Mechanical properties of hybrid fiber reinforced concrete

L.Vandewalle
K.U.Leuven, Department of Civil Engineering, Leuven, Belgium

ABSTRACT: In this research the mechanical properties (compressive strength, ductility according to bending test of RILEM TC162-TDF) of a number of hybrid steel fiber reinforced concrete mixes have been examined. The parameters, investigated, are: steel fiber type (very short straight steel fibers: length = 6 mm, short straight steel fibers: length = 13 mm and long hooked end steel fibers : length = 35mm) and fiber dosage. The program includes 15 different steel fiber reinforced concrete mixes. The obtained results of the deformation controlled bending tests show that the very short and short fibers are very effective in the region of small crack openings while the longer fibers provide a good ductility at large crack widths. The observed scatter of the results decreases when the percentage of very short and/or short fibers increases.

1 INTRODUCTION

Fiber reinforced concrete is a composite material with a postcracking tensile strength due to the bridging of the cracks by the fibers. Consequently, both the durability and ductility of concrete structures enhances. For structural applications normally 0.3 to 1 Vol.-% of steel fibers of the same type are mixed in the concrete matrix.

However, to have a durable construction small crack widths (0.2 to 0.3 mm) are required in the serviceability limit state. Especially the use of very short to short fibers with a high aspect ratio is beneficial for that. Ductility on the other hand, refers to large deformations, i.e. a good bridging effect of the fibers at large crack widths is necessary. To perform this task, large deformed fibers are more obvious.

So to achieve both durability and ductility the application of a mixture of short and long fibers is logical, i.e. hybrid fiber reinforced concrete [Rossi, P. et al. 1987].

In this research the mechanical properties (compressive strength, ductility according to bending test of RILEM TC162-TDF) of a number of hybrid steel fiber reinforced concrete mixes have been examined. The parameters, investigated, are: steel fiber type (very short straight steel fibers: length = 6 mm, short straight steel fibers: length = 13 mm and long hooked end steel fibers: length = 35 mm) and fiber dosage. The program includes 15 different steel fiber reinforced concrete mixes.

The obtained results of the deformation controlled bending tests show that the very short and short fibers are very effective in the region of small crack openings while the longer fibers provide a good ductility at large crack widths. The observed scatter of the results decreases when the percentage of very short and/or short fibers increases.

2 RESEARCH PROGRAM

The compressive strength is measured on cubes (150 x 150 x 150 mm).

The characterization of the flexural behaviour of hybrid fiber reinforced concrete is done by means of the three-point bending test on notched beams (beam dimensions 150 x 150 x 600 mm) as recommended by the RILEM Technical Committee 162-TDF (Test and Design methods for Steel Fiber Reinforced Concrete) [Vandewalle, L. et al. 2002]. The notch depth is equal to 25 mm. The test set-up is shown in Figure 1.

The test is performed under CMOD (Crack Mouth Opening Displacement) control, i.e. the machine shall be operated in such a way that the CMOD increases at a constant rate of 50 μm/min for CMOD from 0 to 0.1 mm, until the end of the test at a constant rate of 0.2 mm/min.

Besides the CMOD and the load, also the relative deflection at midspan at both sides of the prism can be measured optionally.

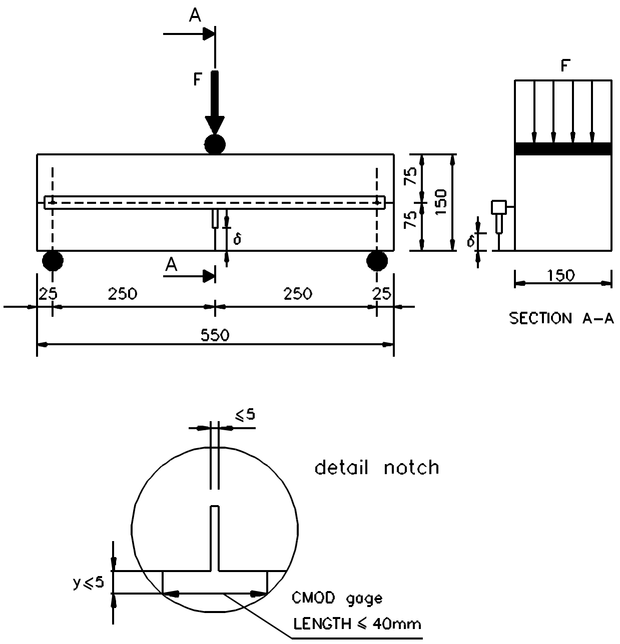

Figure 1. Test set-up [Vandewalle, L. et al. 2002].

Three types of steel fibers are applied, i.e. one very short straight steel fiber (SK) (Figure 2), one short straight steel fiber (K) (Figure 3) and one long hooked end steel fiber (L) (Figure 4).

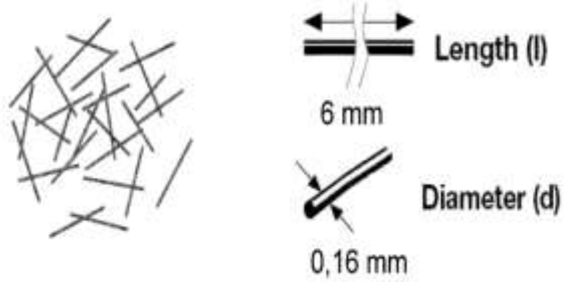

Figure 2. Very short straight steel fiber (SK – OL6/.16).

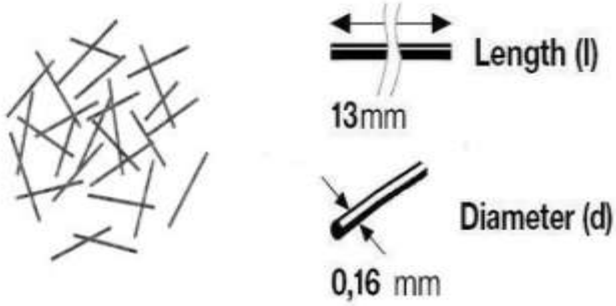

Figure 3. Short straight steel fiber (K – OL13/.16).

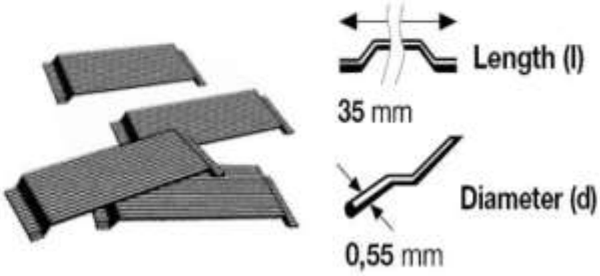

Figure 4. Long hooked end steel fiber (L–RC65/ 35BN).

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.

Table 1. Overview of test program.

Series	SK (kg/m^3)	K (kg/m^3)	L (kg/m^3)	$f_{cm,cube}$ (MPa)
L00K00SK00	-	-	-	54.5
L00K00SK30	30	-	-	59.6
L00K00SK60	60	-	-	62.1
L00K30SK00	-	30	-	62.8
L00K60SK00	-	60	-	66.9
L30K00SK00	-	-	30	55.9
L60K00SK00	-	-	60	57.2
L00K30SK30	30	30	-	76.9
L30K30SK00	-	30	30	65.2
L20K40SK00	-	40	20	67.2
L40K20SK00	-	20	40	61.6
L20K20SK20	20	20	20	64.8
L30K30SK30	30	30	30	69.2
L30K60SK00	-	60	30	67.2
L60K30SK00	-	30	60	58.6

The concrete composition is identical for all mixtures (see Table 2). Only the dosage of superplasticizer changed since the application of steel fibers in concrete has an impact on 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

3 TEST RESULTS

3.1 *Compressive strength*

The mean cube compressive strength of the different mixes is mentioned 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. 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. This is probably due to the fact that the very short and short steel fibers can bridge efficiently the microcracks.

3.2 *Flexural behaviour*

3.2.1 *Variation*

Each series consists of 6 specimens. The load-CMOD-curves of series L00K00SK30 are shown in Figure 5, of series L00K30SK00 in Figure 6, of series L30K00SK00 in Figure 7 and of the hybrid mixes L60K30SK00 and L30K60SK00 in Figures 8 and 9 respectively. The detailed results of the other mixes are given elsewhere [De Smedt, K. & Rolies, K. 2005, Fevrier, B. & Vangoidsenhoven, G. 2006].

In general, the absolute value of the scatter of the test results within a series of concrete reinforced with only very short steel fibers (L00K00SK30), short steel fibers (L00K30SK00) respectively, is much smaller than of steel fiber reinforced concrete with only hooked end steel fibers (L30K00SK00).

The tensile properties of any type of fiber reinforced concrete depend mostly on 2 parameters [Marcovic, I. 2006]:

- the number of fibers in the cracking zone
- the orientation of fibers in the cracking zone with respect to main tensile stresses.

The number of very short and short steel fibers in one kg is much higher than of long hooked end fibers. 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. So, the test series of concrete reinforced with only one type of steel fiber confirm the fact that the variation would be more pronounced in specimens which contain a lower absolute number of fibers.

An analogous trend, however, has not always been found for the steel fiber hybrid mixes. For instance, although the absolute number of fibers in L30K60SK00 is higher than in L60K30SK00 the absolute value of the scatter is almost the same for both mixes.

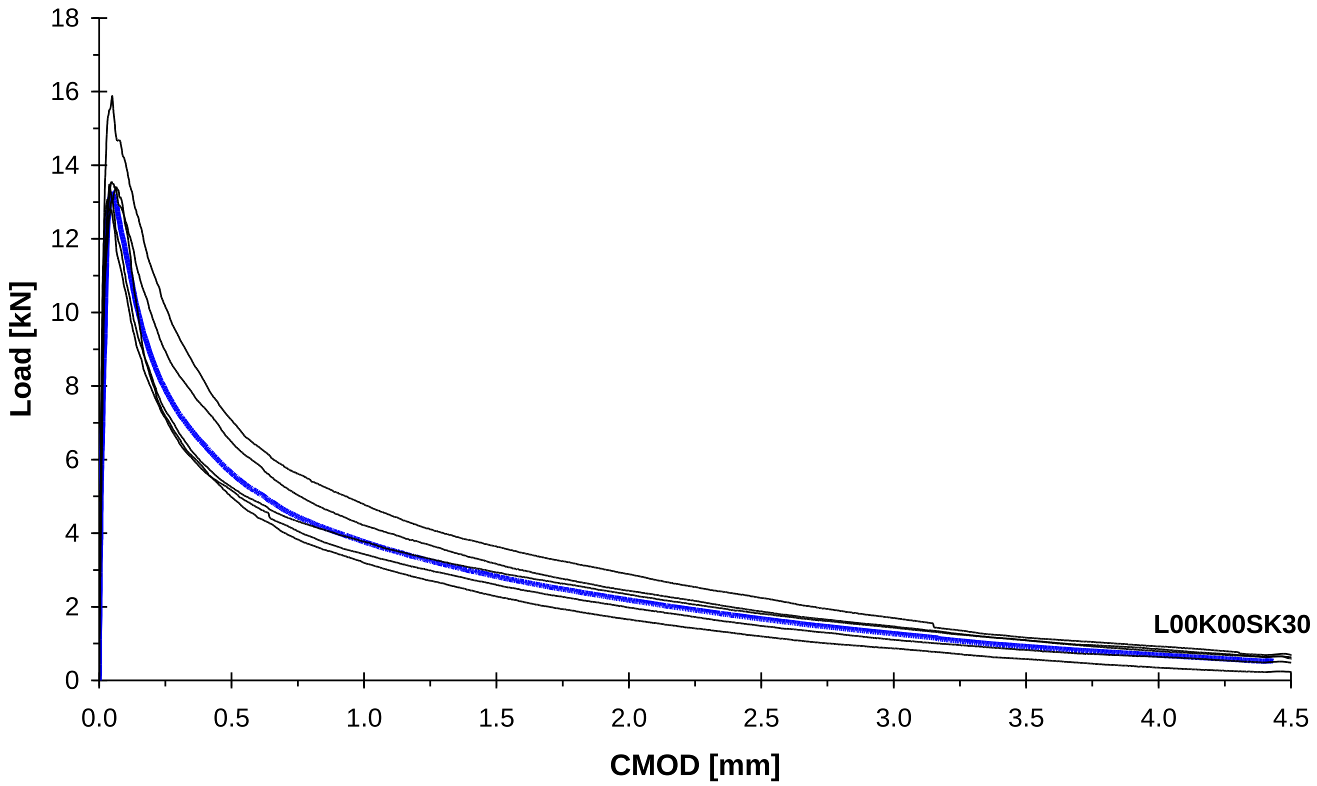

Figure 5. Load-CMOD-curves for L00K00SK30.

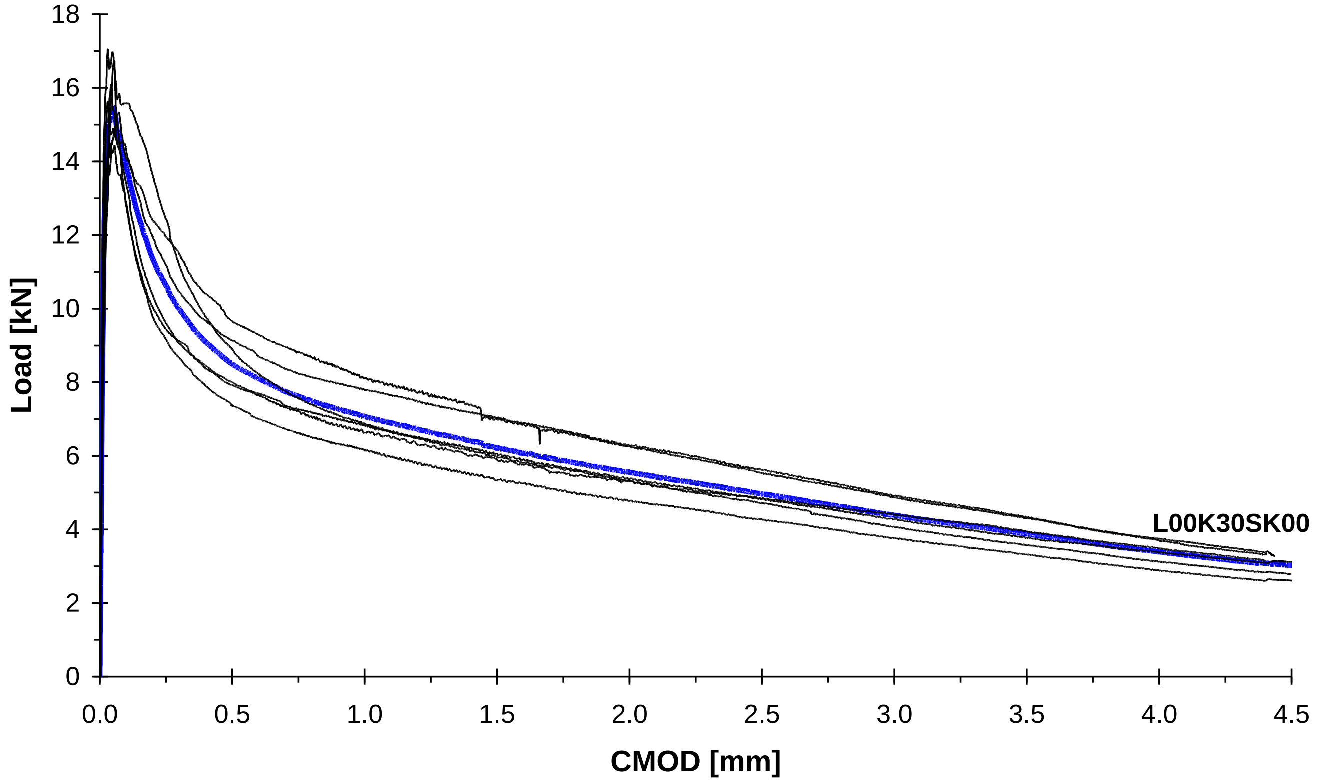

Figure 6. Load-CMOD-curves for L00K30SK00.

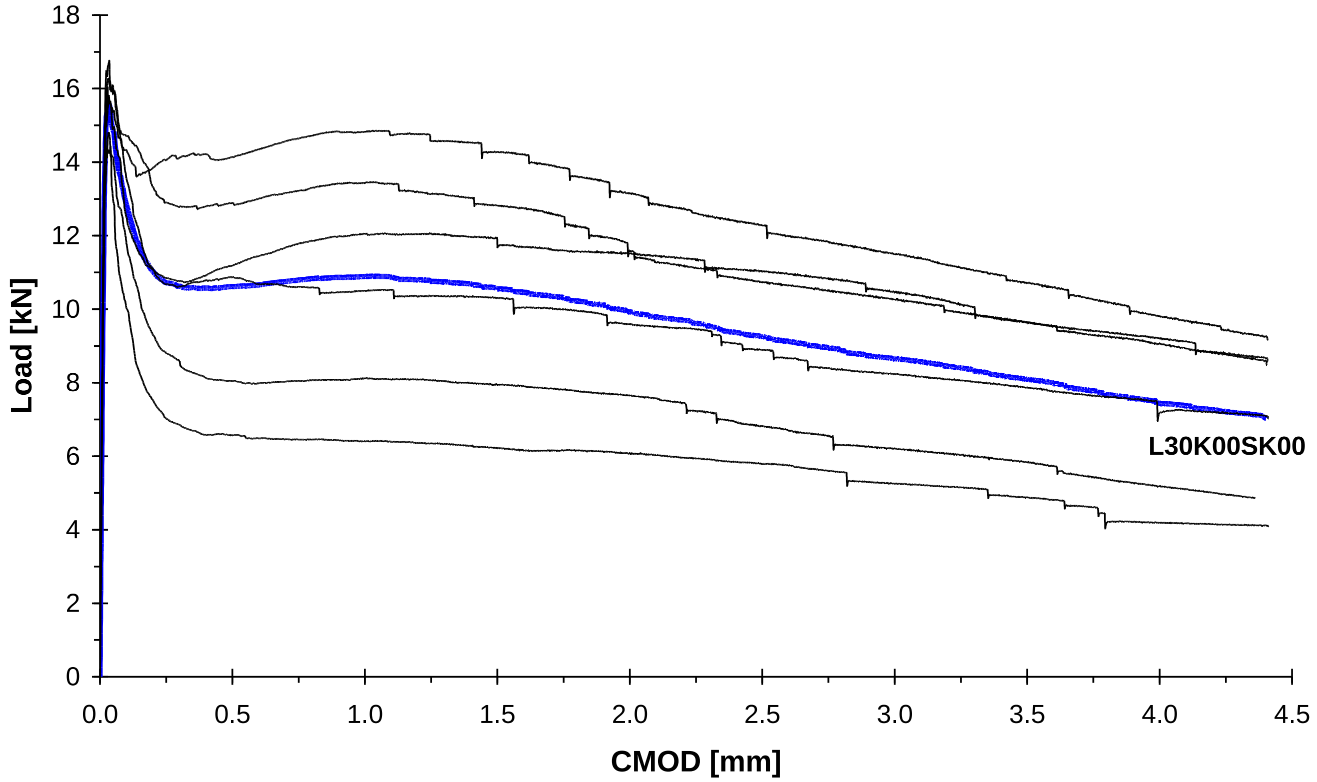

Figure 7. Load-CMOD-curves for L30K00SK00.

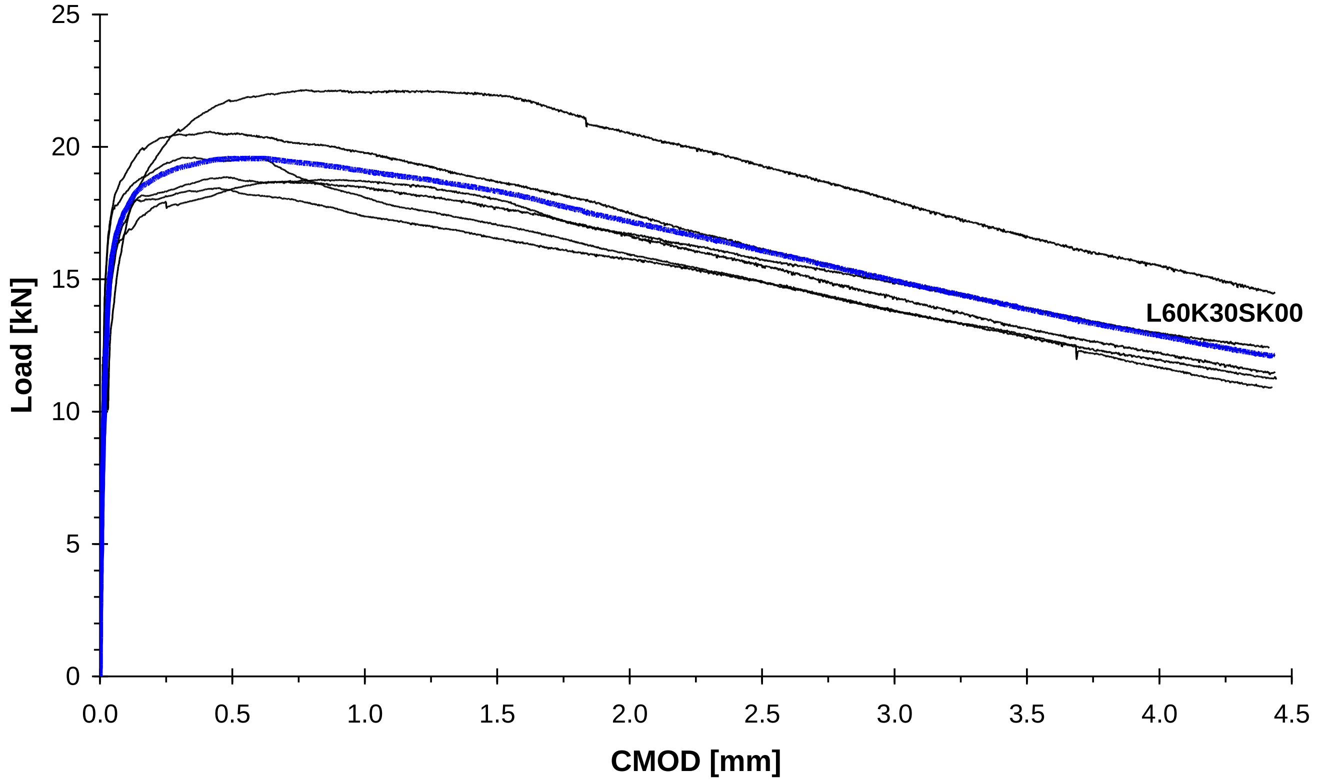

Figure 8. Load-CMOD-curves for L60K30SK00.

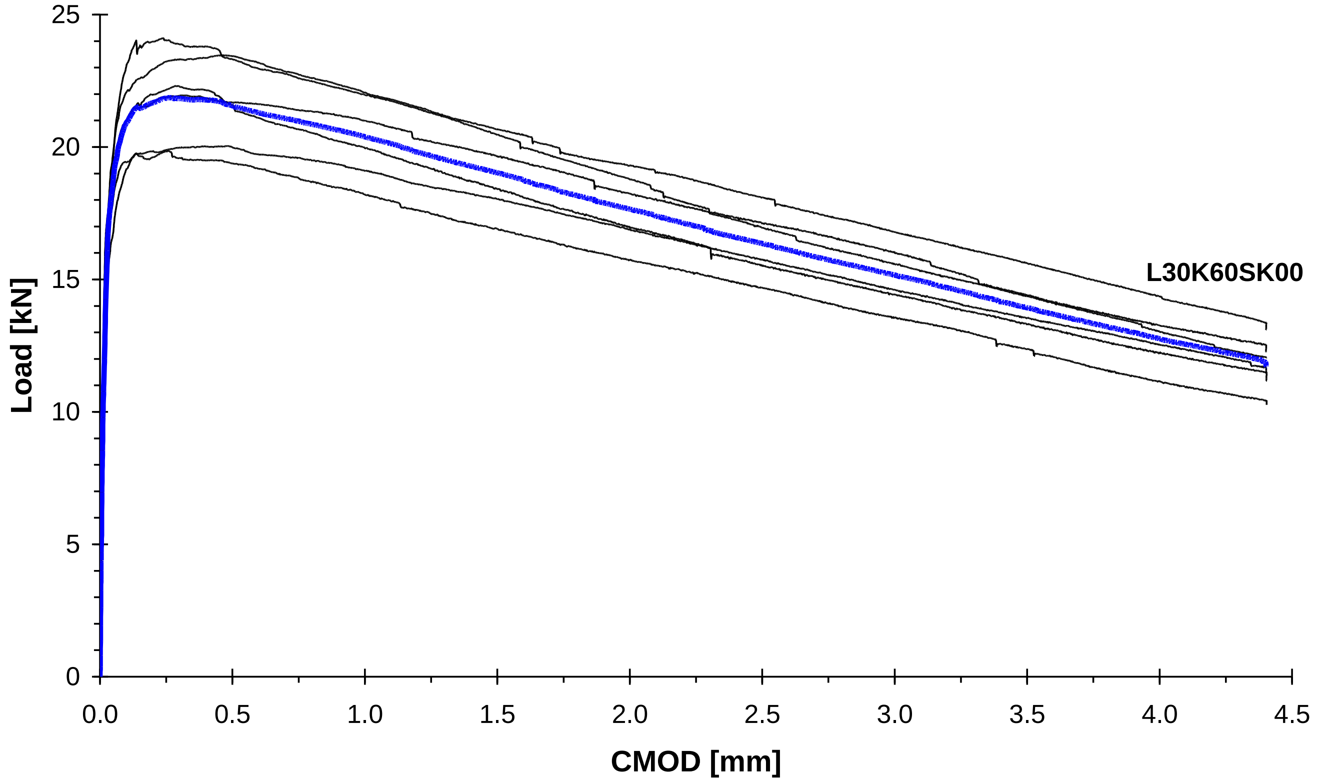

Figure 9. Load-CMOD-curves for L30K60SK00.

3.2.2 *Postcracking behaviour*

The mean load-CMOD-curves for the concretes reinforced with one type of steel fiber are shown in Figures 10 (0–0.5 mm) and 11 (0–4.5 mm). The concretes with short steel fibers show the best postcracking behaviour in the CMOD-region 0 to 0.15 mm in comparison with the respective series with very short fibers on the one hand and long hooked fibers on the other.

Probably the anchorage length of the very short steel fibers is too small in comparison with the dimensions of the aggregates to bridge efficiently the microcracks. Concrete with long hooked end steel fibers, on the other hand, have a much better ductility for CMOD-values larger than 0.15 mm.

Short, thin fibers can bridge microcracks more efficiently than long, thick fibers do because their number in concrete is much higher than that of long, thick fibers for the same fiber 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.

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.

The mean load-CMOD-diagrams for fiber reinforced concrete with 60 kg/m^3 are shown in Figures 12 and 13.

The ductility of the fiber concrete increases with increasing volume of long hooked end fibers. The series with only short fibers and a combination of very short and short fibers show the worst overall postcracking behaviour. The postcracking behaviour in the CMOD-region of 0 to 0.15 mm is somewhat better for mixes containing both long hooked and short fibers in comparison to that of concrete containing only hooked end fibers.

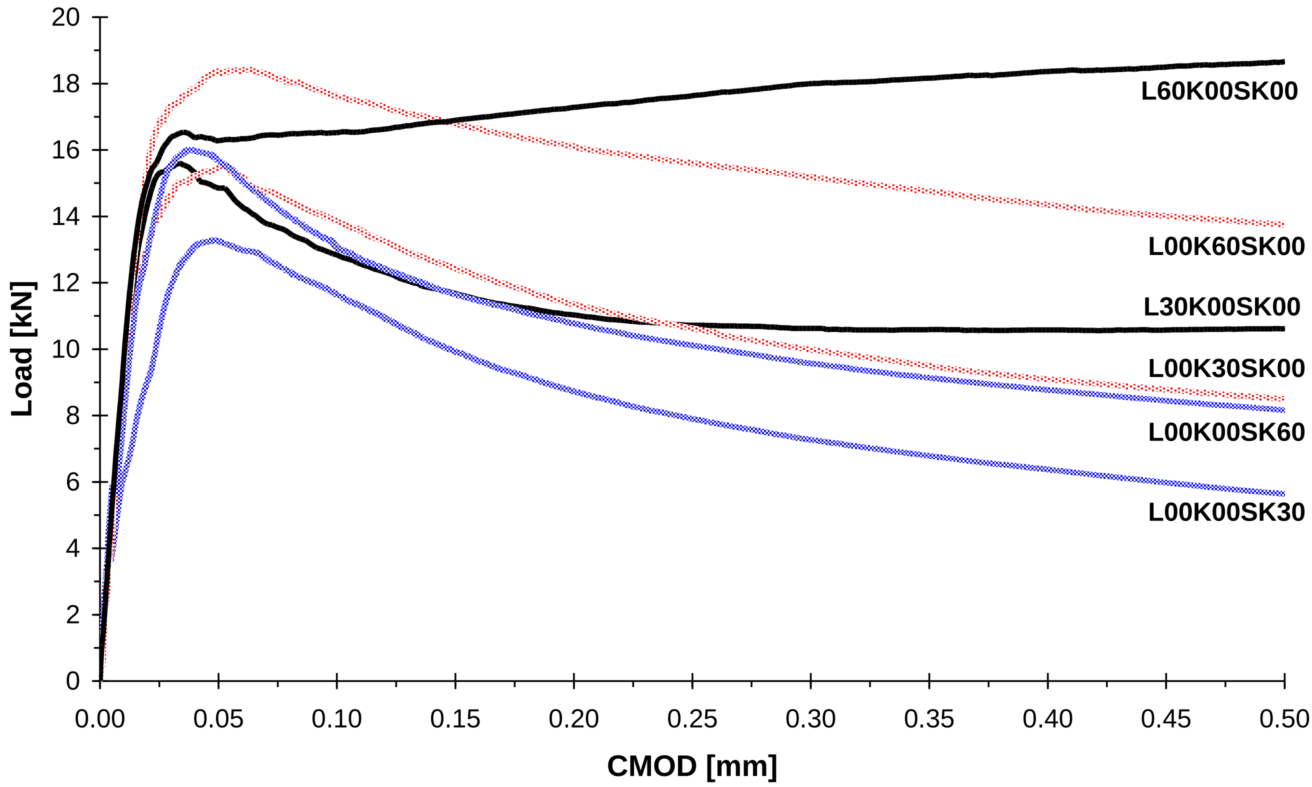

Figure 10. Mean-load-CMOD-curves for concrete with 30 kg/m^3 or 60 kg/m^3 of one type of steel fiber (CMOD: 0-0.5 mm).

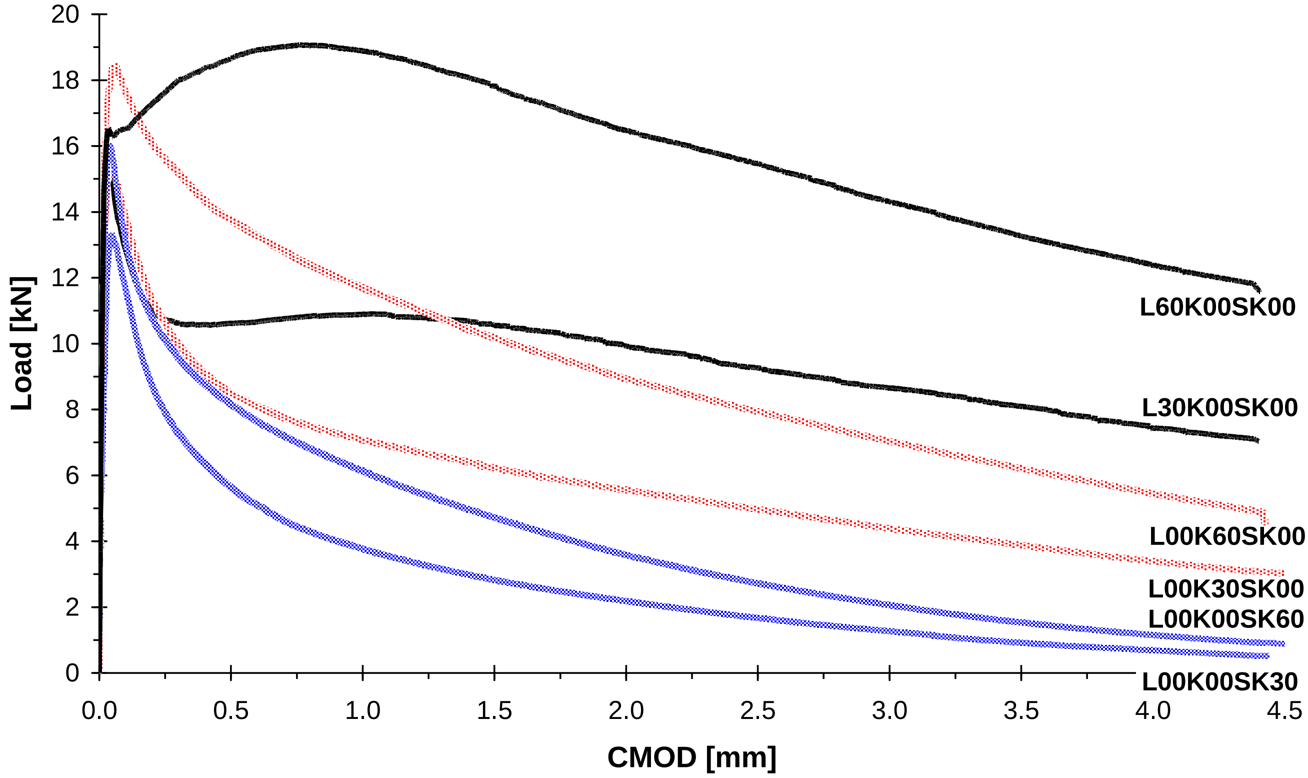

Figure 11. Mean-load-CMOD-curves for concrete with 30 kg/m^3 or 60 kg/m^3 of one type of steel fiber (CMOD: 0-4.5 mm).

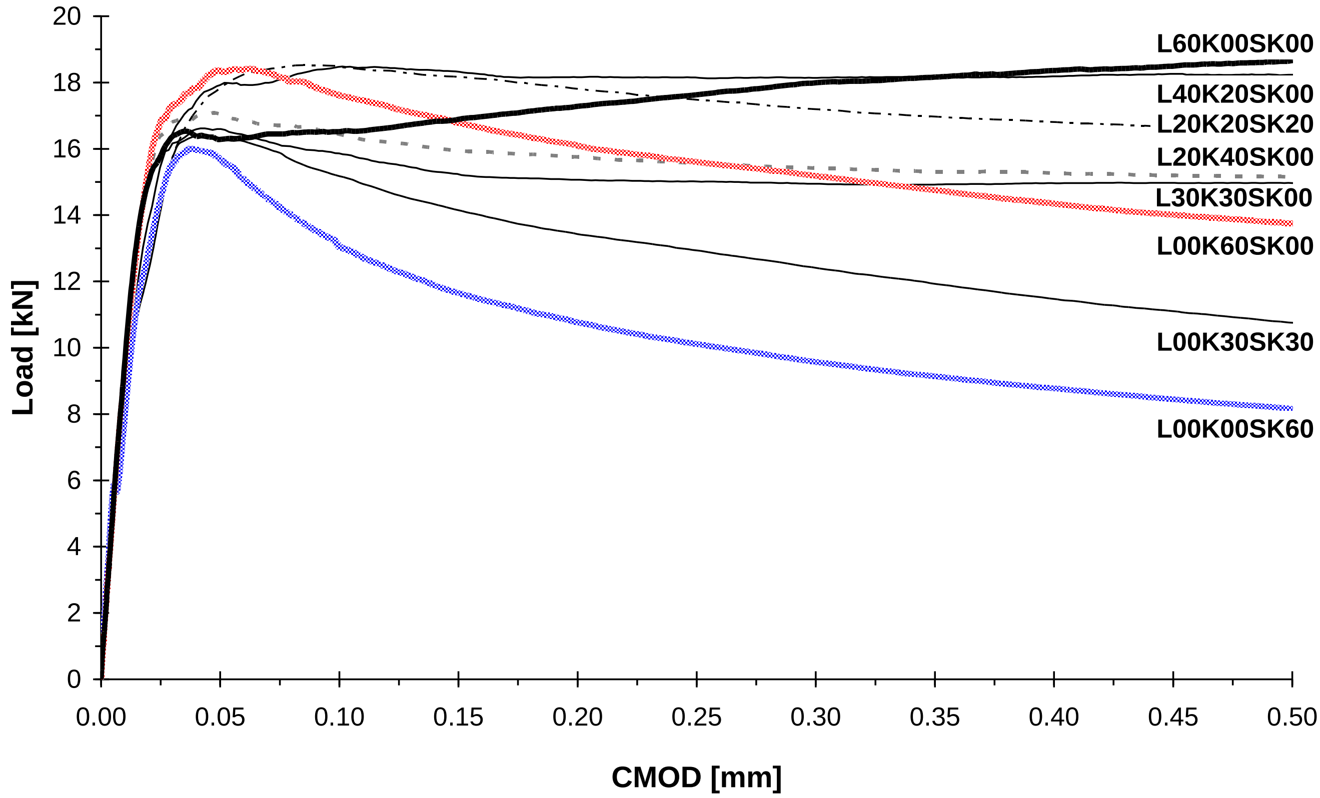

Figure 12. Mean-load-CMOD-curves for concrete with 60 kg/m^3 of steel fiber (CMOD: 0-0.5 mm).

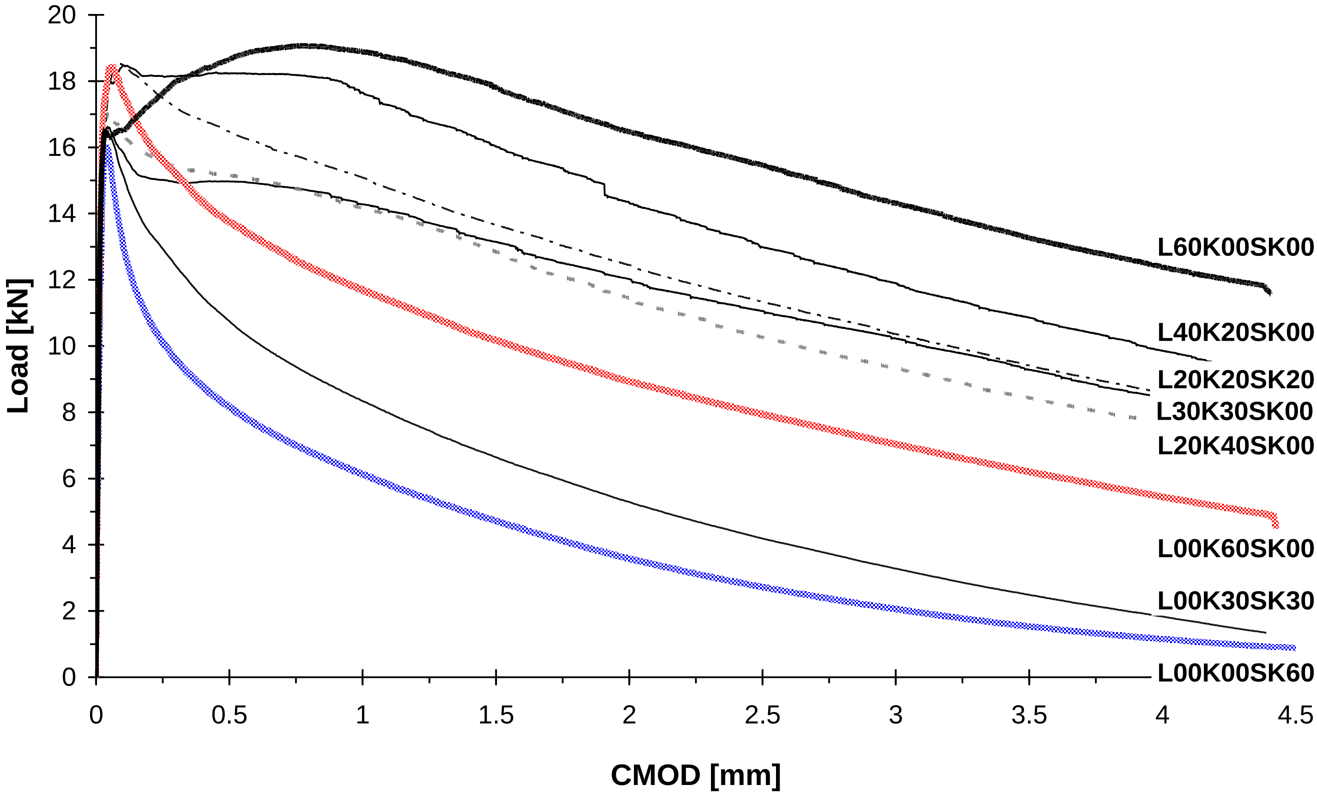

Figure 13. Mean-load-CMOD-curves for concrete with 60 kg/m^3 of steel fiber (CMOD: 0-4.5 mm).

4 CONCLUSIONS

From the investigation, executed at the Department of Civil Engineering of the K.U.Leuven, it can be concluded that:

- the number of fibers in the cracking zone increases for the same fiber volume percentage when the diameter and the length of the fiber decreases. As a result the absolute value of the scatter on the test results within a series is much lower for steel fiber concrete which contains only very short or short steel fibers;
- the efficiency of the very short fibers (L = 6 mm) is worse than that of the short fibers (L = 16 mm) when concrete containing a maximum aggregate size of 16 mm is used;
- the ductility of steel fiber concrete enhances when a higher volume of long hooked end fibers is used.

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