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Published in:
Proceedings of the fib Symposium 2019

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

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THE INFLUENCE OF CONCRETE MATURITY ON THE PULL-OUT BEHAVIOUR OF STEEL FIBRES AT EARLY-AGES

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Abstract

Steel Fibre Reinforced Concrete (SFRC) is being used for the production of in-situ and prefabricated structural elements. The optimization of production and installation processes often require an accurate understanding of the early-age development of the mechanical performance of the hardening SFRC. However, there is limited data available describing the development of the fibre-matrix bond during the first weeks of maturing, and its relation to the mechanical properties of the hardened concrete matrix is not well understood.

Single fibre pull-out tests were performed for straight and hooked end fibres embedded in concrete at ages between 3 and 14 days, to investigate the development of the bond strength over time. The compressive strength and elastic modulus were measured to correlate the pull-out performance with the mechanical properties of the concrete.

The experiments showed an increase of the fibre-matrix bond over time at early ages. The maximum pull-out load for the straight fibres increased during the beginning of the hydration, corresponding to the development of the adhesive bond. Whereas, the mechanical bond of the hooked end fibres developed substantially over the first days of curing but decelerated gradually over the time investigated.

This study provides insight of a correlation between pull-out behaviour of single fibres and the mechanical properties of the concrete matrix. The pull-out strength of steel fibres developed with time similarly to the strength and stiffness of the matrix; presenting a rapid development at early ages which decreases after the first week of curing, for the mix-design investigated.

Keywords: SFRC, steel fibre, pull-out behaviour, adhesive bond, maturity, strength-development.

1. Introduction

Steel Fibre Reinforced Concrete (SFRC) has been used as an alternative to overcome the limited post crack-ductility of plain concrete, while maintaining its performance in compression (Bentur and Mindess, 2006). Among others, SFRC is being used as partial- or total-replacement of conventional reinforcement of prefabricated structural elements (Plizzari and Tiberti, 2006).

Discrete steel fibres are used to improve the post-cracking ductility of the concrete matrix (Boshoff et al., 2009; Skadins and Brauns, 2012; Yoo et al., 2017), by limiting and controlling the propagation and growth of cracks that occur in the matrix both during production and handling at early-ages (Schnütgen, 2003) and during the service life of structural concrete elements (Bentur et al., 1985).

When bridging a crack, the steel fibres are subjected to tensile forces, which result in a partial pull-out of the fibre until equilibrium of forces is reached again in the structural system (Tsai and Kim, 1996). The behaviour of cracked SFRC is typically described by testing SFRC coupons that measure a force vs crack-opening or force vs displacement relation at the composite scale (Löfgren, 2005). However, tests at the composite scale often limit the understanding of deterioration and development mechanisms that
affect the behaviour of the composite, such as in the case of the evolution of the residual performance of SFRC over time (Bernard, 2015).

Therefore, understanding the pull-out behaviour of a single-fibre provides valuable information that can be used to predict the behaviour of the cracked composite; which can be experimentally examined by means of fibre pull-out tests. In this aspect, previous studies have investigated the influence of several parameters on the pull-out behaviour of steel fibres in concrete, among others: the fibre geometry, fibre strength or the matrix strength. Studies showed that, generally: hooked-end fibres lead to higher pull-out loads than straight fibres (Isla et al., 2015), and high-strength fibres lead to higher pull-out loads than low-strength fibres (Breitenbücher et al., 2014). Furthermore, investigations have suggested a direct correlation between the compressive strength of the concrete matrix and the fibre-matrix bond (Bentur and Mindess, 2006; Yoo et al., 2017).

Based on the aforementioned observations, an increase in the adhesive bond is expected as the maturity develops (Alexander et al., 1999). Likewise, the frictional resistance as well as the mechanical anchorage of hooked end fibres are expected to increase over time as the concrete matrix develops (Banthia, 1990; Shen et al., 2016; Soetens et al., 2013). A stronger and stiffer matrix leads to higher pull-out loads (Breitenbücher et al., 2014). Whereas, in some cases such development may even lead to premature fibre rupture, as the fibre-matrix bond strength exceeds the tensile strength of the fibre (Breitenbücher et al., 2014; Isla et al., 2015).

This paper investigates the maturity-dependent performance of steel fibre pull-out, with experiments performed on the basis of the findings in the literature review.

2. Methodology

This study covers the experimental study of single-fibre, single-sided pull-out tests of four different fibres from the same concrete matrix tested at three different maturities: 3, 7 and 14 days; as well as the characterization of the compressive strength and Young’s modulus in compression of companion concrete specimens. The analysis and discussion of the results focus on describing the relation between the mechanical properties of the concrete matrix and the pull-out behaviour of the single-fibres over the first weeks of maturity. The methodology is described in depth in (Kragh and Carlsen, 2017).

2.1. Materials and specimen preparation

The specimens were cast using the mix-design shown in Table 1. The concrete used had 326 kg/m³ of Portland cement and 100 kg/m³ of fly ash, with a water to binder ratio of 0.34. The coarse aggregate used had a maximum size of 8 mm, corresponding to the small specimen size: e.g. in the range 7 – 10 cm. The water content used in the mix was corrected according to the moisture of the aggregates, at saturated-surface-dry (SSD) conditions. Air entraining agent and superplasticizer were added to reach a total volume of entrained air of 4.5±0.5% vol, measured according to DS/EN 413-2:2016; and a slump flow diameter of 93±3mm, measured according to DS/EN 1015-3:1999.

Table 1. Mix proportions per cubic meter

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM-I 52.5 N</td>
<td>326.3</td>
</tr>
<tr>
<td>Water</td>
<td>145.0*</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>100.0</td>
</tr>
<tr>
<td>Sand 00/02</td>
<td>875.8</td>
</tr>
<tr>
<td>Sea-gravel 04/08</td>
<td>943.1</td>
</tr>
</tbody>
</table>

*Value corresponds to the total water content, considering SSD aggregates.

Steel fibres made of cold-drawn carbon-steel wire were used in this study. The properties and geometry of the four different fibres used in the study are described in Table 2 and shown in Figure 1a. Two types of steel wire were investigated: medium-carbon steel fibres (low strength “L”) and high-carbon steel fibres (high strength “H”). For each fibre type, hooked-ended (H) and straight fibres (S) were investigated; the latter being a hooked fibre with the hooks cut-off.

The specimens were cast in a PVC formwork, with a 70 mm cubic shape; where the fibre was placed vertically in a rubber plug at the centre, embedded 30 mm into the concrete matrix, as shown in Figure
1a-b. The production of the specimens comprised a total of 90 cubes of 70 mm for single-fibre pull-out testing and 27 cylinders of 60 x 120 mm for the testing of mechanical properties in compression of the concrete matrix. The ingredients were mixed for 6 minutes using a 40-l pan mixer, and the specimens were filled and vibrated at 75 Hz, in two steps. After casting, the moulds were covered with plastic film for 24 h at laboratory conditions (i.e. 20±2 °C) and afterwards cured in lime-saturated water at 20±2 °C.

<table>
<thead>
<tr>
<th>Code</th>
<th>Shape</th>
<th>Tensile strength [MPa]</th>
<th>Diameter [mm]</th>
<th>Length (total) [mm]</th>
<th>Length (stem) [mm]</th>
<th>Length (hook) [mm]</th>
<th>Hook depth [mm]</th>
<th>Hook angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-H</td>
<td>Hooked</td>
<td>1900</td>
<td>0.75</td>
<td>60</td>
<td>50</td>
<td>~3</td>
<td>~1.8</td>
<td>~45</td>
</tr>
<tr>
<td>H-S</td>
<td>Straight</td>
<td>1900</td>
<td>0.75</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L-H</td>
<td>Hooked</td>
<td>1200</td>
<td>0.75</td>
<td>50</td>
<td>40</td>
<td>~3</td>
<td>~1.8</td>
<td>~45</td>
</tr>
<tr>
<td>L-S</td>
<td>Straight</td>
<td>1200</td>
<td>0.75</td>
<td>40</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The single-fibre test setup is shown in Figure 1c. The pull-out tests were carried out on a 25 kN MTS 858 universal test frame. The fibre was clamped with a collet clamping nut from a CNC Milling Chuck holder. The gripping setup offered a stiff connection with no moving parts and ensured no slipping of the fibre during the pull-out test while not damaging the steel wire at the grip section.

The load was measured with a 10 kN load-cell, and three extensometers were used to measure the fibre displacement. The extensometers were placed vertically around the collet chuck, at 120° between each other and measured the relative displacement of the steel fibre and the surface of the concrete cube.

Each pull-out test was carried out using the following pull-out rates, based on recommendations on EN 14651:2006 for 3-point bending tests: i) the debonding phase, from 0 – 0.1 mm pull-out, was carried out at a rate of 0.05 mm/min, ii) the pull-out phase, in the range 0.05 – 4 mm, was executed at a rate of 0.25 mm/min, and iii) the complete pull-out, at a displacement larger than 4 mm, was executed at a rate of 1 mm/min. The sampling frequency of the data from the pull-out tests was 100 Hz.

Six specimens were tested for each fibre type at each maturity. The data gathered (i.e. load vs displacement) was post-processed: using a median filter and a moving average filter to reduce noise and smoothen the data. After this, the data was resampled to a 0.5 μm resolution. At last, a log-normal distribution was fitted to the data from each group of specimens with a 95% confidence interval.

The compressive strength and elastic modulus in compression of the cylinders was determined in accordance with EN 12390-3 and EN 12390-13, respectively; using nine specimens for each maturity.

The following notations are used to refer to the test specimens onwards: (HH) refers to the high-strength hooked-ended fibre, (HS) is the high-strength straight fibre, (LH) is the low-strength hooked end fibre and (LS) is the low-strength straight fibre. As suffixes 03, 07 and 14 are used for 3, 7- and 14-days maturity, respectively.

![Figure 1](image_url)

**Figure 1.** Dimensions of the specimen and test-setup: a) cross section showing the fibre placement in the mould, b) dimensions of the specimen before testing, and c) single-fibre pull-out setup.
3. Results

3.1. Mechanical properties of concrete in compression

The compressive strength and stabilised elastic modulus of the concrete at 3, 7 and 14 days of maturity are presented in Figure 2. The data shows a gradual development of both the compressive strength and stabilised elastic modulus increase over time, as expected from established knowledge. The increase of compressive strength is noticeably larger between 3 and 7 days than between 7 and 14 days. Whereas, the development of the elastic modulus is close to linear between 3 and 7 days and 7 and 14 days. Furthermore, there is a trend of decrease in the spread of the elastic modulus over time; whereas the compressive strength results at 7 days show a larger spread compared to values at 3 days.

Figure 2. Results of mechanical properties in compression of the hardened concrete over the maturity: a) compressive strength, and b) stabilised elastic modulus in compression.

3.2. Single-fibre pull-out tests

Single-sided single-fibre pull-out tests were carried out for the HH, HS, LH and LS fibres 3, 7 and 14 days after casting. The mean values and their corresponding 95% confidence intervals are illustrated in Figure 3. The figure presents the load vs pull-out displacement data in a range of 0 – 2.5 mm of pull-out; for the high-strength Figure 3a and low-strength Figure 3b fibres, respectively.

Figure 3. The displacement versus the pull-out load at different maturities for: a) high-strength fibres (HS and HH), and b) low-strength fibres (LS and LH). Full lines show the mean value, and dashed lines show the 95% CI bounds of the log-normal distribution.

For both cases, it is observed that the debonding peak occurs for both the straight and hooked fibres around 0.05 mm displacement. After the debonding, only the frictional resistance contributes to the pull-out resistance for the straight fibres. Whereas, for the hooked-end fibres, a decrease in pull-out load is observed before the mechanical anchorage is utilised.

The mechanical anchorage of the hooked-end fibres is responsible for the maximum peak loads observed for the HH and LH groups. After the maximum peak load, the hooked-end fibre begins its plastic deformation, which results in the decreasing pull-out load along the displacement. A large difference in peak load between hooked-end and straight fibres is observed. The pull-out behaviour for
high- and low-strength fibres appear similar although the high-strength fibres reach a larger maximum pull-out load, see Figure 3.

The spread of debonding loads and maximum loads for each fibre are illustrated in Figure 4. The load at debonding peaks are abbreviated “DP” and the maximum loads “Max”.

The data show a general tendency for an increase in pull-out load with increasing age. Furthermore, it can be seen that the maximum load for the straight fibres correspond to the debonding peak load for the hooked end fibres. It is observed that the maximum pull-out loads for the hooked-end fibres are significantly higher than the pull-out load for the straight fibres. However, the spread of the hooked-end fibres’ maximum pull-out load is generally larger than the debonding peak loads.

Figure 4. Boxplot showing pull-out loads at debonding peak and maximum value for each fibre.

Furthermore, the energy dissipated by the system during the pull-out of the fibre was calculated as the integral of the area below the load-displacement curve, resulting in the work-displacement curve, see Figure 5. The figure shows that the energy dissipation for the hooked end fibres is significantly higher than for the straight fibres. There is also a moderate increase in the pull-out work when comparing high-strength fibres Figure 5a, and low-strength fibres Figure 5b. Furthermore, it is observed that the total work increases gradually with the concrete maturity; being the increase more pronounced during the first 3 and 7 days of maturity. Whereas, no distinct increase between 7 and 14 days was observed.

Figure 5. The displacement versus work at different maturities for: a) high-strength fibres (HS and HH), and b) low-strength fibres (LS and LH). Full lines show the mean value, and dashed lines show the 95% CI bounds of the log-normal distribution.

4. Discussion

The discussion below focuses on describing the relationship between the development of the mechanical properties of the concrete and the pull-out loads of straight and hooked-end fibres. However, since the same tendencies were observed between the high-strength and low-strength fibres the discussion presented hereafter covers only the high-strength fibres tested (HH and HS).
The discussion is divided into two parts: the first part covers the variations of the fibre-matrix bond stiffness over the maturity of the matrix, and the second part describes the relation between the mechanical properties of the matrix and the maximum pull-out loads measured.

4.1. 

Variations of the bond stiffness over time

The stiffness of the fibre-matrix bond during the debonding process can be represented by the initial, linear-elastic branch of the load vs pull-out displacement plot. Figure 6 shows the first 25 µm of the pull-out load versus displacement for HH and HS fibres.

The elastic branch of the pull-out process was measured approximately along the first 10 µm of the pull-out process, being similar for hooked-ended and straight fibres, see Figure 6a and Figure 6b, respectively. After the end of the linear branch, there is a “process-zone” which may correspond to a progressive fracture of the bond, as described in (Bentur et al., 1985).

The data, presented in Figure 6, show that there is a clear increase in the bond stiffness after 3 days of maturity. Whereas, the comparison of the bond stiffness of the specimens tested after 7 and 14 days does not indicate a clear development at later ages.

Based on the previous discussion, the stiffness of the fibre matrix bond has been calculated for the initial 10 – 15 µm of the pull-out, where the fibre has not fully de-bonded from the matrix. The bond stiffness is calculated as the shear modulus, assuming a constant embedment length of 30 mm and disregarding the presence of deformed parts (i.e. the hook).

The bond stiffness for the HH and HS specimens is presented in Figure 7 as a boxplot for each of the maturities tested. The data show that there is a slight increase in the bond stiffness from 3 to 7 days, but there is no clear development at later ages, as shown by the limited difference between 7 and 14 days. Whereas, similar trends in the development are observed for hooked-end and straight fibres. Finally, there is a generally large spread of the results, that seems to increase with maturity and may be larger for hooked-ended fibres compared to straight ones.

4.2. Relation between the mechanical properties of the concrete matrix and the pull-out loads

The results and discussion presented so far have shown that there is a development over time of the initial stiffness and the work transferred during the pull-out process. Whereas, the data suggest that the development process decelerates with maturity, following a similar trend as observed for the mechanical
properties of the concrete matrix. Therefore, the maximum pull-out load of the HH and HS fibres are compared in this section to the compressive strength and elastic modulus of the matrix, in the error plots shown in Figure 8a and Figure 8b, respectively.

The comparison of the compressive strength of the matrix and the maximum pull-out force presented in Figure 8a, show that there is a slightly non-linear correlation between the HH fibre pull-out load of the fibre and the compressive strength of the matrix. Furthermore, it is seen that the regression lines for the HH fibres are parallel, while the HS fibre has a slightly steeper slope. The error plot illustrates the spread of the data on both axes, and the 7 days data show a large spread in both directions, especially along the compressive strength.

The data show that the pull-out load may continue to develop along with the compressive strength of the matrix. However, the data presented in Figure 2 show that the development of compressive strength already slows down after 7 days maturity, as expected from theory. Overall, the data illustrate that there is an evident correlation between the debonding load of the straight fibre (HS) and the compressive strength of the concrete, which suggests that there could be an overall correlation between debonding load and the strength of the concrete matrix.

Whereas, the correlation between the pull-out load of the high-strength steel-fibres (HH and HS) and the elastic modulus in compression of the matrix shows that there may be a linear correlation between the pull-out loads of the hooked-end fibre (HH) the elastic modulus of the matrix, see Figure 8b. However, there is a poorer correlation between the maximum load of the straight fibres (e.g. at full debonding) and the elastic modulus of the matrix.

The aforementioned discussion suggests that the debonding peak, which leads to the full rupture of the adhesive bond between the fibre and the matrix, may be controlled by the overall strength of the matrix, i.e. measured in this study as the compressive strength of the matrix. Whereas, the mechanical bond of the hooked-end fibres may be governed by the stiffness of the matrix, characterized in this study as the elastic modulus in compression of the bulk concrete matrix.

Therefore, these observations provide insight that the development of the fibre matrix bond over time may be estimated based on few pull-out experiments at specific reference ages and current strength development models for the mechanical properties of hardened concrete, such as the development model described in the Eurocode-2 (European Commission, 2002).

![Figure 8](image.png)

**Figure 8.** Correlation plots comparing the pull-out forces and mechanical properties of the matrix for the high-strength fibres (HS and HH), showing the correlation of: a) the compressive strength and the maximum pull-out load, and b) the Young’s modulus and the maximum pull-out load. The following abbreviations are used: (Max) maximum force, (DP) debonding peak, (0.5) slip value of 0.5 mm.

### 5. Conclusion

This paper investigated the development of the pull-out performance of steel fibres embedded in a concrete matrix over time and its correlation to the mechanical behaviour of the concrete matrix. The study comprised the investigation of the pull-out behaviour of four different types of fibre and the evaluation of the strength and elastic modulus of the matrix in compression, tested at ages of 3, 7 and 14 days.
The results showed that both the fibre pull-out resistance and the strength and stiffness of the matrix increased over time with the maturity of the matrix. Specifically, the adhesive bond behaviour of straight and hooked-end fibres developed significantly at early ages; shifting from a more plastic debonding failure at 3 days to a stiffer response after 7 days of maturity, not increasing significantly afterwards. Whereas, the total work transferred by hooked-end fibres increased gradually over time.

There was a direct correlation between the compressive strength of the matrix and the maximum pull-out resistance of the fibres as they develop over time. This correlation was linear for the straight fibres; whereas a non-linear trend was observed for the hooked-end fibres. Conversely, the elastic modulus had a linear correlation to the maximum pull-out resistance of hooked-end fibres; while the straight fibres showed a non-linear trend.

These observations suggest that the development of the fibre matrix bond over time may be estimated based on a combination of pull-out experiments at a reference age, the mechanical behaviour of the concrete matrix and current strength development models for the mechanical properties of hardened concrete. Specifically, by relating the pull-out resistance of hooked-end fibres to the stiffness of the matrix, and the debonding strength to the strength of the concrete matrix.

Further research investigating the development of the fibre-matrix bond during both longer curing times and early ages is needed in order to better understand and predict the development of fibre-matrix bond over time.

Acknowledgements

The contribution of the corresponding author was funded by: CowiFonden, InnovationsFonden, the German association of steel fibre producers (VDS), VejDirektoratet and Mapei-Denmark.

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