The effect of the length of macro synthetic fibres on their performance in concrete

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Abstract. Nowadays macro synthetic fibres are able to compete with steel fibres despite their low Youngs Modulus. This is due to their different pull-out mechanism and a larger number of individual fibres per kilo compared to steel fibres. Macro synthetic fibres bond to the concrete along their full length, usually with an embossed surface, while steel fibres are mostly anchored by their hooked ends. If the bond is defined by the length of the embossed surface, logically the longer the synthetic fibre the higher post-crack capacity. In this paper the same type of macro synthetic fibre was researched with different lengths but at the same dosage. The consistency of the fresh concrete together with the quality of the distribution of the fibres have been analysed and compared with the residual strength. After analysing these data the optimum fibre length was able to be determined.

1. Introduction

Fibre reinforcement generally increases the ductility of the concrete by increasing the fracture energy of the quasi-brittle concrete. By adding fibre the consistency and workability of the concrete will also change, and has to be managed by using a proper concrete mix design. The effect of the fibre can be characterized by the increase of the fracture energy, dividing the fracture energy of the fibre reinforced concrete into two parts: fracture energy of the plain concrete (G_f) and the added fracture energy (G_{ff}). This added fracture energy is dependent on the fibre type, dosage and the concrete matrix [1].

Macro synthetic fibres generally pull-out from the concrete matrix first, the fibre will only rupture at bigger crack widths. The length of the fibre will increase the energy absorption, but after a certain fibre length it could also impair the consistency, workability and the quality of the concrete mix, which could lead to lower strength values.

Furthermore the orientation of the fibres also depend on their length. The added fracture energy is a material constant if there is no wall effect. In case of formwork structures there is a wall effect which is nominally a distance of half the length of a fibre, where the orientation of the fibres can be changed. This wall effect cannot be neglected during the evaluation and has to be calculated.

The fibre length for steel fibre also has an effect on the mixing properties of the aggregates [2, 3], although this effect is much less than for synthetic fibre [4]. Because of the flexibility of the individual fibres, macro synthetic fibres can bend around the aggregate and thus do not change the distance between the aggregate.

The optimal length of macro synthetic fibre was researched and an exact value of 54 mm was given by MacDonald [5]. Other researchers developed a testing method to specify the optimal length based on the characteristic length, this length is where the fibre will pull out from the matrix before rupture [6].

Our research will investigate the effect of the length of macro synthetic fibres in a direct way from beam test results where fibres with a different lengths but with the same dosage were mixed in similar concrete.

2. Problem statement

Manufacturers produce macro synthetic fibres with different lengths. The macro fibres can increase the ductility of the concrete by increasing the fracture energy. Research has identified methods to determine the characteristic length (l_c) of steel fibres [6] determining where the fibre will pull-out from the concrete matrix before rupture. Fibre with an anchorage length longer than this characteristic length will rupture instead of pull-out, which will lead to a lower added fracture energy.

In the case of macro synthetic fibres this length is not necessarily the optimal length. Firstly, using standard test methods the crack opening is measured to CMOD=3.5 mm (Crack Mouth Opening Displacement), which is approximately a crack width of 2.5-3 mm. If the fibre ruptures at a higher value this won't be seen in the test result. Secondly, even if these fibres rupture during the test this would only be seen at the higher values. Thirdly, if the fibres are randomly but perfectly distributed and orientated, then fibres only in the perfect position and orientation (anchorage in the middle point and perpendicular to the cracked section) would rupture. Fibres with a shorter anchorage length or with a smaller angle will probably pull-out from the matrix.

Based on the above determining the characteristic length of the fibre could lead to an improper optimal length. In our research the effect of the length of the fibres is investigated by a direct test method: instead of a pull-out test using a concrete beam tests.

Increasing the length of macro synthetic fibres increases its anchorage in the concrete and also its pull-out force in order to reach an upper limit where the fibre will rupture before being pulled-out. Based on this the longer fibre will lead to an increase in added fracture energy up to a certain length. However, because of practical reasons the fibre's length cannot be increased indefinitely. The results of previous research and practical experience also shows that during mixing fibre-balls can be formed. These balls can grow during mixing as other fibres join to the ball. These fibre-balls degrade the quality and performance of the fibre reinforced concrete and mostly must be taken out during the mixing. This leads to less fibre in the concrete and obviously a decrease in its added fracture energy. To some extent the formation of these fibre-balls depends on the length of the fibre: as longer fibres are easier to lock to each other than the smaller ones.

Fibre orientation is random and although the formwork has a wall-effect on the fibres which restricts their orientation. The wall effect is only evident on their orientation if the fibres make contact with the wall. For the same beam the wall-effect is bigger with longer fibres, which will also be analysed here.

3. Laboratory tests

3.1. Concrete mix design

The concrete mix design used was a typical industrial flooring concrete, with a concrete strength class C30/37. The water/cement ratio was 0.4. The actual mix design can be seen in Table 1.

Table 1. Concrete mix design

Name	Type	Dosage [kg/m^3]
Cement	CEM I 42.5 R	400
Water		160
Sand	0/4	735
Fine Aggregate	4/8	294
Course Aggregate	8/16	808
Superplasticizer	Mapei Dynamon NRG 1012	3.2
Fibres	BarChip 30, 40, 48, 55, 70 mm	4.0

3.2. Fibre types

All the fibres used were the same synthetic macro fibre type: BarChip (Elasto Plastic Concrete), but with different lengths: 30 mm, 40 mm, 48 mm, 55 mm and 70 mm. The dosage was the same: 4 kg/m^3. The fibres are made from modified polyolefin, with an effective diameter of 0.72mm and with an embossed surface.

3.3. Test matrix

There were 7 beams for every type of concrete. The test matrix can be seen in Table 2.

Table 2. Test matrix

Sign	Concrete	Fibre type	Dosage [kg/m^3]	Dosage [number of pieces]
BC30 1-7	C30/37	BarChip 30	4.0	93240
BC40 1-7	C30/37	BarChip 40	4.0	69930
BC48 1-7	C30/37	BarChip 48	4.0	58275
BC55 1-7	C30/37	BarChip 55	4.0	50858
BC70 1-7	C30/37	BarChip 70	4.0	39960

3.4. Specimens and testing method

The concrete was made using a Collomatic XM2 forced-action mixer, which represents well the industrial environment and provides perfect mixing. At first the plain concrete was mixed for 1 minute, then the fibre was added and mixed for a further 1 minute. The fibres mixed well and the fresh concrete consistency was F2. The concrete was poured into the steel formwork and was vibrated for 15 seconds. The upper surface of the beam were smoothed with a steel tool. The specimens were stored in air for 15 days. The size of the beams were 150 mm x 150 mm x 550 mm and tested at 500 mm span. In the middle of the beam there was a notch 2 mm wide by 25 mm deep for the CMOD measurement.

The testing method was a 3 point bending beam test according to RILEM TC162 [7]. The beams were loaded in the middle, above the notch. The testing speed was 0.2 mm/min. The tests were done in the Laboratory of Czako Adolf, Department of Mechanics, Materials and Structures, Budapest University of Technology and Economics. The test was carried out using a universal testing machine: Zwick-Roell Z150, with a capacity of maximum 150 kN.

3.5. Evaluated results

The loading force, F in N and the CMOD in mm were measured during the test as an output data. After the bending test the beam was divided into two parts using the loading machine to break the beam completely to be able to see the cracked surface clearly.

The location of the fibres were analysed by firstly dividing each cracked face into 6 strips each with a thickness of 25 mm. The 6th strip was the notch as can be seen in figure 1a. Secondly, the effect of the formwork was analysed by counting the fibres in the zones where the wall-effect occurs. Fibres were counted near the surface at a distance of a half length of fibre (l_f), as can be seen in figure 1b. During counting both the fibres that were pulled-out and the ruptured fibres were recorded.

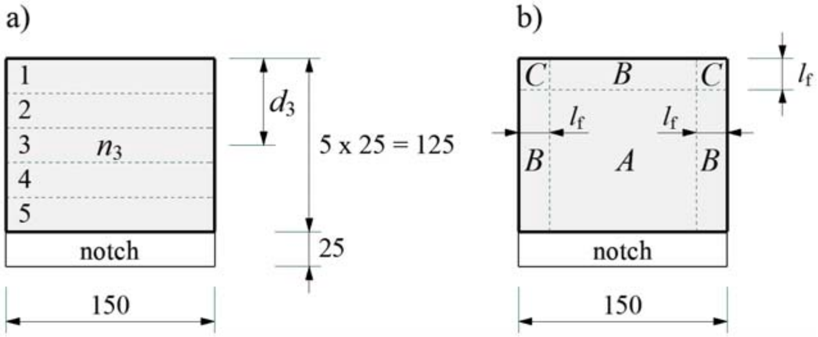

Figure 1. Face of the cracked surface for fibre counting

4. Test results

4.1. Distribution and amount of the fibres in the cracked section

The distribution and position of the fibres on the cracked surface had a significant effect on the results so this must be taken into account during the evaluation. The point where the fibres crossed the cracked section were measured from the top of the beam which was the edge of the beam that was loaded. This is taken the compressed zone as an approximation to zero thickness. Using this method the *fibre-moment* (S_f) can be determined. Assuming perfect mixing the fibres crossing the crack per unit area can be determined. This is based on the work of many researchers [8, 9, 10] and which could lead to the determination of the *ideal fibre-moment* ($S_{f,i}$). By comparing the actual and ideal fibre-moments the ideal *fibre-work* (W_f, area under the load-CMOD diagram up to 3.5 mm) can be calculated. This method is explained in detail in [11].

4.2. Wall-effect

The fibres have free orientation in the concrete if unaffected by the aggregates. To calculate the number of fibres crossing the cracked section the average length of the fibres in perpendicular direction to the cracked section need to be calculated. If this value is known the specific number of fibres crossing the cracked section can be determined according to equation (1) which was derived by Krenchel [12].

$$n_a = \frac{2\, l_{f,x,m}\, N}{V}$$

where	n_a	number of fibers crossing the section, pieces/mm^2
	$l_{f,x,m}$	average fiber length in the undistributed zone, mm
	N	number of fibers in the volume
	V	volume, mm^3

It can be seen that if the dosage is the same the number of the fibres crossing the section are independent of the fibre length. In this test series this means that in the undisturbed zone of the section (where there is no wall-effect, zone *A* at figure 1/b) the number of fibres crossing the cracked section is the same.

The average fibre length was first calculated by Romualdi and Mandel [8]. They used polar coordinates to define the orientation of the fibre, but this had a densification in the *z* axis if the input parameters were chosen randomly (see figure 2a). In order to eliminate this, cylinder coordinates must be used. First the angle between the *x* axis, and the distance from the *xy* plane: *t*. By defining the orientation of the fibre with Φ and *t*, and choosing the parameters randomly, the distribution is equable (see figure 2b).

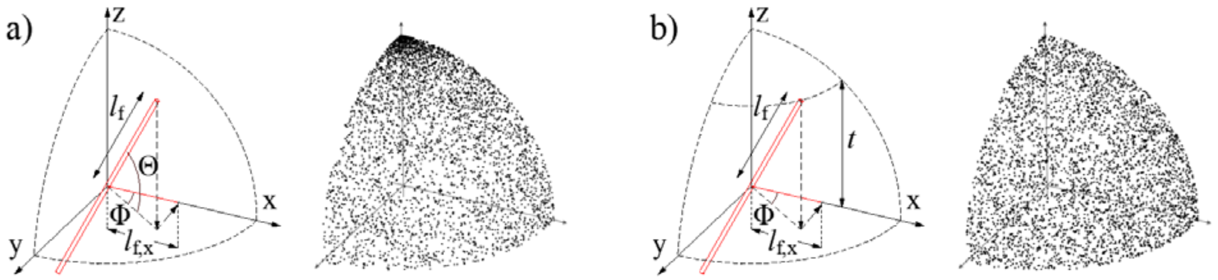

Figure 2. Definition of the fibre in the coordinate system and the dispersion at random input parameters a) *Φ-Θ* b) *Φ-t*

The average fibre length in direction x is defined in equation (1):

$$l_{\mathrm{f,x,m}} = \frac{\int_0^{\frac{\pi}{2}}\int_0^{l_f} l_\mathrm{f} \cos\Phi \cos\left(\arcsin\frac{t}{l_\mathrm{f}}\right)\Delta\Phi\,\Delta t}{\frac{\pi}{2}l_f} = 0.5\,l_\mathrm{f} \qquad (1)$$

Including the wall effect the equation will change as (2):

$$l_{\mathrm{f,x,m}} = \frac{\int_0^{\frac{\pi}{2}}\int_0^{T} l_\mathrm{f} \cos\Phi \cos\left(\arcsin\frac{t}{l_\mathrm{f}}\right)\Delta t\,\Delta\Phi + \int_0^{\frac{\pi}{2}}\int_T^{l_\mathrm{f}} l_\mathrm{f} \cos\Phi \cos\left(\arcsin\frac{T}{l_\mathrm{f}}\right)\Delta t\,\Delta\Phi}{\frac{\pi}{2}l_f} \qquad (2)$$

where T is the wall distance from the middle point of the fibre.

This average fibre length is valid only for steel fibres (rigid material). Assuming that fibres that make contact with the mould are deflected (flexible material) the following model in figure 4 can be used. The average length of the fibres in the case of steel (rigid material) and synthetic (flexible material) can be seen in figure 5 and 6, respectively. It can be seen that the effect of the formwork is lower in case of synthetic fibre, therefore less fibre will cross the cracked section compared to steel fibre

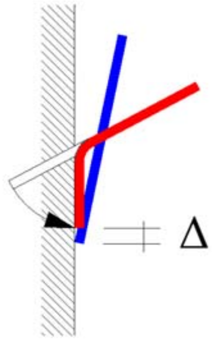

Figure 4. rigid (steel) and flexible (synthetic) model

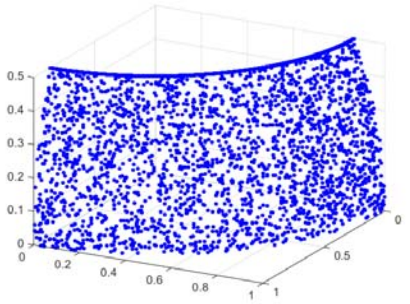

Figure 5. Distribution of the steel fibres at T=0.5 l_f

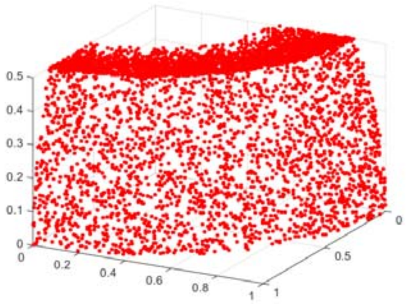

Figure 6. Distribution of the synthetic fibres at T=0.5 l_f

The numbers of fibres according to both the theoretical and actual test results can be seen in figure 7. According to the theoretical calculation the number of fibres crossing the cracked section is the same if the same dosage was used. The theoretical model in most cases gave a higher result, which could be because of the difficulty of counting the number of fibres. Fibres on the surface could be pulled-out (figure 8a) or ruptured (figure 8b and 8c). The pulled-out fibres are visible only one side of the cracked surface. The point of fibre's rupture could be either seen outside of the concrete (ruptured fibres, figure 8b) or could have occurred in the concrete (ruptured-in, figure 8c). In this second case only half of the fibres are counted, because the part which has ruptured in the concrete is not visible. Because of this the number of fibres that were actually counted could be less than were in the concrete.

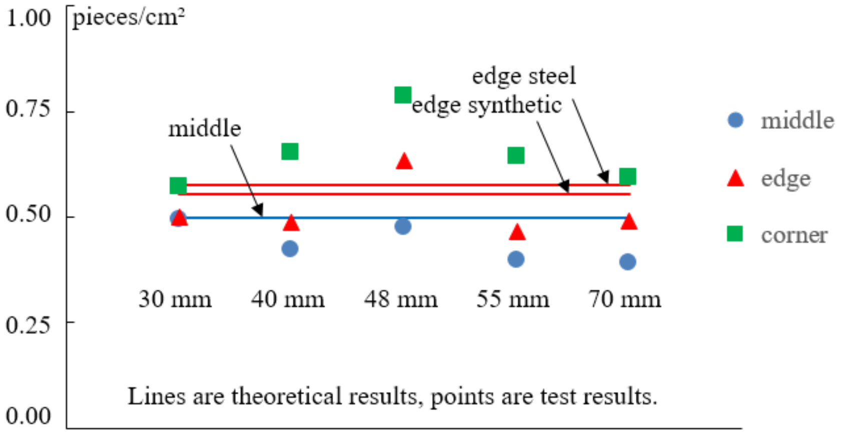

Figure 7. Comparing the theoretical and test results

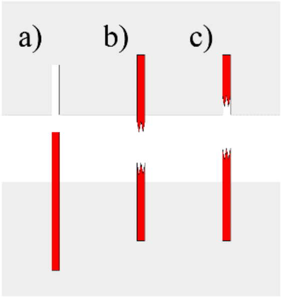

Figure 8. Explanation of the pulled-out (a), ruptured (b) and ruptured-in (c) fibres

4.3. *Effect of the length of the fibres to the fibre-work*

According to previous research fibre has pulled-out from the concrete at 15 mm anchorage length, but has ruptured at 22.5 mm. Because of this the characteristic length (l_c) is between 15 mm and 22.5 mm, so the optimal length of the fibre is between 30 mm and 45 mm.

Plotting the length of the fibre and its *fibre-work* (W_f) in a diagram shows a different correlation than was expected which can be seen in figure 9. The length of fibre which has the highest *fibre-work* is the fibre with 55 mm length, after this length a significant decrease in performance can be seen at 70 mm. Assuming zero *fibre-work* at zero fibre length a line can be fitted on the points up to 55 mm from the origin. This would represent a linear relationship between the length of the fibre and its effect on the *fibre-work*. After this point the *fibre-work* decreased, although the flexural strength of the concrete did not change. This meant that the length of the fibre did not have any influence on the matrix strength, so the fall in the *fibre-work* is because of the changes in the fibre's energy absorption mode.

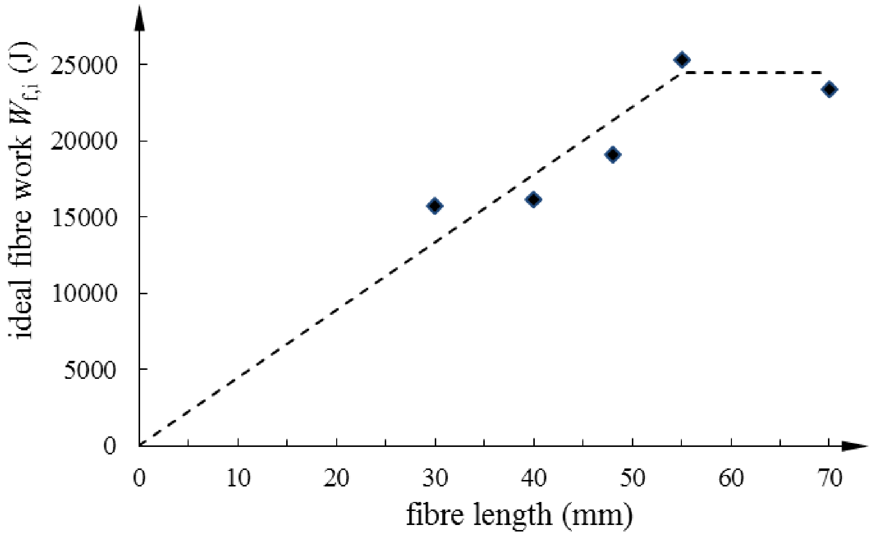

Figure 9. Fibre length and *fibre-work* correlation

5. Conclusion

The length of the fibre has a major effect on its performance in fibre reinforced concrete, both with steel and macro synthetic fibres. With steel fibres the length will change the mixing properties of the fresh concrete as the longer fibres will generate more space between the aggregates, while the macro synthetic fibres will bend around the aggregate. After pouring the concrete into moulds the wall-effect will occur. The length of the fibres will determine the width of the wall-effect zone, where the orientation of the fibres will change, which will be different for both steel and macro synthetic fibres. Steel fibres are rigid, and the fibres will rotate as they touch the mould, while synthetic fibres will bend. This difference can be seen in our numerical models. The length of the steel fibres were optimised with the help of the critical length (l_c), which is the maximum length where fibres are pulled-out from the matrix instead of rupturing. In this paper it was shown that for the macro synthetic fibre this length is different. The optimal fibre length where the fibre will have the maximum *fibre-work* (W_f) is longer than the optimal length calculated according to the critical length.

Acknowledgments

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