EXPERIMENTAL STUDY ON THE BEHAVIOUR OF BONDED ANCHORING SYSTEMS IN FIBRE REINFORCEMENT CONCRETE


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*Our research mainly focuses on the behaviour of post-installed anchors in fibre reinforced concrete (FRC)***.** *In our tests three types of fibres (two types of steel and one type of polypropylene) were used as fibre reinforcement together with two different bonded anchoring systems (vinyl-ester hybrid, epoxy resin). Based on our test results we can state that application of shorter steel fibres has better effect on the resistance of bonded anchors compared to application of longer steel or polymer fibres.*

Keywords: fibre reinforcement concrete, fastening systems, bonded anchor, pull-out test, concrete cone failure, pull-out failure

1. INTRODUCTION

1.1 Fibre reinforced concrete (FRC)

Behaviour and properties of concrete can be amended by addition of fibres with different sizes and materials. At first, addition of steel fibres became general that improves the properties of hardened concrete mainly. It is widely applied for industrial floors because fibres improve the resistance against dynamic effects of vehicles and machines. Steel fibres can also be applied in reinforced concrete structures to reduce the amount or fully replace shear reinforcement. They can be effectively used in bent and tensioned structures because of their advantageous crack-bridging properties (*Fig. 1*) (Falkner, 1998). Based on previous studies, higher steel fibre content can also increase the compressive strength of concrete and the displacement. *Fig. 2* shows that energy dissipation (area below the stress-strain curve) increases as fibre content increases.

1.2 Anchorage in concrete

Several post-installed anchors are available with different methods of load-transfer. The commercially available fastenings can transfer the load to the host material via the following mechanisms: mechanical interlock, friction or bond. Furthermore, the most recent techniques use combined bond and friction (e.g. bonded expansion anchors). In case of expansion anchors, the load is transferred by friction. Generally, an expansion sleeve is expanded by an exact displacement or torque applied on the anchor head during the installation process. Chemical fastenings are anchored by bond. Bonded anchors can be divided into two subgroups: capsule or injection systems. The bond material can be either organic, inorganic or a mixture of them. In this case the loads are transferred from the steel (normally a threaded rod, rebar) into the bonding material and are anchored by bond between the bonding material and the sides of the drilled holes. The load bearing capacity of bonded anchors with the same embedment depth depends on the type of the resign. (Eligehausen, Hofacker, Lettow, 2001; Eligehausen, Malée, Silva, 2006; Eligehausen, Cook, Appl, 2006).

Load bearing of fastenings can be determined by taking the minimum of ultimate loads corresponding to different failure modes. In case of tensioned anchors steel failure, concrete cone failure, pull-out failure and splitting can occur (Fig. 3) (Eligehausen, Malée, Silva, 2006).

Fig. 1: Crack propagation in fibre reinforced concrete (Li, Majer, 1996)

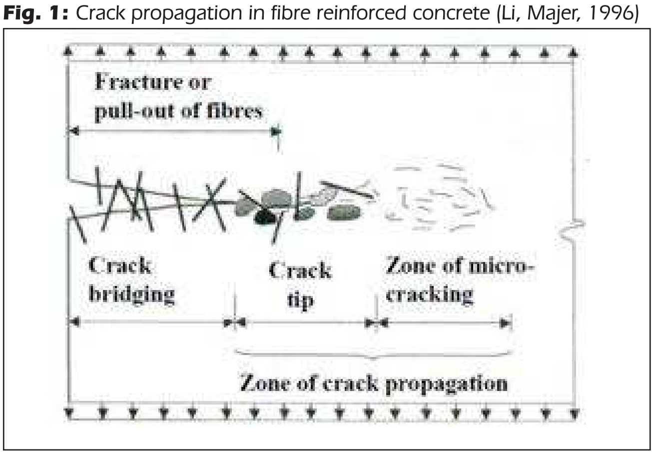
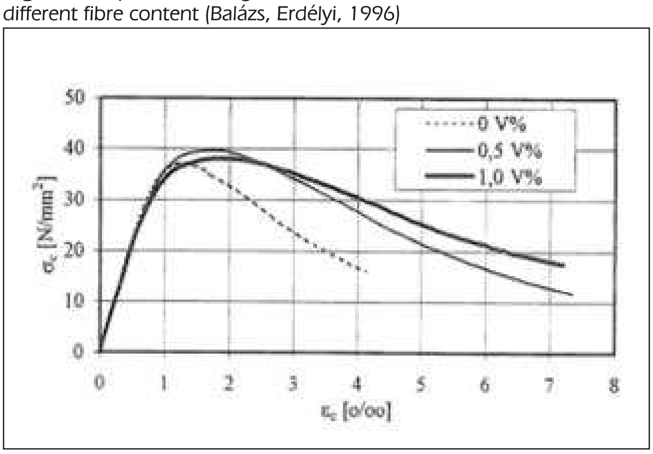


Fig. 2: Compressive strength of steel fibre reinforced concretes with different fibre content (Balázs, Erdélyi, 1996)



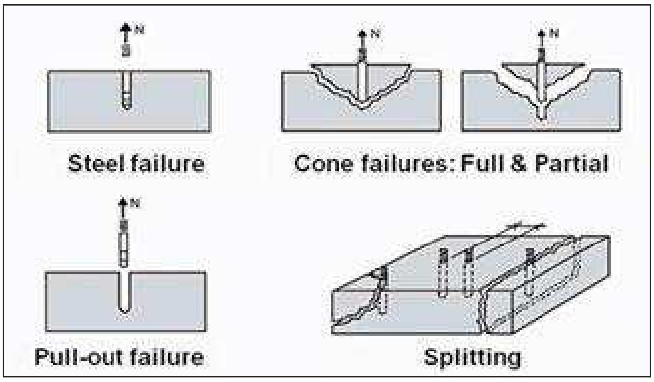


Fig. 3: Failure modes of anchors

Steel failure depends on the tensile strength of the steel rod. Steel capacity can be calculated from the ultimate steel strength and the cross-sectional area.

Splitting failure is caused by reaching the critical edge-spacing distances. Load bearing capacity can be influenced by distances from edges and by spacing distances; these effects can be taken into account by reduction factors.

Pull-out failure has to be discussed separately for bonded and expansion anchors. Pull-out failure of mortar bonded anchors means bond failure between mortar and concrete, while pull-out failure excluding mortar means bond failure between the steel fastening and the bonding material. The bond strength depends on the certain product, but its value is included in the corresponding approvals.

$$N_u = \pi \cdot d \cdot h_{eff} \cdot \tau_u \qquad (1)$$

where:
d = anchor bolt diameter [mm]
τ_u = bond strength [MPa]

Concrete cone failure can be calculated by the C-C Method (Concrete Capacity Method) (Fuchs, Eligehausen, 1995; Eligehausen, Ožbolt, 1999). The method is based on laboratory tests and numerical calculation:

$$N_u = k \cdot \sqrt{f_c} \cdot h_{ef}^2 \cdot \frac{1}{h^{0.5}} = k \cdot \sqrt{f_c} \cdot h_{ef}^{1,5} \qquad (2)$$

where:
k = factor that depends on the type of the anchor
h_{ef} = embedment depth [mm]
f_c = concrete compressive strength [N/mm^2]; $(\sqrt{f_c} \approx f_{ct})$
f_{ct} = concrete tensile strength [N/mm^2]

In Eq. (1), h_{ef}^2 corresponds to the failure surface and $1/h_{ef}^{0.5}$ takes into account the size effect (Bažant, 1984). New result of this method is that it assumes a cone angle of 35° compared to former methods that used 45° (ACI Committee 349, 1985). Nowadays several design guides and standards suggest this method (CEB, 1994; fib MC2010, 2013; fib BULLETIN 58, 2011; prEN 1992-4, 2015; ETAG 001, 2013).

Different papers preceded the final form of the C-C Method. One of these used the bases of fracture mechanics to calculate the resistance against concrete cone failure (Eligehausen, Sawage, 1989):

$$N_u = k \cdot \left(E_c \cdot G_f\right)^{0.5} \cdot h_{ef}^{3/2} \qquad (3)$$

where:
k = factor that depends on the type of the anchor
h_{ef} = embedment depth [mm]
E_c = modulus of elasticity of concrete [N/mm^2]
G_f = fracture energy of concrete [N/mm]

There is no sharp change between cone failure and pull-out failure, the two failure modes combined, and partial cone failure occurs (Bajer, Barnat, 2012).

The calculation methods detailed above are only valid in case of normal concretes. Design guides and codes do not deal with the behaviour of anchors is fibre reinforced concretes. Meanwhile, based on Eqs. (2) and (3) it is visible that the resistance of anchors depends on the strength, Young's modulus and fracture energy of concrete, which parameters can be highly affected by the fibre type and fibre content applied. Therefore the formulae used in case of normal concretes may not be used in case of FRC, or only with modifications. Until now only few tests intended to examine and specify the behaviour of anchors installed in FRC.

Holschemacher et al (2002) tested expansion, undercut and bonded anchors with 60 mm embedment depth in FRC. In each case they applied steel fibres, but with two different geometries (elliptical, waved sheet cut steel fibres; round steel wire fibres with end hooks). The applied fibre content was 50 kg/m^3. They experienced that the resistance values of the anchors in FRC were close to the resistance values in case of normal concretes, but the deviation of the measured values significantly increased. The reason for this could be the increased air content because of the fibres and the non-homogenous distribution of the fibres in the concrete. Non-homogenous distribution could lead to low number of effective fibres (fibres that perpendicularly crossed the cracks and therefore had significant crack-bridging effect).

Bokor et al (2017) tested bonded anchors individually and installed in a group in steel fibre reinforced concrete (SFRC). The applied embedment depth was 70 mm, the fibre content was 50 kg/m^3. Their results showed 18 % increase in resistance in case of individual anchors, and 25-42 % increase in case of groups, depending on the loading (centric, eccentric). They showed that the effect of fibres was more significant in case of anchor groups, mainly because of ductile failure, during which, if one anchor reaches its ultimate limit state, it could still bear some load, and consequently it transmitted less load to the other anchors.

2. EXPERIMENTAL STUDY

2.1 Tested anchors

During our tests two different types of bonded anchors were used, one type with epoxy resin, and on type with vinyl-ester hybrid bonding material.

Proper mixing of high performance epoxy resin glues is ensured by special mixing rods. The bond is stress-free; therefore it can be applied in case of small edge distances and spacing. Consistency of the epoxy resin is higher than that of other glues therefore it can enter to the pores and can reach an adequate depth before hardening, resulting in higher amount of load transmission by adhesion. Average bond strength of the glue (τ_u) is 21.1 N/mm^2 (determined on the basis of confined tension test results in non-cracked normal concrete).

Vinyl-ester hybrid is a combined glue, that includes organic (vinyl-ester) and inorganic (cement) compounds. The glue is universal, it can be used for all kinds of building materials and loading types. The bond is stress-free; therefore it can be applied in case of small edge distances and spacing. The consistency of it is more granular than that of the epoxy resin and this property also remains after hardening. Its characteristic bond strength (τ_u) is 15.0 N/mm^2 (determined on the basis of confined tension test results in non-cracked normal concrete).

During our tests with bonded anchors, size M8 and grade 10.9 threaded rods were applied. The high tensile strength of the rod prevented steel failure therefore cone failure of concrete could be examined.

Applied embedment depth was 50 mm in each case.

2.2 Concrete mixtures

During our tests two types of steel and one type of polypropylene fibres were used. Properties of the chosen fibres are included in Table 1.

Beside FRC specimens, normal concrete specimens were also manufactured. The initial composition was always the same, in case of FRCs, the consistency class (T4) that belonged to normal concretes was set by addition of plasticizer. In case of fibre S1, four different fibre contents (20, 30, 40, 80 kg/m^3), in case of fibre S2 two different fibre contents (40, 80 kg/m^3), while in case of fibre P three different contents (3.0, 4.5, 6.0 kg/m^3) were used. Composition of concrete mixtures is summarized in Table 2.

The specimens were held under water for 7 days and then kept at laboratory temperature (20 °C) for additional 21 days. The dimensions of concrete specimens for pull-out tests were 300×300×150 mm. This geometry corresponds to the prescribed parameters of the ETAG 001 (2013). In case of this geometry the probability of splitting is very low. For each mixtures compressive strength was tested on 3 cubes with 150×150×150 mm dimensions, flexural tensile strength was measured on 3 prisms with 70×70×250 mm dimensions (that were cut out from the 300×300×150 mm specimens to prevent the effect of fibre orientation), while splitting-tensile strength was measured on 4 cylinders with height and diameter 150 mm.

2.3 Pull-out test

Our unconfined test setup is shown in *Fig. 4*. The loading device was a displacement controlled test apparatus, which allowed the recording of residual stress after the failure. This setup enabled the formation of all possible failure modes, the

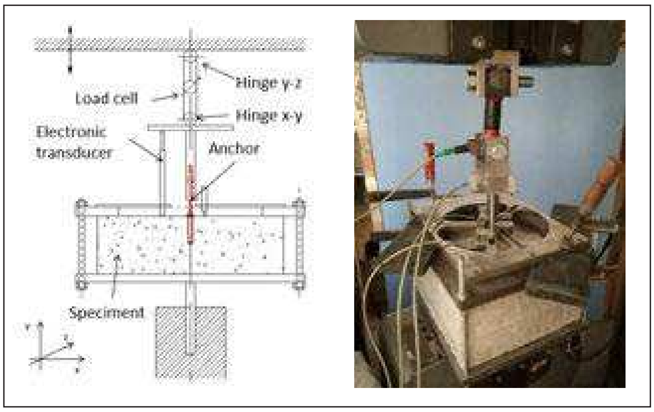


Fig. 4: Arrangement of pull-out test

results were not affected by the geometry of the investigated samples (thickness of the test member, critical edge, placing). The measurement setup was capable to measure, record and show the applied load and related displacement of the anchor in real-time. The perpendicular pin-joints ensured the centrality of the acting force. Two electronic transducers measured the displacement, while three additional independent displacement transducers were used to record the deformation of the surface. The load was measured by a calibrated load cell. The tests were carried out in accordance with the instructions given in ETAG 001 (2013). The support distance was greater than 4 h_{ef}.

3. RESULTS AND DISCUSSION

3.1 Concrete strengths

Compressive strength of concrete was tested 28 days after mixing. The test results are presented in *Fig. 5*.

From the compressive strength test results we can see that due to the addition of fibre S1 between 20 and 40 kg/m^3 content the strength slightly increases, while in case of 80 kg/m^3 it decreases. Decrease of strength due to higher fibre content can be explained by the extra air content that was added during addition of fibres. In case of mixtures with fibres S2 and P slight decrease of strength can also be seen, which also can be explained by the increased air content. The different level of this decrease can be explained by the different geometry of the fibres.

Table 1: Properties of fibres

Name	Material	Legths [mm]	Diameter [mm]	Tensile strength [N/mm^2]	Surface
S1	steel	50	1,0	1000-1200	smooth and hooked end
S2	steel	12	0,2	3000	smooth
P	polypropylen	50	0,5	618	roughened along the length

Table 2: Concrete mixtures

Name	Cement CEM I 42,5 N [kg/m^3]	Aggregate 0-4 mm [kg/m^3]	Aggregate 4-8 mm [kg/m^3]	Aggregate 8-16 mm [kg/m^3]	Water [kg/m^3]	Fibre content [kg/m^3]	w/c [-]
N	290	833	463	556	196	0	0,675
S1						20, 30, 40, 80	
S2						40, 80	
P						3.0, 4.5, 6.0	

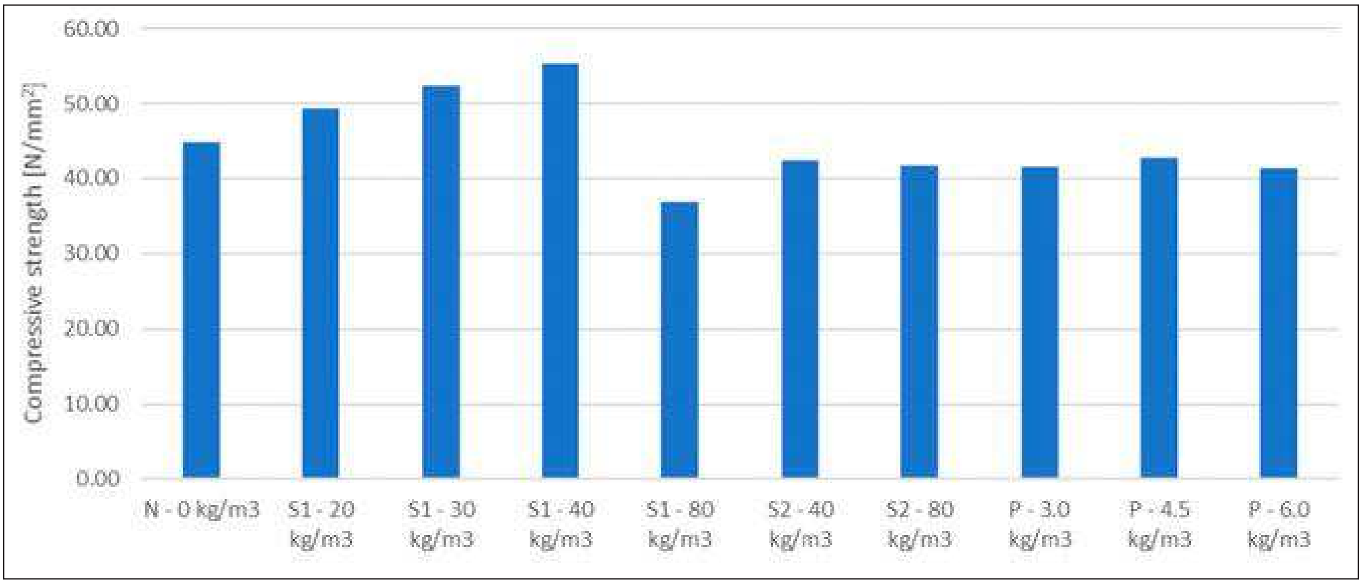


Fig. 5: Results of the concrete compressive strength test

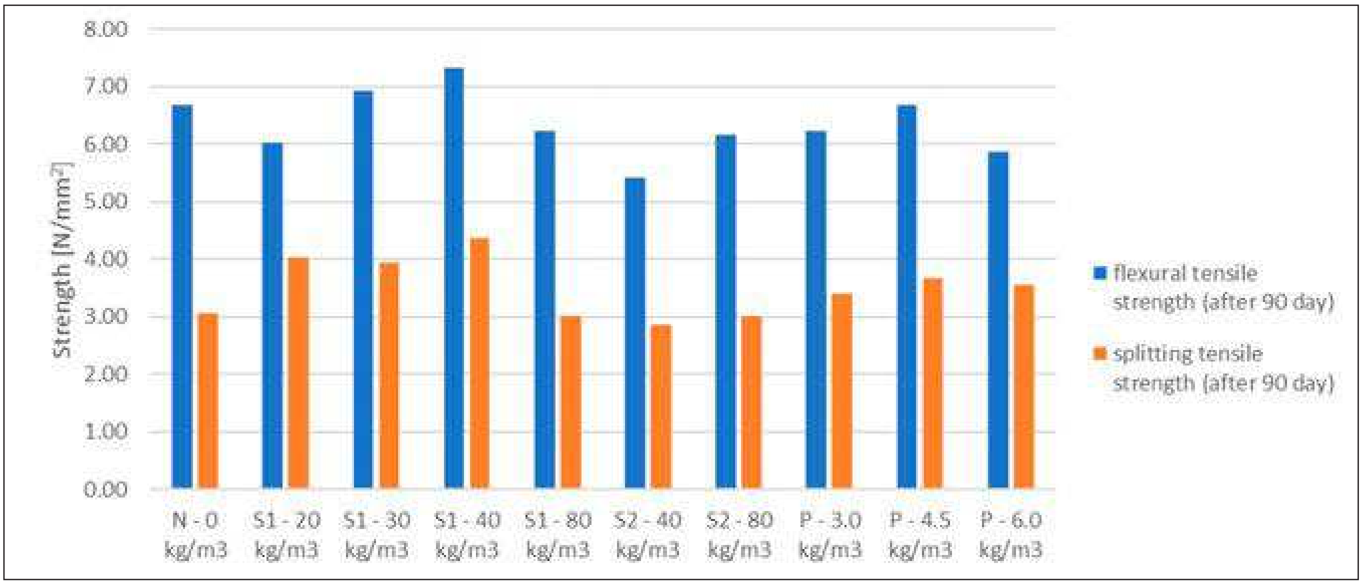


Fig. 6: Results of the concrete flexural tensile and splitting tensile strength tests

Flexural and splitting tensile strength of concrete were tested 90 days after mixing, because the specimens were cut out from the 300×300×150 mm specimens (to avoid uneven fibre-orientation) that were at first used during the pull-out tests. Flexural and splitting tensile strength values of the different mixtures are summarized in *Fig. 6.*

3.2 Results of the pull-out tests

Results of the pull-out test are detailed in *Table 3*.

The results show that in case of both types of glues, in case of fibre S1 with 20-30 kg/m^3 content, resistance and failure mode are the same as for concrete without fibres. In case of 40 kg/m^3 fibre content the resistance increases, but failure mode does not change, while in case of 80 kg/m^3 the resistance increases and in case of epoxy resin, the failure mode changes to the combination of cone failure and pull-out of the glue. (*Fig. 7.*).

In case of steel fibre S2, 40 kg/m^3 content already results in significantly higher resistance in case of both types of glues, failure mode changes to the combination of concrete cone and pull-out failure in case of epoxy resin, while in case of vinyl ester to pull-out failure. Pull-out of the anchor is the consequence of the cease of the bond between the glue and the concrete, which also means that the fixing system reached its ultimate state. In case of 80 kg/m^3 the resistance further increases, and pull-out occurs in case of both epoxy resin and vinyl ester *(Fig. 8.*).

In case of polypropylene fibre P, in case of epoxy resin the resistance and the failure mode do not change between 3-6 kg/m^3 fibre content. In case of vinyl-ester the resistance slightly decreases, while the failure mode does not change (*Fig. 9*).

4. CONCLUSIONS

Our research mainly focuses on behaviour of post-installed anchors in fibre reinforced concrete (FRC). In our tests three types of fibres were used as fibre reinforcement together with two different bonded anchoring systems (vinyl-ester hybrid, epoxy resin).

During the tests two types of steel fibres with different geometry and one type of polymer fibre were used. Steel fibres were different in dimension and length: fibre type S1 had length 50 mm, diameter 1 mm, had smooth surface and hooked end; while fibre type S2 had length 12 mm, diameter 0.2 mm, with smooth surface. Length of polymer fibre P was the same as length of the longer steel fibre (50 mm), its diameter was 0.5 mm and its surface was roughened.

Table 3: *Mean tensile resistances and typical failure modes of pull-out tests*

Name	Epoxy resin		Vinyl-ester resin	
	Mean tensile resistance [kN]	Typical failure mode	Mean tensile resistance [kN]	Typical failure mode
N	24.78	concrete cone	22.84	partial concrete cone
S1 - 20 kg/m³	25.67	concrete cone	23.27	partial concrete cone
S1 - 30 kg/m³	24.54	concrete cone	20.96	partial concrete cone
S1 - 40 kg/m³	28.31	concrete cone	-	-
S1 - 80 kg/m³	29.85	partial concrete cone	24.85	partial concrete cone
S2 - 40 kg/m³	32.68	partial concrete cone	26.38	pull-out
S2 - 80 kg/m³	36.04	pull-out	28.14	pull-out
P - 3.0 kg/m³	23.52	concrete cone	17.52	partial concrete cone
P - 4.5 kg/m³	23.69	concrete cone	19.11	partial concrete cone
P - 6.0 kg/m³	24.01	concrete cone	17.76	partial concrete cone

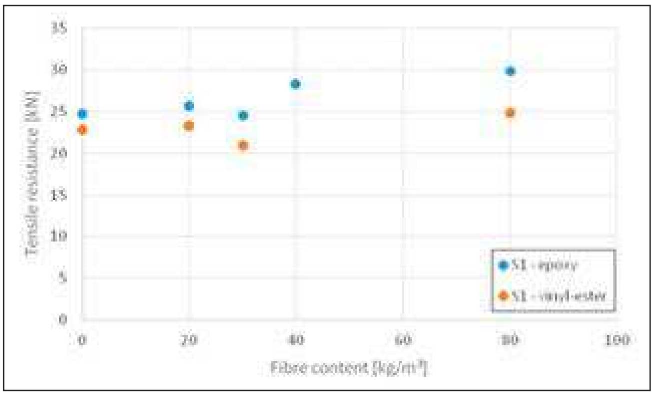


Fig. 7: Effect of type S1 fibre content on the tensile resistance of anchors (each point is the mean value of 3 results)

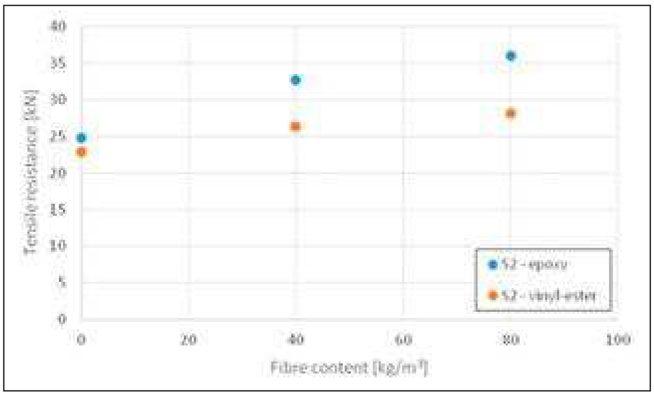


Fig. 8: Effect of type S2 fibre content on the tensile resistance of anchors (each point is the mean value of 3 results)

In addition to fibre reinforced concrete specimens, normal concrete specimens were also cast and tested. Initial concrete composition was the same at each case. In case of fibre S1, four different fibre contents (20, 30, 40, 80 kg/m³), in case of fibre S2 two different fibre contents (40, 80 kg/m³), while in case of fibre P three different contents (3.0, 4.5, 6.0 kg/m³) were used.

Based on the results of the pull-out tests the following can drawn:

- In case of the addition of the longer steel fibres (type S1): 20-30 kg/m³ fibre content did not have an effect on the resistance of the bonded anchors, 40 kg/m³ fibre content slightly, while at 80 kg/m³ significantly increased the resistance.

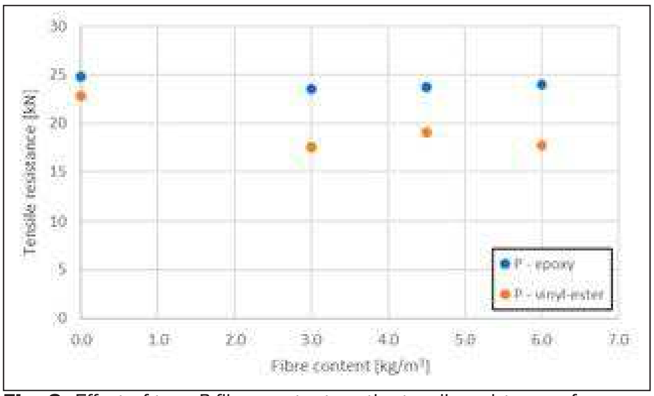


Fig. 9: Effect of type P fibre content on the tensile resistance of anchors (each point is the mean value of 3 results)

- In case of the shorter steel fibres the resistance increased significantly already in case of 40 kg/m³ fibre content, while in case of 80 kg/m³ fibre content the failure mode changed to pull-out failure which means the ultimate capacity of the bonded anchor system.
- In case of polymer fibre P, if epoxy resin was applied then the resistance did not change between 3-6 kg/m³ fibre content. In case of vinyl-ester the resistance slightly decreased, while failure mode remained the same.

Based on our test results we can state that application of shorter steel fibres has better effect on the resistance of bonded anchors compared to application of longer steel or polymer fibres. The reason for this is the higher number of fibres if same content is applied, higher number of fibres results in more effective fibres that bridges the cracks of the concrete cone.

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