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# Time-dependent pull-out behaviour of hooked-end steel fibres in concrete

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ABSTRACT

The popularity of Fibre Reinforced Concrete (FRC) is increasing in the industry due to its property to resist crack initiation, to control crack widening and improve the mechanical properties of concrete. Numerous studies have been done on the mechanical behaviour of FRC subjected to short term loading conditions. Although studies have been performed on the long term loading behaviour, little information is still known about it, especially in the cracked state. Even though the fibres resist crack widening, it has been revealed that the crack opens significantly under sustained loading. This unknown behaviour is associated with time-dependent fibre pull-out. In this study the pull-out behaviour of single hooked-end steel fibres embedded in concrete was investigated under both sustained loading and pull-out under different loading rates. Four pull-out loading rates were considered ranging from 2.5 mm/s to 0.00025 mm/s. The sustained load tests were performed over a period of 249 days and the sustained load was varied from 30% to 85% of the maximum (short term) interfacial shear resistance. Finally, a model is proposed that is able to simulate both the long term and short term time-dependent single fibre pull-out behaviour.

## 1. Introduction

The concept of fibre reinforcement in concrete is not new [1]. The use of fibre-like materials such as horse-hair, straw and other vegetable fibres to strengthen brittle building materials, e.g. the clay bricks, can be traced back to more than 3500 years ago. Today more advanced type of fibres are available, namely glass fibres [2], carbon fibres [3], polymeric fibres [4] and steel fibres [5].

The performance of steel fibres has been found to be the most adequate fibre for structural concrete [1]. It is a common misconception by users of fibre reinforced concrete that by adding any amount of fibres will increase the tensile strength of concrete. Scholars have revealed that the addition of low volume steel fibres to concrete, typically ranging between 0.5 and 1%, does not significantly improve the tensile strength of the concrete but significantly improves the post-crack behaviour [6,7]. These studies are based on short-term loading conditions. However, the properties of concrete changes due to aging and the mechanical behaviour is dependent on the duration of loading. It is well known that the deformation of concrete structures under sustained loading increases significantly due to creep [8,9]. Therefore, creep deformation is an important factor to consider in the designing of concrete structures. The long term behaviour of Steel Fibre Reinforced Concrete (SFRC) has been investigated before. Bissonnette and Pigeon [10] and Bissonnette et al. [11] revealed that the addition of steel fibres tends to increase the tensile creep of uncracked concrete. In contrast Garas et al. [12] showed that the addition of short straight steel fibres decreases the tensile creep of uncracked Ultra-high Performance Concrete (UHPC). They proposed that the decrease in creep is due to the enhancements at the fibre/matrix interface during thermal treatment. It was only recently that the long term behaviour of cracked SFRC has been included in the investigations. Mouton and Boshoff [13] and Zhao et al. [14] are among the few that investigated the long-term crack widening of pre-cracked SFRC under sustained uni-axial tensile loading. Babafemi and Boshoff [15] did similar work on the creep of macro-synthetic fibre reinforced concrete. There is also research available on the long-term crack widening of pre-cracked SFRC under flexural loading [16–19]. These investigations revealed that even though the creep is similar to conventional concrete, the creep increased significantly after the concrete has cracked. This phenomenon is associated with the crack widening over time as a

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result of fibre pull-out. Typical Fibre Reinforced Concrete (FRC) structural design codes, e.g. *fib* Model Code [20], only considers the time-dependent behaviour of conventional concrete without fibres. This raises an important issue as typical FRC design codes would under predict long-term deflections. It is therefore vital that this is investigated.

Due to the relative small volume of fibres added in concrete, typically less than 1%, the fibres only contribute to the mechanical behaviour once the concrete has cracked. The effectiveness of a single fibre between randomly distributed fibres in a cement-based composite is often represented by a single fibre pull-out test, where the pull-out force is represented as a function of fibre slip [21–24]. The pull-out force-slip relationship of these studies is based on short term loading conditions. It is expected that the fibre/matrix interface is dependent on the duration of loading, due to the fact that the matrix properties is time-dependent. Babafemi and Boshoff [15] performed single fibre sustained load tests on macro-synthetic fibres and concluded that the time-dependent pull-out displacement is dependent on the sustained applied load. The pull-out was also found to be a combination of the fibre lengthening and the fibre pulling out. It is expected that time-dependent fibre lengthening will not occur for steel fibres.

Numerous investigations have been performed on modelling the single fibre pull-out behaviour. However, Cunha et al. [23] and Sujivorakul et al. [25] are among the few that have derived models to predict the pull-out force-slip relationship for hooked-end steel fibres. To the authors' knowledge no literature is available on methods to model single fibre pull-out behaviour when subjected to different loading rates and sustained loading.

Based on the above it is evident that the understanding of the time-dependent behaviour of cracked SFRC is not sufficient at a single fibre level. The main focus of this study is to assess the short and long term single fibre pull-out behaviour of hooked-end steel fibres. This includes both pull-out rate tests and sustained loading tests with the latter not available in literature to the authors' knowledge. The results derived from these assessments were used to develop a model that simulates the single pull-out behaviour for both quasi-static loading rates and sustained loading. The final aim of this work is to predict the time-dependent crack widening on the macroscopic level using this model of the single fibre behaviour presented here. This will assist in predicting and, eventually, designing for long term creep deflections of cracked SFRC structural members.

## 2. Experimental method

To investigate the time-dependent pull-out behaviour of steel fibres embedded in concrete and the mechanisms causing it, single fibre sustained loading and single fibre pull-out rate tests were performed. All tests were performed in a climate controlled room with a temperature of 23 ± 1 °C and a relative humidity of 65 ± 5%.

### 2.1. Mix composition and material properties

The materials used in the mix composition for SFRC were: Portland cement CEM I 52.5N supplied by Pretoria Portland Cement, Dynamon SP1 superplasticiser supplied by MAPEI South Africa, water, two types of aggregates [natural sand known locally as Malmesbury sand with a finess modulus (FM) of 2.3 and 6 mm crushed greywacke stone] and DRAMIX 3D-65/60-BG hooked-end steel fibres, supplied by BEKAERT in Belgium. Straight fibres were obtained by cutting the hooked-ends of the 3D-65/60-BG fibres with pliers. Care was taken to ensure that no rough edges were created after cutting the hooked-ends. The mix proportions and fibre properties (as supplied by the supplier) are given in Tables 1 and 2, respectively. Note that no fibres were added during the mixing process as a single fibre was embedded in each specimen only during the casting process.

A slump test [26] reading of 230 mm was determined for the mix design without any signs of segregation. The average compressive strength at 28 days assessed by four cubic specimens with an edge length of 100 mm and was 51.0 MPa with a coefficient of variation (COV) of 0.77%.

The single fibre pull-out specimens were cast and the fibres were carefully inserted vertically in the middle of the specimen to a depth of $l_f/4$ (15 mm). Thereafter the moulds were gently vibrated to ensure that no voids were formed between the fibre and the matrix. Specimens were demoulded after 24 h and then placed in curing baths at 23 °C for an additional 27 days. The specimens that were cast for the sustained load tests were taken out of the curing baths a day before testing. A 12 mm hole was then drilled on the opposite side of the specimen to the protruding fibre to a depth of about 40 mm. A 10 mm threaded bar was affixed in the holes with epoxy glue. The specimens were then left in the climate controlled room for a further 24 h before testing commenced.

### 2.2. Single fibre pull-out rate tests

Pull-out rate tests were performed on hooked-end and straight steel fibres to investigate the short term time-dependent pull-out behaviour. The pull-out rate was varied over four orders of magnitude ranging from 2.5 x $10^{-4}$ mm/s to 2.5 mm/s. The test programme is shown in Table 3 together with the number of specimens tested at each pull-out rate.

A specimen shape was designed so that it can fit in the hydraulic clamps of the test machine. 100 × 100 × 100 $mm^3$ cube moulds were modified in order that the specimens could be cast in a rectangular prism shape. The dimensions of the single fibre specimens are shown in Fig. 1.

The pull-out tests were performed in a Zwick Z250 Universal Materials Testing Machine that has a capacity of 250 kN. The specimens were gripped with the hydraulic clamps. The protruding fibre gripping setup was designed to ensure that the bond between

**Table 1**
Mix composition for SFRC.

| Material type | kg/$m^3$ |
|---|---|
| Cement (CEM I 52.5N) | 395 |
| Water | 190 |
| Sand (Malmesbury) | 990 |
| Stone (Greywacke = 6 mm) | 800 |
| Superplasticiser (0.5% by weight of binder) | 1.975 |

**Table 2**
Properties of DRAMIX 3D-65/60-BG hooked-end steel fibres (as provided by the supplier).

| | |
|---|---|
| Relative density | 7.85 |
| Modulus of Elasticity | 210 GPa |
| Tensile (strength on the wire) | 1160 MPa |
| Length ($l_f$) | 60 mm |
| Diameter ($d_f$) | 0.9 mm |
| Aspect ratio ($l_f/d_f$) | 67 |

**Table 3**
Test programme for single fibre pull-out rate tests.

| Pull-out Rate (mm/s) | 0.00025 | 0.0025 | 0.025 | 0.25 | 2.5 |
|---|---|---|---|---|---|
| No. of specimens (Straight) | 5 | 4 | 4 | 3 | 7 |
| No. of specimens (Hooked-end) | 5 | 7 | 8 | 6 | 9 |