PULL-OUT BEHAVIOR OF STEEL FIBERS

HALVAX Katalin [1], LUBLÓY Éva [2]

Abstract

In this paper a laboratory investigation of steel fibers bond strength will be presented. The steel fibers were embedded into a cement based sample with different water to cement ratios (w/c=0.4, 0.5 were used). The other variable parameters were the embedded length, the fiber shape (hooked-end, corrugated and anchoraged fibers were tested) and in case of hooked fiber the diameter of the fiber. The aim of this investigation was to study the effect of the water to cement ratio, embedded length, fiber shape and diameter on the pull-out behavior and to determine which fiber shape performing at its best. The bond strength between the fiber and the surrounding concrete plays an important role in the steel fiber reinforced concrete (SFRC) elements shear capacity.

Keywords: fiber reinforced concrete, steel fiber, pull-out test, bond strength

1. Introduction

Today's the application field of fiber reinforced concrete is constantly expanding. The material and shape of the fibers used for reinforced concrete have become varied. The mechanical properties of fibers from different materials are different, so the choice of the material depends on which concrete property want to be improved. The main advantage of using steel fibers lies in their crack-bridging ability and after cracking the tensile strength does not fall down to zero but stabilize at a nearly constant value. One interesting area of research is that steel fibers can enhance concrete elements shear strength. Many researchers have already studied this area and some have even proposals on how to define a fiber reinforced concrete element shear capacity [1] [2] [3]. In these proposed formulas the bond-strength (τ_f) between the fiber and the surrounding concrete (matrix) plays an important role in the shear capacity. The bridging action provided by the steel fibers depends on the pull-out mechanism. The pull-out test, when steel fibers are embedded into a cement based sample then pull out from the matrix, can be used to study the effectiveness of the fiber. Some researchers have already carried out experiments with straight and mechanically deformed steel fibers. The results have shown that in improving the pull-out resistance mechanically deformed fibers are more effective than the straight fibers [4-8]. In these tests in case of mechanically deformed fibers the commercially available hooked-end [4-8] and corrugated steel fibers [4, 7, 9] were used. In the experiment reported in this paper hooked-end, corrugated and a special type the anchorage fiber were used in the pull-out tests. We have not found experiments with anchorage fibers in the literature.

[1] HALVAX Katalin, Széchenyi István University, H-9026 Győr, Egyetem tér 1., Hungary, +36-96-503-400(3304), halvax@sze.hu

[2] LUBLÓY Éva, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3.-9., Hungary, +36-30-759-1843, lubeva@web.de

2. Experimental program

Experiments were performed about steel fibers pull-out behavior. In the tests different type of steel fibers were embedded individually into a cement based sample with different embedded lengths. During the tests fiber pull-out load and displacement were measured. The experiment aim was to investigate the effect of fibers shape, embedded length, water to cement ratio (matrix strength) and fiber diameter on the pull-out behavior.

2.1 Specimens, test setup and testing procedure

Commercially available hooked-end steel fibers, corrugated steel fibers and a special type the anchorage steel fibers were used in the pull-out tests. In Table 1 the features of these steel fibers can be seen. Three different embedded length were used for each fiber types, L_b=10, 15 and 20 mm. Almost all fibers length (except the anchorage fiber) is ~50 mm, so in case of these embedded lengths only the twenty percent (if L_b=10 mm), thirty percent (if L_b=15 mm) or forty percent (if L_b=20 mm) of their length are embedded into the cement based sample. Therefore the effect of embedded length in case of each fiber types could be studied. Fibers were embedded individually into a cement based sample. Figure 1 shows the specimens formwork and dimensions also.

Tab.1: Features of the steel fibers

fiber shape	L [mm]	D [mm]	L/D	f_u [N/mm^2]
anchorage fiber 	54	1.0	54	1100
corrugated fiber 	50	1.0	50	1100
hooked-end fiber 	50	1.0	50	1100
hooked-end fiber 	50	0.75	50	1100
L: length of the fiber D: fiber diameter L/D: aspect ratio f_u: tensile strength				

Two different mixtures were used. The mixtures consist of sand, Portland cement CEM I 42.5N, water and plasticizer. The maximum aggregate size was 4 mm. From every mixture 40x40x160 mm size specimens were prepared also to determine the mixtures compression strength and splitting-tensile strength. The lower water to cement ratio was w/c=0.4, the average compression strength of this mixture was f_c=62.1 MPa. The higher water to cement ratio was w/c=0.5, the average compression strength of this mixture was f_c=45.5 MPa.

Specimens were cast in plastic molds. Oil was applied to the interior surface of the molds to allow easy removal of the specimens from the molds. One day after the casting the specimens were removed from the molds and put into water bath for curving for 7 days. After 28 days the pull-out tests were carried out. Figure 1 shows the testing device. Two instruments were used to measure the displacement (LVDT=Linear variable differential transformer) and a load cell to measured the pull-out load.

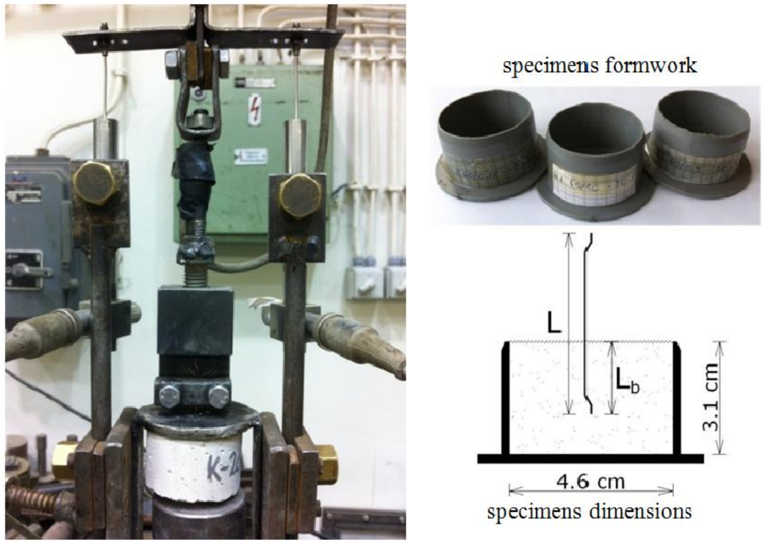

Fig. 1: Testing device, specimen formworks and dimensions

3. Experimental results

In this section the result of the pull-out tests will evaluate. During the tests fiber pull-out load and displacement were measured and registered. The experiment variable parameters allowed us to study the effect of fiber shape, embedded length, water to cement ratio and fiber diameter on the pull-out behaviour of steel fibers.

3.1 Failure mode

During the tests two failure mode were observed. The most frequent mode of failure corresponds to the debonding of the fiber followed by its slipping with friction until it was completely pulled out. The other was when the fiber was broken before being pulled out from the matrix. Table 2 presents the proportion of debonded fibers for each configuration. In case of lower water to cement ratio (in case if higher matrix strength) the number of debonding failure mode reduce for all three fiber types. As the embedded length of the corrugated and hooked fibers increase the frequency of debonding failure mode decrease in case of w/c=0.4. If the matrix strength was lower (w/c=0.5) the higher embedded length did not lead to broken failure, almost every hooked and corrugated fibers were pull-out from the matrix after debonding. In case of anchorage fibers if the water to cement ratio was 0.4 every fiber were broken before being pulled out regardless of the embedded length. When the water to cement ratio was 0.5 although some debonding failure were observed in case of shorter embedded length but in most cases the fibers were broken also. So these anchorage fibers have a good resistance against pull-out even in case of shorter embedded length or weaker matrix also. It follows that this type of fiber shape provides much better anchoring than the hooked-end or the corrugated shape.

Tab.2: Frequency of pull-out mode by debonding

Corrugated steel fiber	L_f=50 mm D_f=1.0 mm			
w/c	L_b=10 mm	L_b=15 mm	L_b=20 mm	L_b=22.5 mm
0.4	100%	100%	33%	33%
0.5	100%	100%	100%	100%

Hooked-end steel fiber L_f=50 mm D_f=1.0 mm				
w/c	L_b=10 mm	L_b=15 mm	L_b=20 mm	L_b=22.5 mm
0.4	100%	100%	33%	66%
0.5	66%	100%	100%	100%
Anchorage steel fiber L_f=54 mm D_f=1.0 mm				
w/c	L_b=10 mm	L_b=15 mm	L_b=20 mm	L_b=24.5 mm
0.4	0%	0%	0%	0%
0.5	33%	33%	66%	0%

Chanvillard et al. [9] investigated the effect of the embedded length and fiber orientation of corrugated steel fibers in different water to cement ratio matrixes (w/c=0.3, 0.4, 0.5). A similar conclusion was drawn by them: in case of shorter embedded length (one or two waves long) almost all the fibers were pulled out from the matrix whatever was the matrix strength but in case of three waves long embedded length the broken failure appeared and the number of broken failures increases as the matrix strength increase. Zile E. and Zile O. [7] performed experiments with corrugated and hooked fibers in case of w/c=0.5 and the embedded length was 15 mm and 30 mm long. They have found that the failure mode was debonding in case of hooked fibers whatever was the embedded length and the fibers straightened during the pull-out process. In case of corrugated fibers with shorter (15 mm) embedded length the failure mode was also debonding but with embedded length of 30 mm all corrugated fibers failed by rupture. All of these are also in line with our findings. We did not find experiments with anchorage fibers in the literature, so we do not have any data which can be compared with our results.

Figure 2 presents typical load-displacement curves of a hooked, an anchorage and a corrugated fiber in case of 20 mm long embedded length and w/c=0.4. In these cases the failure mode was fiber rupture. The first part of the anchorage fibers curve is a sharply ascending part until maximum load is recorded. Throughout this process the fiber works at first elastic then plastic deformation. The recorded loads at failure were about 850 N in all cases. This load corresponds to a stress of 1082 MPa when the fibers were broken. This stress value agrees closely with the given for steel fiber in the manufacturer’s data sheet which is 1100 MPa. In case of hooked and corrugated fiber there is a point when the slope of the curves strongly changes. We assumed that at this point the adhesion between the fiber and the matrix ended, and the hooked end or the corrugated shape started trying to straighten. Because of this initial plastic deformation the pull-out load increased until reached the maximum when the fiber was broken. This maximum load, when the broken failure occurs, is lower than in case of anchorage fiber. We assumed that this happens because the hooked and corrugated fibers are cold formed fibers so initial inner stresses and diameter reduction may occur.

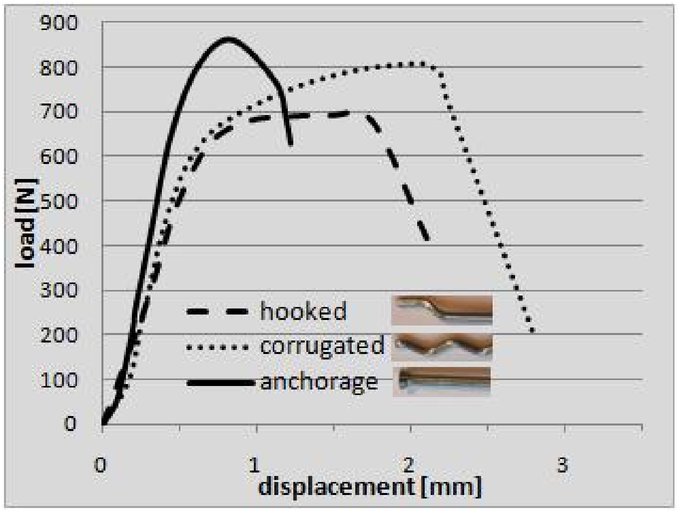

Fig. 2: Typical load-displacement curves of broken fibers (L_b=20 mm, w/c=0.4)

Figure 3 shows typical load-displacement curves of different fiber shapes in case of debonding failure. During the pull-out process the corrugated and the hooked fibers have lost their original shape, they were almost straightened. The anchoraged fibers kept their shape so the matrix has been completely destroyed in the fiber area during the pull-out process. The first section of the load-displacement curve of hooked fiber is a nearly linear part and it lasts until adhesion between fiber and matrix ends. After this the force increased under significant displacements until reach a peak and after this point decreased, then stabilize at a nearly constant value for a while. The reason for this: after debonding the fiber begins to slip and the main energy absorbing mechanism are plastic deformation of the hooked end while it is trying to straighten and the friction between steel fiber and porous surface of the matrix. The pull-out load increases until the reaction force from the matrix hole acting on the hooked end is sufficient to initiate plastic deformation of the steel fiber. After plastic deformation finished, the hooked end straightened, only the friction remained as a single energy absorption process which develops between the not perfectly straight steel fiber and the hole surface of the matrix. In this section the pull-out load is nearly constant. Finally the last section is when the load suddenly drops to zero as the fiber completely pulls out from matrix. The pull-out process of a corrugated fiber is similar to this. It is also starts with a nearly linear section until the adhesion ends and the fiber starts to slip and the plastic deformation takes place. After this the load decreased under significant displacement while the not perfectly straight fiber slips in the hole until it is completely pulls out. In case of anchorage fiber the curve also starts with the nearly linear section until the adhesion ends after this the slope of the curve changes not because of the plastic deformation but the anchoraged end of the fiber have to destroy the matrix around the end of the fiber in order to be able to pull out from the matrix. Then the load decreased while the fiber slipping with friction until it is completely pulls out from the matrix. Similar load-displacement curves of corrugated fibers can be found in [4, 9] and in case of hooked fibers in [4, 5, 6, 8].

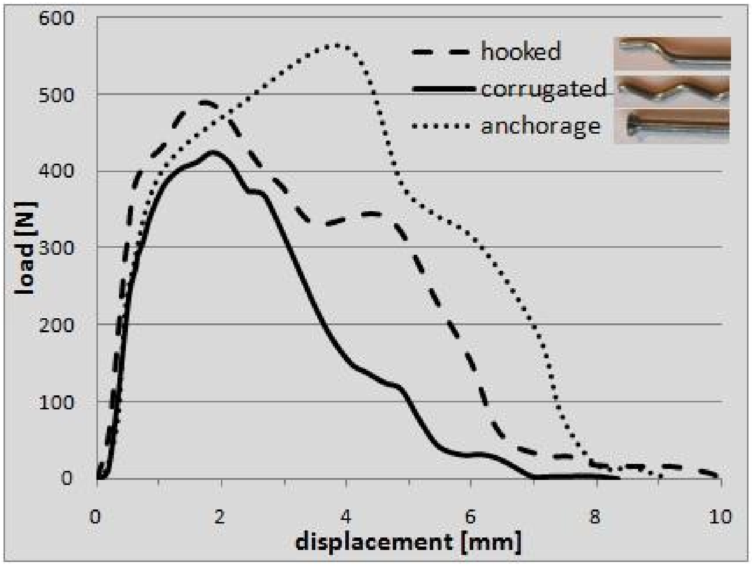

Fig. 3: Typical load-displacement curves of different fiber shapes in case of debonding failure (L_b=10 mm, w/c=0.5)

3.2 Effect of water to cement ratio

Two different water to cement ratios (w/c=0.5 and 0.4) were used to investigate the effect of matrix strength on the pull out process. The average compression strength of the mixture with w/c=0.5 was 45.5 MPa and 62.1 MPa in case of w/c=0.4. Figure 4 shows the peak load values of each tested specimens. For all three fiber shapes we found that higher matrix strength resulted higher peak loads. Figure 4 shows also load-displacement curves of corrugated fibers with embedded length of 10 mm in case of different water to cement ratios. Observe that, for equal slips, the load increases with matrix strength even beyond the peak load, so in the ascending and in the descending branch of the curve also. Abdu-Lebdeh T. et al [6] and Naaman E. A. et al [4] studied the effect of matrix strength on the pull out mechanism in case of hooked fibers also and they have drawn the same conclusion: the maximum pull-out load increase as matrix strength increase. In case of corrugated fibers Chanvillard et al. [9] made the same conclusion: the lower the w/c ratio, the higher the failure load but they also said that the w/c ratio is a less significant parameter influencing the fiber matrix behavior and the embedded length and the fiber orientation plays the major role in the pull-out process.

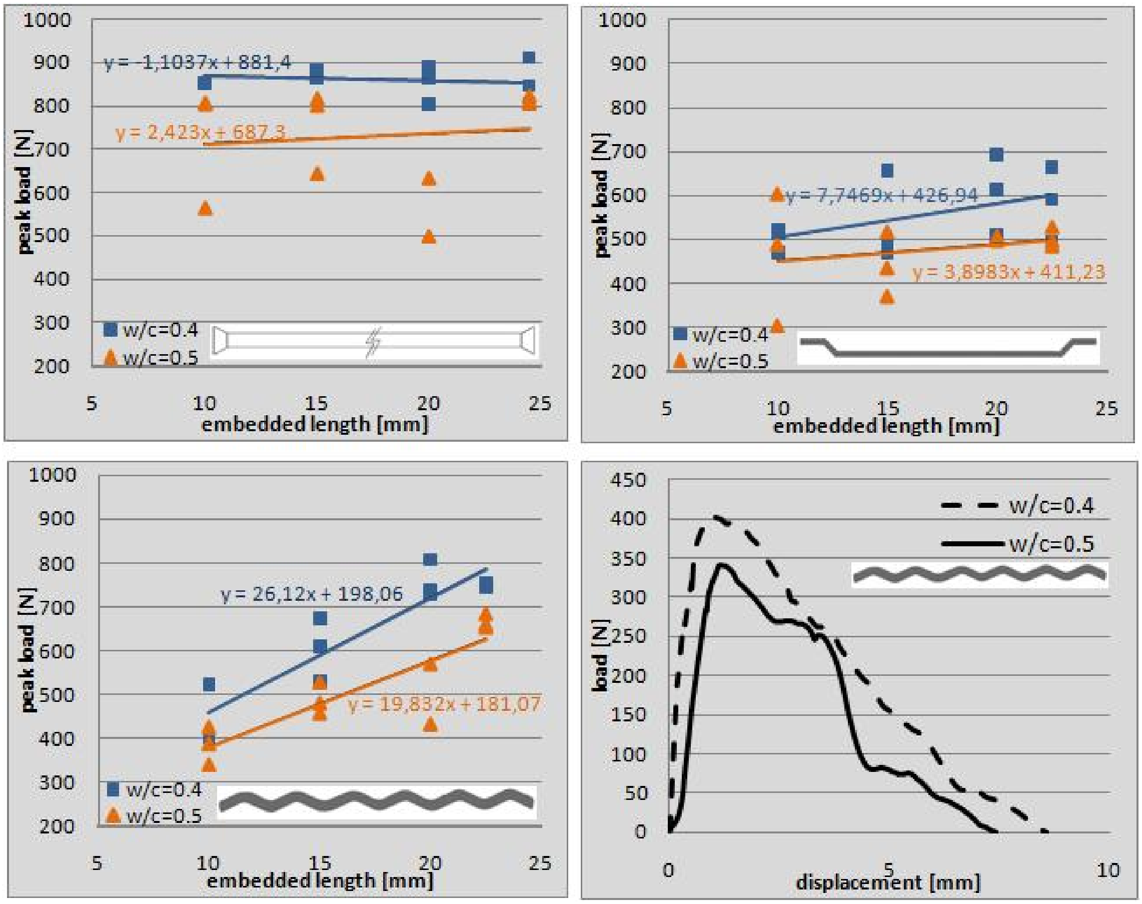

Fig. 4: Peak load values of the tested specimens and load-displacement curves of corrugated fibers in case of different water to cement ratios (L_b=10 mm)

3.3 Effect of embedded length

Figure 4 shows the effect of the embedded length on the peak load in case of all three fiber shapes. The data shows that the effect of the embedded length depends on the fiber shape. In case of hooked fiber if the embedded length increased by 50% (from 10 mm to 15 mm) this results a 7.8% increase in the average maximum pull-out load when w/c=0.4 and 26.9% increase when w/c=0.5. If the embedded length increased by 100% (from 10 mm to 20 mm) this results a 20.8% increase in the average maximum pull-out load when w/c=0.4 and 26.9% increase when w/c=0.5. In case of corrugated fiber if the embedded length increased by 50% (from 10 mm to 15 mm) this results a 36.9% increase in the average maximum pull-out load when w/c=0.4 and 27.1% increase when w/c=0.5. If the embedded length increased by 100% (from 10 mm to 20 mm) this results a 71.4% increase in the average maximum pull-out load when w/c=0.4 and 30.34% increase when w/c=0.5. Based on these we can say that peak load increases with the embedded length in case of hooked and corrugated fibers. If we compared the slopes of the trend lines in case of hooked and corrugated fiber in Figure 4 we can see that the effect of the embedded length is much more significant in case of corrugated fiber. This can be seen also in Figure 5 which presents load-displacement curves of hooked and corrugated fiber in case of different embedded lengths (w/c=0.5). The reason for this stems from the fiber shape. For hooked fiber, since the hook contributed most to the pull-out load, changing the embedded length did not cause as large increase in the maximum pull-out load as in case of corrugated fiber. Naaman E. A. et al. [4] have drawn the same conclusion, in case of corrugated fibers Chanvillard et al. [9] also and in case of hooked fibers Tuyan M. et al. [8] as well. The anchorage fibers in almost every cases broken regardless of the embedded length. The reason for this is similar to in case of hooked fiber but this type of fiber end shape provides much better anchoring than the hooked-end.

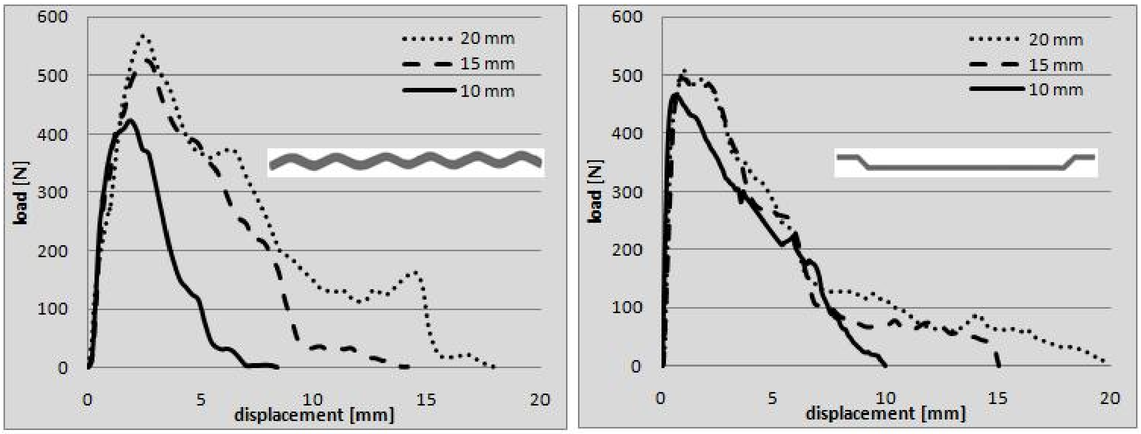

Fig. 5: Load-displacement curves of corrugated and hooked fibers in case of different embedded lengths (w/c=0.5)

3.4 Effect of the fiber diameter

In this section the result of pull-out test of hooked fiber with different diameter in case of w/c=0.4 will evaluate. The aspect ratios of the selected fibers are 50 and 66.7 and the corresponding diameters of these fibers are 0.75 mm and 1.0 mm. The embedded length was 15 mm for each fiber. Figure 6 shows the load-displacement curves for hooked fibers with different diameter. The general characteristics of the graph did not change with the change of the diameter. Figure 6 shows that increasing the diameter of the fiber maximum pull-out load increases which means improved bond between the fiber and the matrix. This can be attributed to the fact that higher fiber diameter causes a greater bond surface between the fiber and the surrounding matrix and more energy required for the plastic deformation of the hooked-end in case of higher fiber diameter. If the fiber diameter increased by 33.3% (from 0.75 mm to 1.0 mm) this results a 50.3% increase in the average maximum pull-out load. Tuyan M. et al. [8] studied the effect of fiber diameter on pull-out behaviour also and have drawn the same conclusion: increasing the diameter of the fiber means improved bond between the fiber and the matrix.

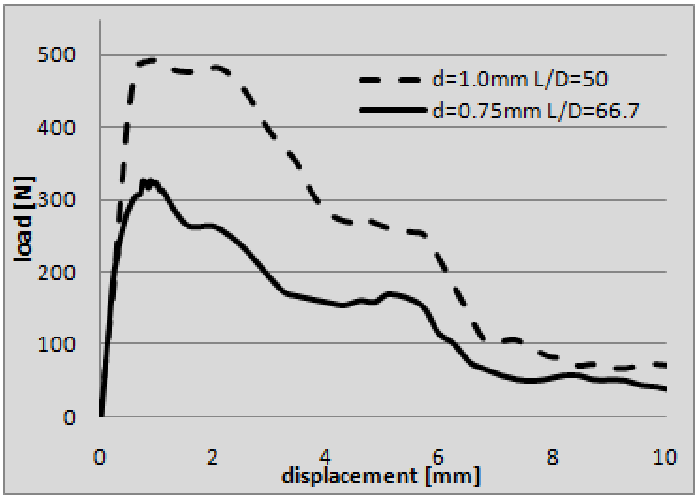

Fig. 6: Load-displacement curves of hooked fibers in case of different diameters (L_b=15 mm, w/c=0.4)

4. Conclusions

Experiments were performed in which different steel fibers were embedded into a cement based sample with different embedded lengths, and during the pull-out tests the displacement and pull-out load were measured. The aim of the experiments was to study the effect of fiber shape, embedded length, matrix strength, fibers diameter on the pull-out behaviour and to determine which fiber shape performing at its best. After the evaluation of the experimental results we made the following conclusions:

- In case of different fiber shapes (anchorage, hooked-end, corrugated), but with the same embedded length and fiber diameter, in terms of pull-out the anchoraged fiber shape was the most favourable, this type of fiber shape provides much better anchoring than the hooked-end or corrugated shape;
- The effect of water to cement ratio on the maximum pull-out load was studied and it was found that in all cases (for each types of fiber shape) higher matrix strength resulted higher peak load whatever was the embedded length;
- The effect of the embedded length on the maximum pull-out load was studied and it was found that in case of hooked-end and corrugated steel fibers the peak load increases with the embedded length. The anchorage fibers in almost every cases broken regardless of the embedded length so this type of fiber end shape provides much better anchoring than the hooked-end or the corrugated shape.;
- The effect of the fiber diameter in case of hooked-end fiber was studied and it was found that increasing the diameter of the fiber means improved bond between the fiber and the matrix.

Acknowledgements

The Authors would like to thank to the MG-Stahl Ltd. for the steel fibers used in this experiments.

References

[1] Narayanan R., Darwish I. Y. S. *Use of steel fibers as shear reinforcement*, ACI Structural Journal, Vol. 84, 1987, pp. 216–227.

[2] Lim D. H., Oh B. H. *Experimental and theoretical investigation on the shear of steel fiber* reinforced *concrete beams*, Engineering Structures, Vol. 21, 1999, pp. 937–944.

[3] Kwak Y. K., Eberhard M. O., Kim W. S., Kim J. *Shear strength of steel fiber-reinforced concrete beams without stirrups*, ACI Structural Journal, Vol. 99, 2002, pp. 530–538.

[4] Naaman E. A., Najm H.: *Bond-slip mechanism of steel fibers in concrete*, ACI Materials Journal, March-April 1991, pp. 135-145.

[5] Pompo A., Stupak P. R., Nicolais L., Marchese B. *Analysis of steel fiber pullout from a cement matrix using video photography*, Cement and Concrete Composites, Vol. 18, 1996, pp. 3–8.

[6] Abu-Lebdeh T., Hamoush S., Heard W., Zornig B.: *Effect of matrix strength on pullout behavior of steel fiber reinforced very-high strength concrete composites*, Construction and Building Materials, Vol. 25, 2011, pp. 39-46.

[7] Zile E., Zile O.: *Effect of the fiber geometry on the pullout response of mechanically deformed steel fibers*, Cement and Concrete Research, Vol. 44, 2013, pp. 18-24.

[8] Tuyan M., Yazici H.: *Pull-out behavior of single steel fiber from SIFCON matrix*, Construction and Building Materials, Vol. 35, 2012, pp. 571-577.

[9] Chanvillard G., Aitcin P. C.: *Pullout behavior of corrugated steel fibers*, Advanced Cement Based Materials, Vol. 4, 1996, pp. 28–41.