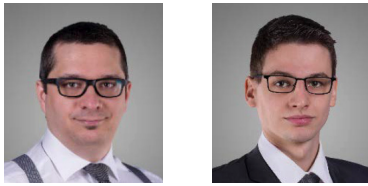


THE EFFECT OF AGE AND TESTING METHOD ON THE ADDED FRACTURE ENERGY OF FIBRE REINFORCED CONCRETE



Károly Péter Juhász – Péter Schaul

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The use of Fibre Reinforced Concrete (FRC) is widely accepted in the tunnelling industry. The generally accepted method to determine the material parameters of FRC is the standard 3-point beam test. The effect of age can be relevant for tunnels, because these structures are usually designed for life cycles over 100 years. In this paper the test results of FRC specimens with different fibres using different testing methods (beam and square panel) at different ages will be presented. FRC changes its properties over time in case of both fibre types. The post crack capacity of steel FRC increases in beam tests, while it decreases in panel tests, which yields the conclusion that steel fibres work better at smaller crack width. This changes only a small amount over time. The energy absorption measured from panel tests reduces in case of steel fibre, but stays at a constant level for synthetic fibre.

Keywords: fibre reinforced concrete, testing age, panel test, beam test

1. INTRODUCTION

Fibre reinforced concrete has been widely used over recent decades in the tunnelling industry, in infrastructural structures like tramlines, railway track slabs and in industrial floors for instance, primarily due to its main advantage of increasing the ductility of the quasi-brittle concrete while providing a post-cracking strength to the composite material (Juhász, 2014). There are several raw material sources for these fibres, but the two main types are steel and macro synthetic fibres. Steel fibres usually have hooked ends and macro synthetic fibres typically have a fully embossed surface. The interaction between these fibres and the concrete matrix can define the properties of the fibre reinforced concrete material. Under loading the addition of fibres in the concrete can bridge the crack sides, but after reaching a critical load level they will fail either in rupture or in pull out (Zollo, 1997). The best residual strength capacity can be obtained when the bond strength of the fibres is high and where the fibres are not rupturing. To reach this performance, highly engineered fibres are needed where both the tensile strength of the fibres and the pull-out resistance of the fibres are high. To increase the pull-out resistance multiple hooks can be used in the case of steel fibres, while in the case of macro synthetic fibres the embossing on the surface plays a key role in pull-out resistance. However, the chemical treatment of the surface (sizing) is also a very important factor. Over time the bond between the fibres and the concrete matrix can change, which can lead to an unfavourable behaviour of the composite material. It can happen that the bond strength of the matrix becomes too strong over time and the composite exhibits brittle fibre rupture instead of ductile pull-out behaviour. This phenomenon is called embrittlement in recent literature (Bernard, 2008). Over time the bond strength can also decrease, which in turn leads to a similar loss of post-crack performance.

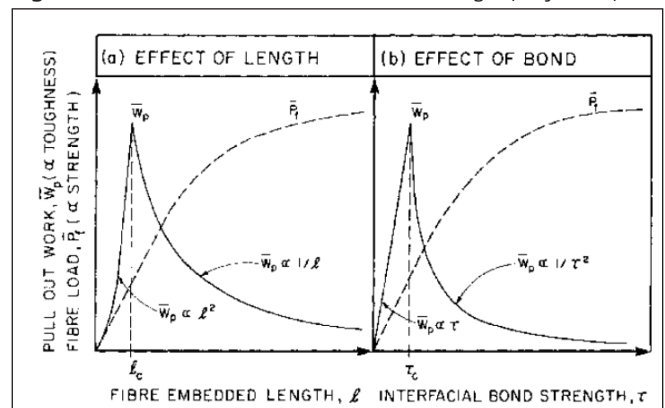
In this paper the results of experimental investigations on panel and beam specimens reinforced with steel and macro

synthetic fibre at different test ages will be presented and discussed.

2. CORRELATION BETWEEN THE BOND STRENGTH AND TOUGHNESS

The pull-out phenomenon of fibres in fibre reinforced concretes was investigated by Bartos (1980, 1981). According to his study the failure mode of the composite depends on the length and the tensile strength of the fibres. With regard to the fibre length the failure mode can be a sudden de-bonding or a progressive de-bonding. Regarding the strength of the fibres, the failure mode can be pull-out or rupturing. The fibre is optimal if it can maximally increase the ductility of the composite material. According to Kelly (1973), maximum ductility can be achieved when the bond strength of the fibres is equal to τ_c , which is the critical bond value. If the bond strength is less than this value the fibres will pull out from the concrete matrix, if it is larger the fibres will rupture and the ductility will decrease (Figure 1).

Figure 1. Pull-out work and interfacial bond strength (Kelly, 1973)



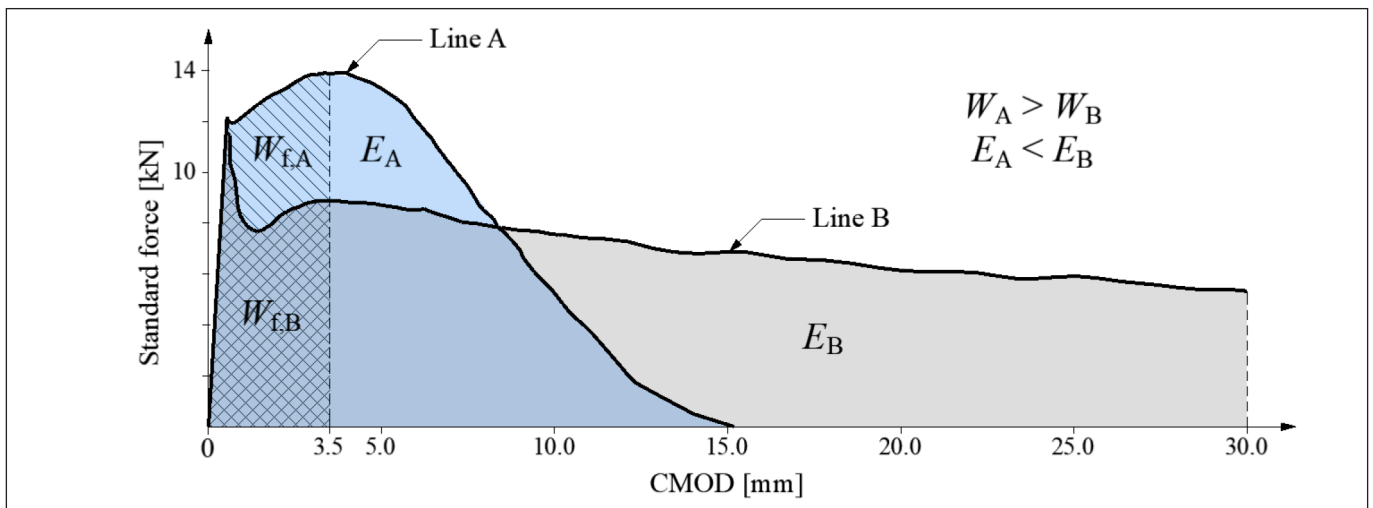


Figure 2. Load – CMOD curves of FRC specimens

The most common way to examine fibre reinforced concrete properties is the three point bending beam test according to the European harmonised standard EN 14651:2005 by measuring the applied load versus the constantly increasing Crack Mouth Opening Displacement (CMOD). The maximum value of the CMOD is 3.5 mm in these tests, i.e. the fibres are not necessarily pulling-out from the concrete matrix and thus their effect on the ductility cannot be fully investigated.

Figure 2 shows the Load-CMOD diagrams of two fibre reinforced concrete specimens out to a displacement of 30 mm. One of the fibres has a high pull-out resistance, which is limited to small crack widths only, while the other one has a lower initial pull-out resistance, but it is not significantly decreasing even at wider cracks. The 3.5 mm CMOD value is marked in the figure, representing the standard limit of the beam test.

These diagrams represent well the characteristic behaviour of steel fibre and macro synthetic fibre reinforced concrete specimens. While the steel fibres are working well at small crack widths, they lose efficiency dramatically with increasing crack width (line A). On the contrary, macro synthetic fibres exhibit constant pull-out resistance, even at much wider cracks, due to the different energy absorption characteristic (line B) (Juhász, 2013; Bernard, 2009). This difference can be clearly seen in those tests where the maximum crack width or deflection values are larger than the mentioned 3.5 mm, for example in case of square panel tests according to EN 14488-5:2006. In such a testing configuration, the difference is much larger and in addition, the absorbed energy characteristic will change, i.e. the energy absorption capacity of the macro synthetic fibres will be greater than the capacity provided by steel fibres.

The area under the Load-CMOD diagram of a beam test is referred to as “fibre-work” (Tóth, Juhász, Pluzsik, 2017), where the area under the load-displacement curve of a square panel test is referred to as “energy absorption” (see Figure 5). These two parameters represent very well the ductility and the post crack performance of fibre reinforced concrete specimens.

The interaction between the fibres and the concrete matrix is very important, but due to ageing of the surrounding concrete several chemical-physical effects can occur, which have an influence on the bond performance. In “figure 1” it can be seen that the bond strength is a highly sensitive element in the performance of fibre reinforced concrete, whether increasing or decreasing, it can cause a significant change in the ductility of the composite.

3. EXPERIMENTAL INVESTIGATIONS

Steel and macro synthetic fibre reinforced concrete beam and square panel specimens were cast and tested at the Czakó Adolf Laboratory of the Budapest University of Technology and Economics. The objective of this research was to investigate the performance of different fibre reinforced concrete specimen types with increasing age. Specimens were tested at 28 days, 90 days and one year of age.

The concrete mix design was identical in all cases, which was a typical shotcrete mix according to Table 1

Table 1. Concrete mix design

Component	Type	[kg/m ³]
Cement	CEM I 42.5 R	480
Water content		216
Aggregate 0/8		1620
Superplasticizer	Mapei Dynamon SXN	4
Fibres	Macro synthetic and steel	6 & 8, 55
w/c	0.45	

To investigate the performance of different fibres one steel fibre and three types of synthetic fibres were used in the test with different dosages. The types of the fibres and their main parameters can be seen in Table 2.

In all cases three square panels and seven beams were cast. To measure the compressive strength of the concrete with every fibre dosage three cubes were also cast. The compressive strength of the concrete was C50/60 according to Eurocode 2. The concrete was mixed with a Collomix –XM2 - 650 professional mixer. The slump of the concrete was 210 mm and the air content was 6% (Figure 3).

In all cases the fibre mixing was good with the stated dosages, the fresh fibre reinforced concrete was homogeneous and well compacted. The square panels were poured into

Figure 3. Air content and slump test

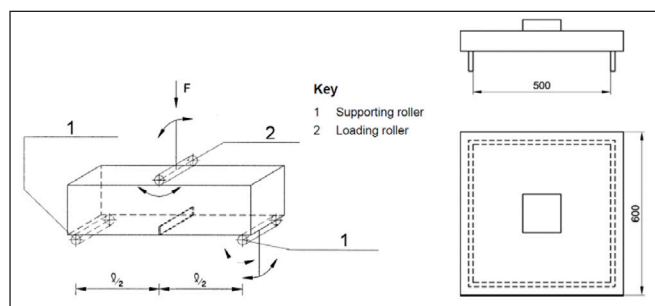


Table 2. Fibre types and properties

Reference	Fibre name	Fibre type	Fibre dosage	Fibre length	surface/end
BC48-6kg	BarChip48	Macro synthetic	6 kg/m ³	48 mm	embossed
BC48-8kg	BarChip48	Macro synthetic	8 kg/m ³	48 mm	embossed
BC54-6kg	BarChip54	Macro synthetic	6 kg/m ³	54 mm	embossed
BC54-8kg	BarChip54	Macro synthetic	8 kg/m ³	54 mm	embossed
DT57-6kg	DucTil57	Macro synthetic	6 kg/m ³	57 mm	embossed
DT57-8kg	DucTil57	Macro synthetic	8 kg/m ³	57 mm	embossed
SF35-55kg	SF35	Steel	55 kg/m ³	35 mm	hooked

Table 3. Test matrix

Reference	28 days		90 days		1 year	
	Beams	Panels	Beams	Panels	Beams	Panels
BC48-6kg	7	3	-	-	-	-
BC48-8kg	7	3	7	-	7	-
BC54-6kg	7	3	-	-	-	-
BC54-8kg	7	3	7	3	7	3
DT57-6kg	7	3	-	-	-	-
DT57-8kg	7	3	-	3	7	3
SF35-55kg	7	3	7	3	7	3

**Figure 4.** Test supports and arrangement (left: beam test, right: panel test)

the formwork without any vibration, while the beams were compacted on a high frequency shaking table. All specimens were stored underwater at room temperature until tested.

The full test matrix with the testing ages can be seen in Table 3.

The beam tests were conducted according to EN 14651:2005 and the panel tests according to EN 14488-5:2006. In both cases the testing machine was a deflection controlled universal testing machine type Zwick Z150.

In case of the beam tests the speed of the crack mouth opening displacement was 0.05 mm/min until CMOD = 0.1 mm, after that the speed was 0.2 mm/min. In case of the square panel tests the speed of the centre displacement was 1 mm/min. The load-displacement curve was recorded and the test was continued until a deflection of at least 30 mm was achieved at the centre point of the slab. The supports and loading devices of the beams and panels can be seen in Figure 4.

4. TEST RESULTS

The “fibre work” of the beams and the “energy absorption” of the square panels can be seen in Figures 5a and 5b.

In the case of steel fibres the ductility decreased continuously with increasing testing age. According to Kelly (1973) (Figure 1) the bond strength is unknown but the decreasing ductility can be due to two reasons: the bond strength decreased and thus the pull-out resistance also decreased or the bond strength exceeds the critical value and the energy absorption of the fibre changed or the fibres rupture instead of pulling-out. On

checking the cracked surfaces, it was found that none of the fibres were ruptured. The loss of ductility is a well-researched topic in case of steel fibre reinforced concrete (Bernard, 2009) who relates this embrittlement effect with the rupture of the fibres due to the increased chemical-physical bond. According to the results it can be seen that the decrease in the bond strength can also decrease the ductility of the fibre reinforced concrete specimens.

In case of synthetic fibre reinforced specimens, the ductility increased or remained constant over the test period. According to Kelly this can be because of the increasing or the decreasing of the bond strength. The number of the ruptured fibres on the cracked cross section was not higher after one year than after 28 days which means that the bond strength increased during the ageing process but it did not reach the critical value.

From the beam test results, it can be seen that the beam test does not represent very well the real fibre performance during the ageing process due to the low level of the deformation and crack widths. Thus, it is questionable whether testing of beams at 28 days of age alone yields sufficient information with regard to the design values obtained hereof and with regard to the design life of the structure.

5. CONCLUSIONS

By adding fibres to plain concrete, the ductility and the post crack performance increases. The bond interaction between the concrete and the fibres is a very important parameter in the case of ductility but it highly depends on the age of the material. With an optimal anchorage length the bond strength can change during the ageing process which can lead to both an increase and a decrease in ductility.

Steel and synthetic fibre reinforced concrete beams and square panel tests were carried out at different ages. While the performance of steel fibre was better in case of beam tests, the energy absorption was superior with synthetic fibres. During the test period the ductility of steel fibres decreased while most of the synthetic fibres’ ductility increased or remained constant. On the cracked surface of the steel fibre reinforced concrete specimens none of the fibres were ruptured, which means that the bond strength decreased during the test period. In the case

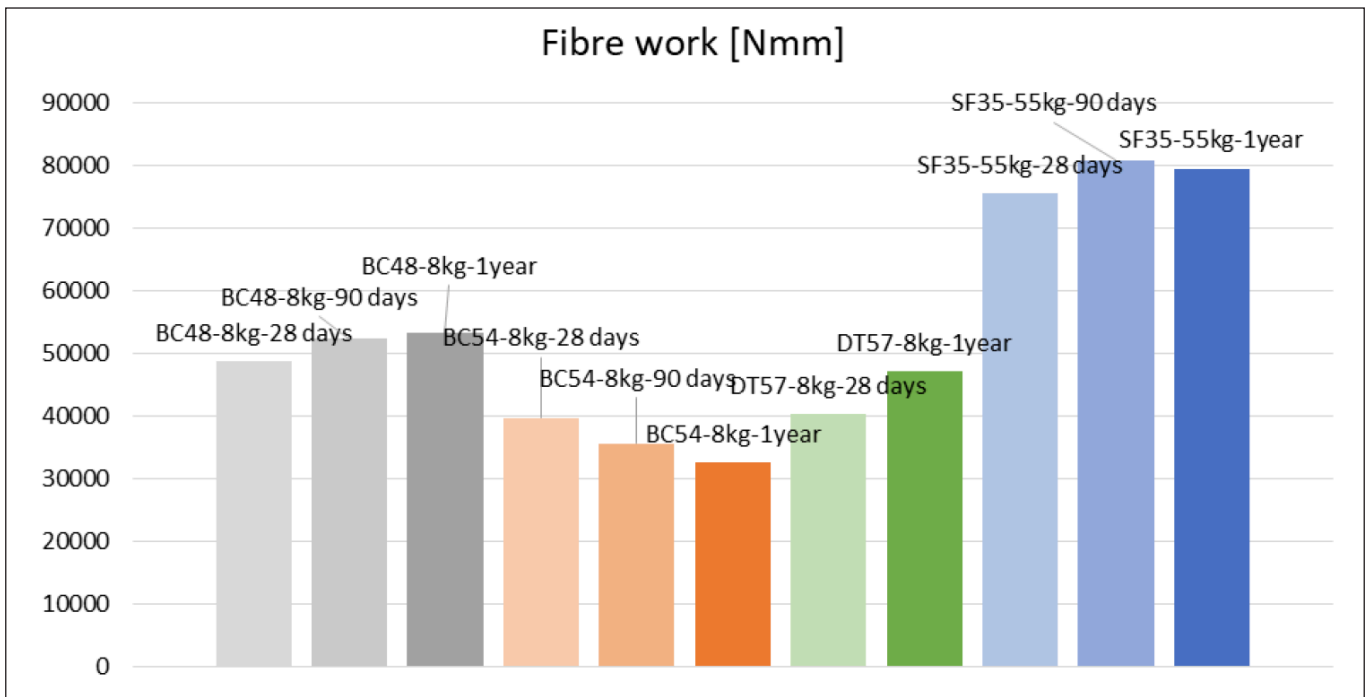


Figure 5a. Fibre work of the beam specimens

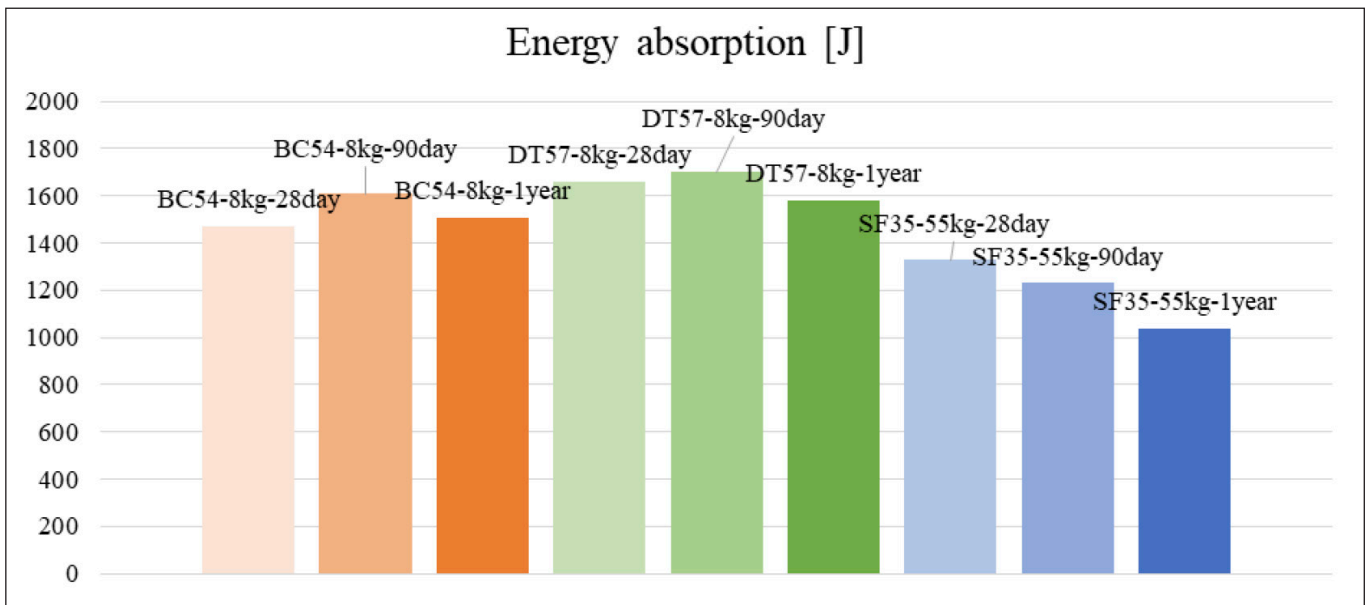


Figure 5b. Energy absorption of the square elements

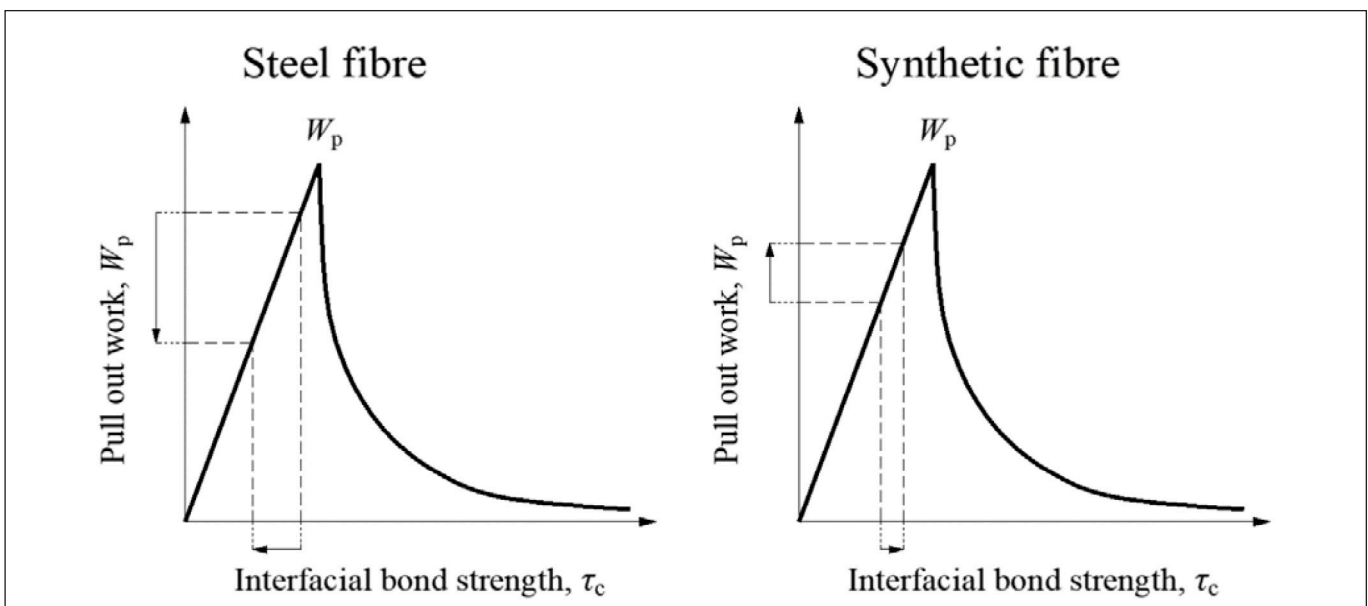


Figure 6. Interfacial bond during ages

of synthetic fibres, the number of the ruptured fibres was not larger over the test period, the bond strength in those cases increased (Figure 6).

Panel tests better represent the ductility of fibre reinforced concrete specimens, the beam test does not represent the real fibre concrete composite performance during the ageing process due to the low level of displacement and crack width.

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