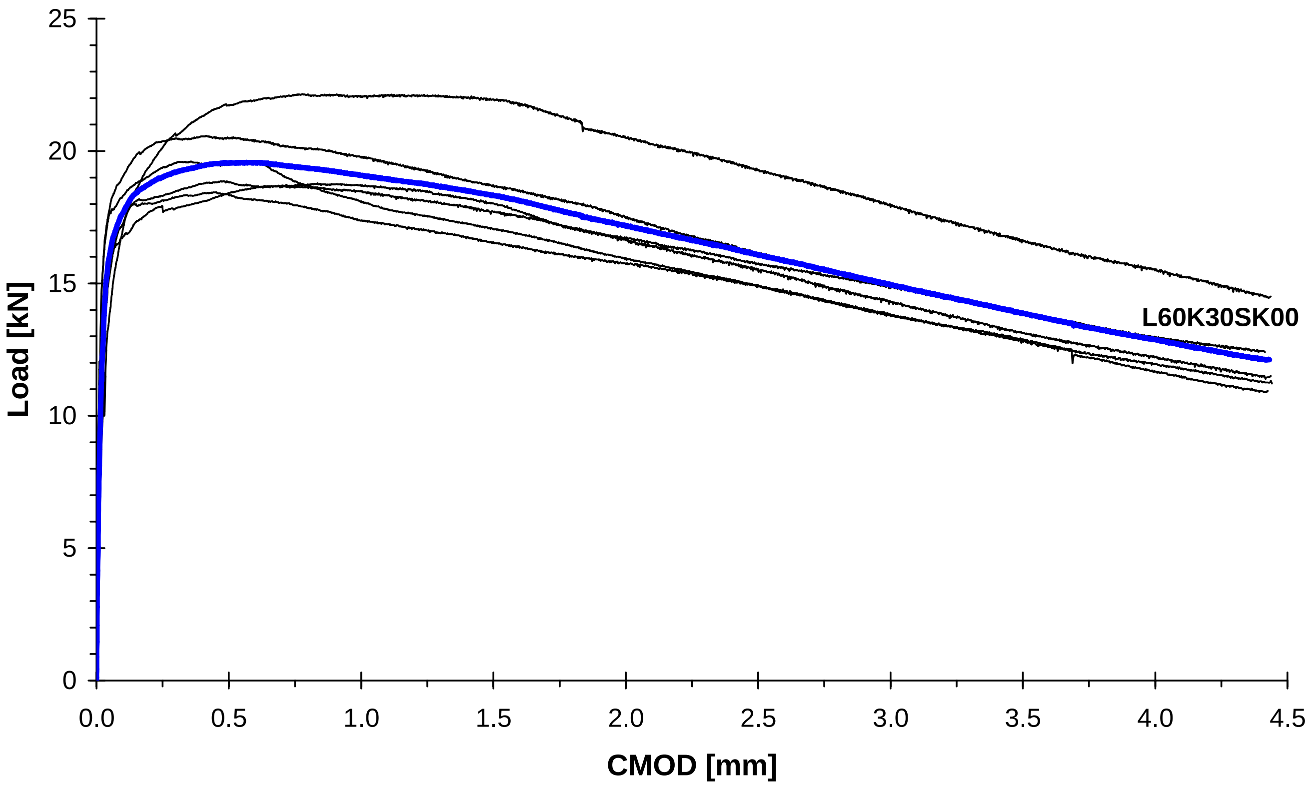

Figure 6. Load-CMOD-curves for L60K30SK00.

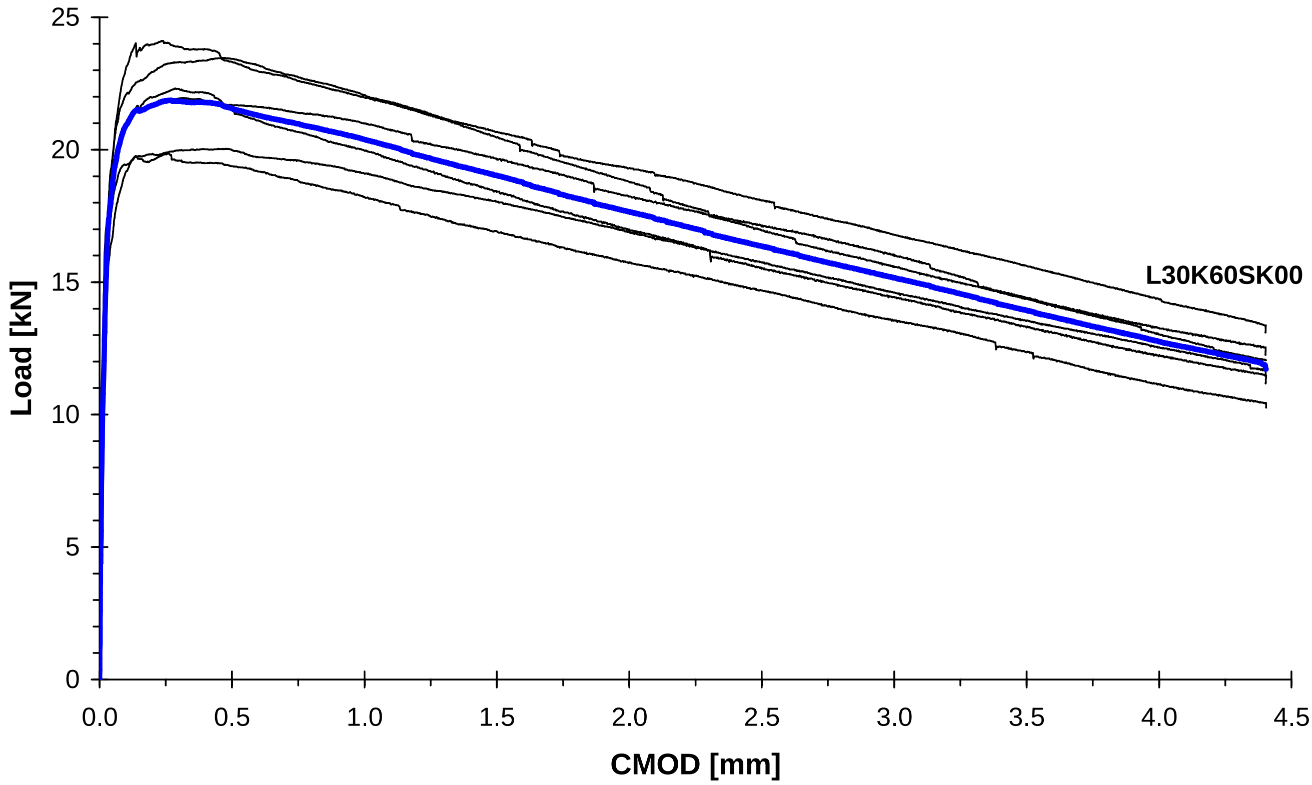

Figure 7. Load-CMOD-curves for L30K60SK00.

The number of fibers in one kg increases when its shape decreases. Fiber counts have shown that the thoughness parameters were directly related to the number of fibers intersecting the fracture surface. A small variation or difference in number of fibers has a direct and relatively large influence on the postcracking behaviour of the materials tested. This is particularly important for low fiber dosages and relatively small cross sections (Barr et al., 2003). As a result the mixtures with only one fiber type (see Table 1) confirm the statement that the scatter would be more pronounced in specimens with a lower absolute number of fibers.

However, the same tendency can not always be found for the hybrid steel fiber concretes. For instance, although the absolute number of fibers in L30K60SK00 is higher than in L60K30SK00 both the absolute and relative scatter are almost the same in the two mixtures

3.2.2 *Postcracking behaviour*

The mean-load-CMOD-curves for concrete reinforced with 60 kg/m^3 of fibers are shown in Figure 8 (0 – 0.5 mm) and 9 (0 – 4.5 mm).

For concrete reinforced with one type of steel fiber, it can be seen that the overall postcracking behaviour in the CMOD-region 0 to 0.15 mm is the best for concrete reinforced with short steel fibers. The length of the very short steel fibers is probably. too small in comparison with the size of the used aggregates (gavel 4/16) to bridge efficiently the microcracks. On the other hand, the tensile behaviour for CMOD-values larger than 0.15 mm is much better for concrete reinforced with long hooked-end fibers.

Short fibers can bridge microcracks more efficiently because they are very thin and their number in concrete is much higher than that of the long thick fibers for the same fiber volume quantity. However, for larger crack widths the ductility of the mixtures with long fibers is much better than that of the corresponding mixtures with the short fibers. As the microcracks grow and join into larger macrocracks, the long hooked-end fibers become more and more active in crack bridging. The origin of the higher residual forces for long hooked-end fibers at larger CMOD-values is twofold:

- presence of a hooked-end
- long embedded length (anchorage length).

Both aspects provide a higher pull-out force for long hooked-end fibers in comparison with short fibers, particularly at larger crack widths. Long fibers can therefore provide a stable post-peak response. Short straight fibers will be less active because they are being pulled out more and more as the crack increases.

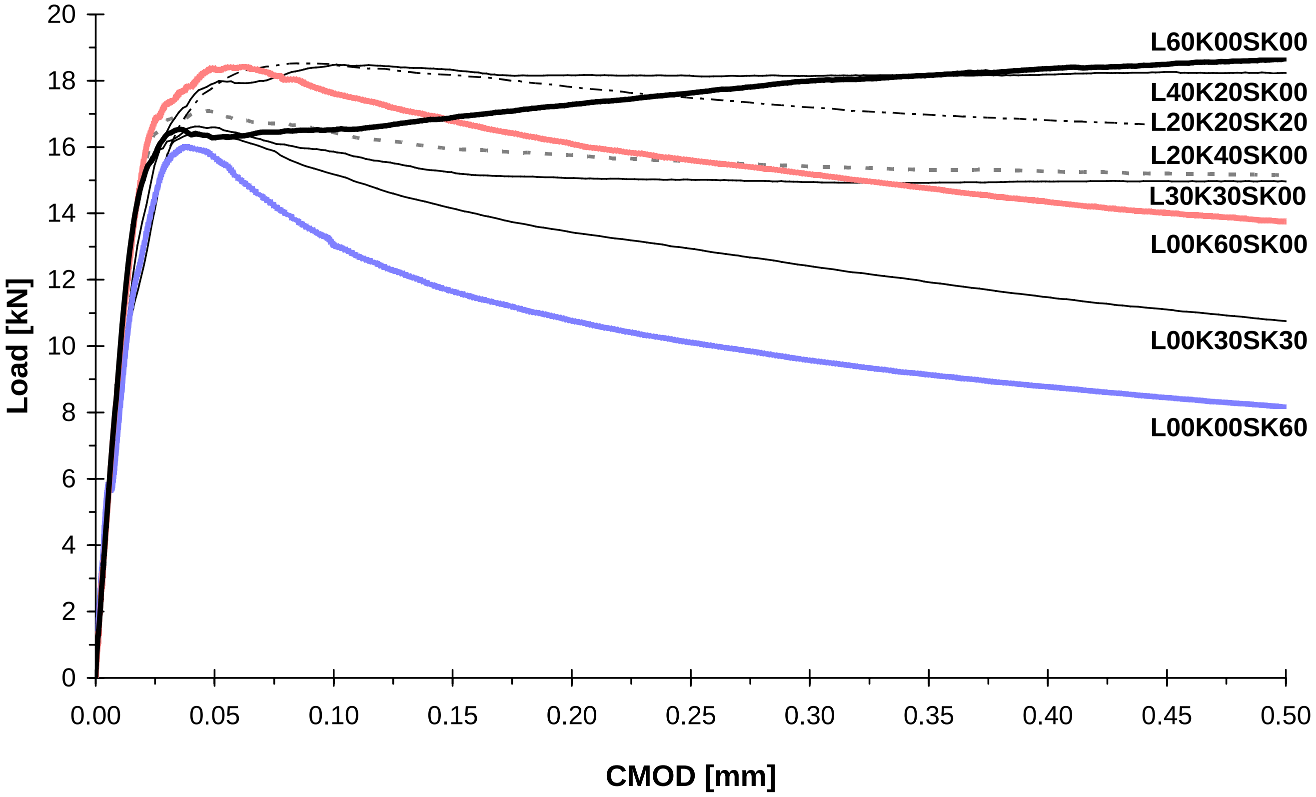

Figure 8. Mean load-CMOD-curves for concretes with 60 kg/m^3 of fibers (CMOD: 0-0.5 mm).

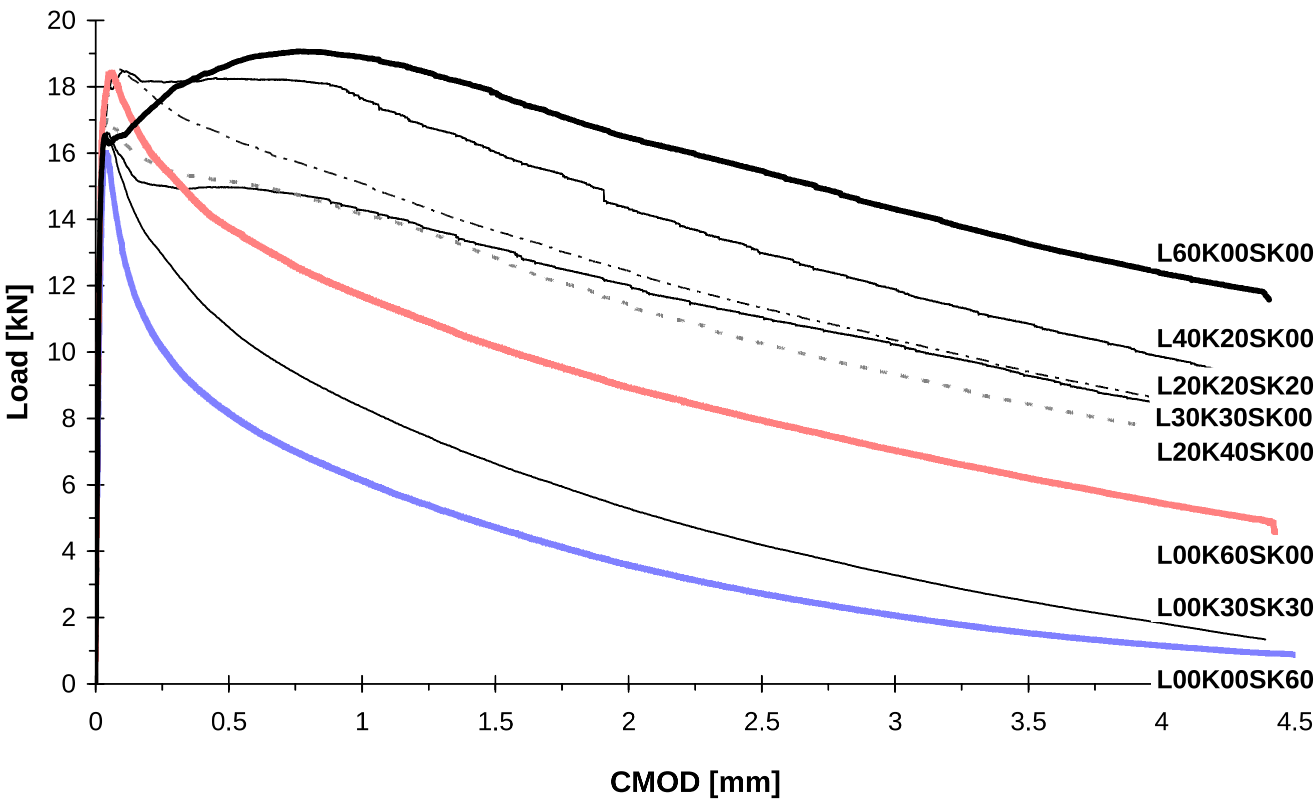

Figure 9. Mean load-CMOD-curves for concretes with 60 kg/m^3 of fibers (CMOD: 0-4.5 mm).

The postcracking behaviour in the CMOD-region of 0 to 0.15 mm is for the hybrid mixes relatively similar when taking the scatter of the individual results within a series into account. For larger CMOD-values, however, the ductility increases when a higher volume percentage of long hooked-end fibers in the mixture is used. The series with only very short fibers and/or a combination of very short and short fibers show the worst overall postcracking behaviour.

3.2.3 *Synergetic effect*

Synergy is the phenomenon where acting of two or more subjects together leads to a better result than the action of the same subjects independently of each other. Translated to hybrid fiber concrete, the synergy of very short or short fibers and long fibers should lead to an improved tensile response of the hybrid fiber concrete, compared to the arithmetic sum of tensile responses of two concretes, one of which contains only long and another only very short or short fibers (in the same quantity as the hybrid fiber concrete) (Markovic, 2006).

In this paper the synergetic effect has been investigated for two hybrid fiber concretes, i.e. L60K30SK00 as shown in Figure 10 and L30K60SK00 as shown in Figure 11. The calculated curve in both figures starts from a CMOD of 0.3 mm in order to account only the effect of the fibers.

As shown in Figure 10 no synergetic effect at all can be observed for L60K30SK00. On the contrary the sum of the individual curves gives a smaller stress at a certain CMOD than the experimental curve does. With regard to L30K60SK00 it can be seen that the arithmetic sum of the two individual curves for CMOD-values larger than 2 mm is almost identical to the experimental curve. Again no synergy can be recorded.

Markovic (Markovic, 2006), however, did find synergetic effects. The reason for this is perhaps due to the fact that the maximum grain size of the used concrete in his research was only 1 mm and the fiber dosages used were rather high, i.e. 1 to 2 Vol.%. Further research with regard to this phenomenon is necessary.

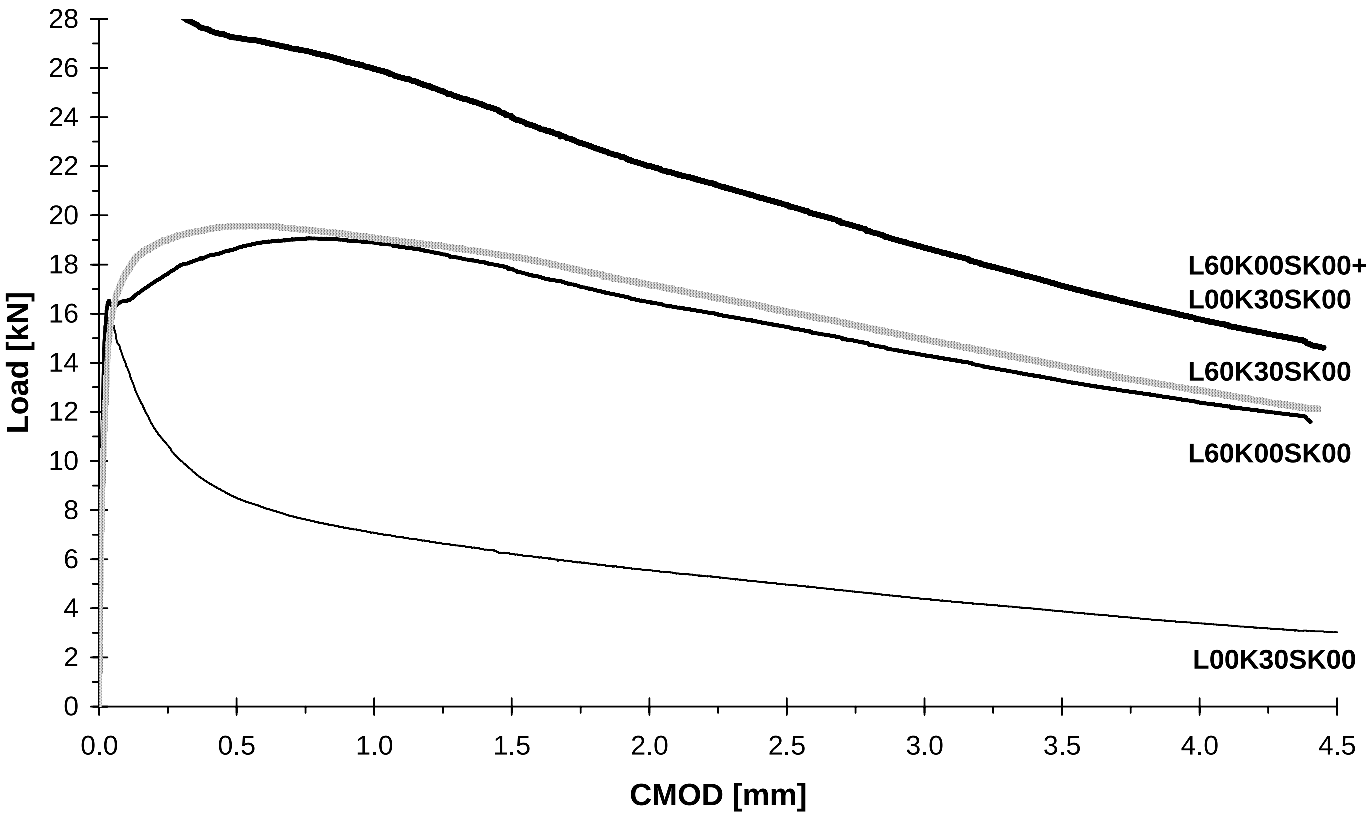

Figure 10. Synergetic effect of L60K30SK00.

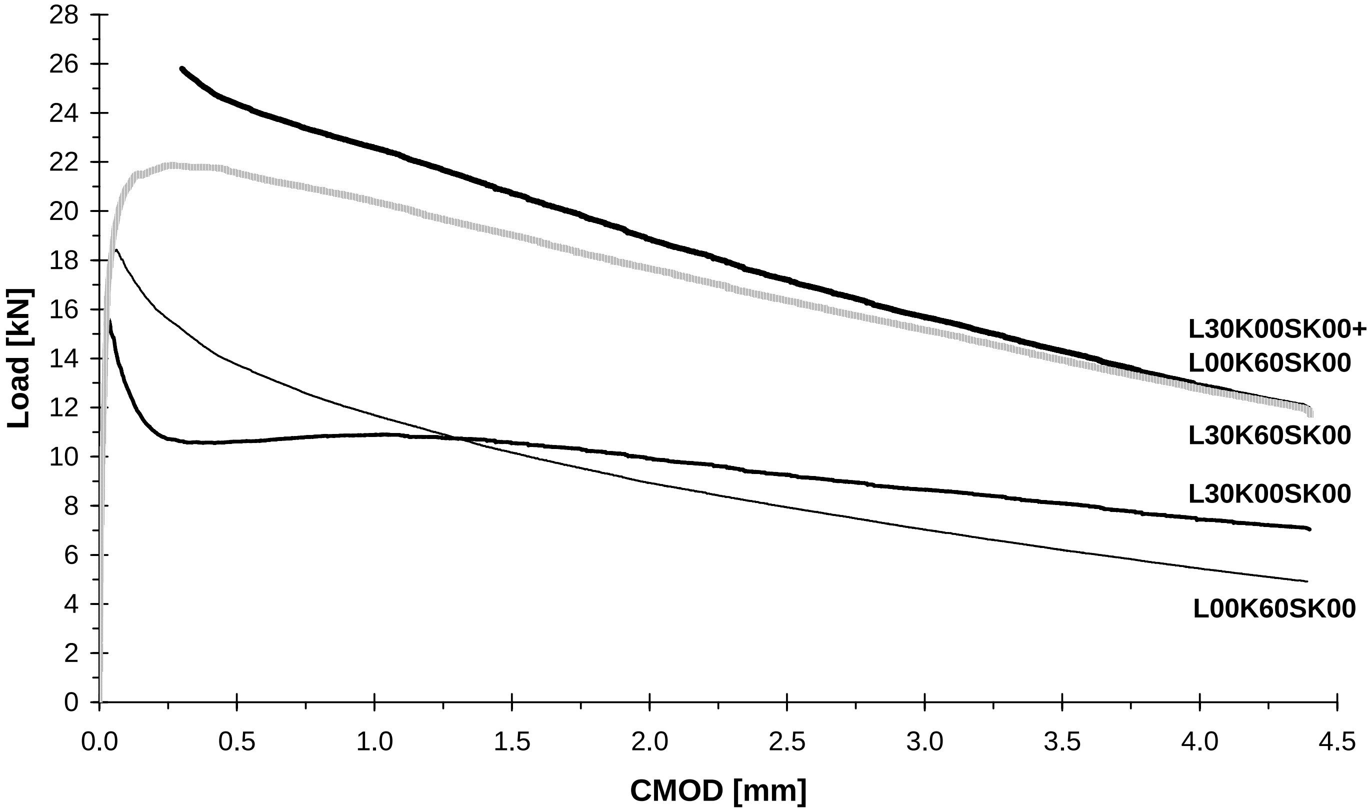

Figure 11. Synergetic effect of L30K60SK00.

4 CONCLUSIONS

Fifteen series of steel fiber reinforced concrete have been investigated at the Department of Civil Engineering of the K.U.Leuven. The following conclusions can be drawn :

- for a certain applied fiber volume percentage, the number of fibers crossing a cracked section increases as the size of the used steel fiber decreases. This results in a lower absolute scatter on the test results of steel fiber concrete which contains only very short or short fibers. An analogous conclusion can not be drawn for the hybrid fiber concrete mixes;
- for the used concrete containing aggregates with a maximum size of 16 mm, the efficiency of the very short fibers is worse than of the short fibers even in the CMOD-region of 0 to 0.15 mm;
- the overall ductility of the fiber concrete is dominated by the volume of the long hooked-end steel fibers : the higher is the dosage of the long hooked-end steel fibers, the better is the postcracking performance of the fiber concrete;
- no synergetic effect has been found in the hybrid mixes.

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