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The response of cracked steel fibre reinforced concrete under various sustained stress levels on both the macro and single fibre level

P.D. Nieuwoudt, A.J. Babafemi, W.P. Boshoff *

Unit for Construction Materials, Department of Civil Engineering, Stellenbosch University, South Africa

HIGHLIGHTS

- The tensile creep of cracked SFRC is a function of the applied stress level.
- The creep has a linear relationship with load up to 50% of its capacity.
- The non-linear portion has been found to be due to micro cracking in the matrix.
- Single fibre pull-out creep tests show similar behaviour to the tensile creep tests.
- Fibres should be pre-slipped to simulate cracked conditions.

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ABSTRACT

If fibre reinforced concrete structures are to be accurately designed, an understanding of the time-dependent response under sustained loadings and in the cracked state must be well understood. It is known that the fibres pull-out with time under sustained loadings. However, the quantification of the pull-out creep is still understudied, particularly under uniaxial tensile loading. In this study, the tensile creep response of cracked steel fibre reinforced concrete under varying sustained stress levels has been performed. Furthermore, single fibre pull-out and pull-out creep tests were also undertaken to describe the mechanisms responsible for the crack widening of steel fibre reinforced concrete. The influence of fibre orientation angle, fibre mechanical anchorage, stress level, and fibre pre-slipping on the pull-out response at the single fibre level was also investigated. X-ray computed tomography (CT) scans of specimens subjected to pull-out creep tests are also shown to demonstrate the prominent mechanisms causing the time-dependent pull-out of steel fibres. All tests were performed under a controlled environment. The results of the investigations have revealed that the tensile creep of cracked steel fibre reinforced concrete increases as the stress level increases. X-ray CT scan images have shown that instantaneous pull-out is caused by the collapse of the interface between the fibre and the matrix. This damage to the interface also increases with time under sustained loading and increased load levels. At higher stress levels, pull-out creep increases due to micro-cracking at the region of the hooked end of the fibre.

1. Introduction

It is now common knowledge that the use of steel fibres in concrete production as a reinforcing material is steadily on the increase in the construction industry. The significant influence of steel fibres on conventional concrete regarding improved ductility, impact resistance, post-cracking strength (flexural or tensile), fatigue strength, resistance to spalling, delayed crack propagation, etc. is not in doubt. These significant improvements to the properties of concrete have been the subject of research in the last three decades and are well reported in the literature [1–6].

However, one area of fibre reinforced concrete (FRC) that is lacking sufficient knowledge in literature is its time-dependent behaviour under sustained loading. While attention is now drawn to the time-dependent behaviour of FRC, particularly in the cracked state [7–20], much still needs to be done to understand the time-dependent behaviour of FRC fully. Quantifying the creep and understanding the mechanisms responsible for the creep is of great importance. Limited studies have been done to determine the mechanism causing the time-dependent deformation of FRC.

Using the single fibre pull-out test method, Boshoff et al. [15] reported fibre pull-out as the mechanism responsible for the creep

* Corresponding author at: Civil Engineering Department, Stellenbosch University, Private Bag X1, Stellenbosch 7602, South Africa.

E-mail address: bboshoff@sun.ac.za (W.P. Boshoff).

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of a cracked polyvinyl alcohol (PVA) strain hardening cement composites (SHCC). Babafemi & Boshoff [17] reported fibre pull-out and fibre creep as the mechanisms causing the time-dependent crack widening of a cracked macro synthetic FRC under sustained loadings. Recently, Abrishambaf et al. [21] have reported the contribution of fibre pre-slipping, fibre orientation and fibre hooked-end on the pull-out creep of a steel fibre reinforced self-compacting concrete.

The pull-out mechanism of the fibre from the cement matrix, which leads to an increase in crack width has much to do with the fibre properties, cement matrix and the fibre-matrix interface. In this study, the tensile creep of cracked steel fibre reinforced concrete (SFRC) under different stress levels have been quantified over a period of 8 months. Furthermore, investigations on the effect of fibre orientation angle, fibre mechanical anchorage, stress level, and fibre pre-slipping (to simulate the pre-cracking at the macro level) on the pull-out response at the single fibre level have been performed. To fully understand the factors influencing the pull-out of fibres under sustained loadings, X-ray computed tomography (CT) scans have also been carried out on specimens tested for pull-out creep.

2. Experimental programme

2.1. Materials and mix design

The concrete mixture materials used to produce specimens for all the tests performed in this investigation are Portland cement CEM I 52.5N, with a relative density (RD) of 3.14, locally available fine (with a RD of 2.62) and coarse crushed aggregates (with a RD of 2.80) known as Malmesbury sand and Greywacke stone, respectively. Other constituents are hooked-end steel fibres, superplasticiser and portable water. The fine aggregate passed through a 4.75 mm sieve and had a fineness modulus (FM) of 2.3. For the coarse aggregate, at least 90% passed through the 6 mm sieve size and retained on the 4.75 mm sieve. The basis for the choice of the stone size is described in Babafemi & Boshoff [17]. Three types of hooked-end steel fibre, designated by Type A, Type B and Type C, have been used. The properties of the fibres, as provided by the supplier (BEKAERT in Belgium), are presented in Table 1. The superplasticizer, Dynamon SP1, supplied by MAPEI South Africa, and conforming to the requirement of EN 934-2 [22], was used to adjust the workability of the mixes.

The SFRC mixture proportions are shown in Table 2. Dry materials in the order of sand, cement and stone were added to the 50-litre pan concrete mixer (Gustav Eirich), mixed for a minute before the water and superplasticizer were added. Further mixing with all the constituent materials except the fibre was done for about 2 min. The specimens without fibres were cast after this stage. However, for SFRC mixture, the fibres (0.5% by volume) were gradually added over a minute to ensure they were well distributed and then mixed for another 2 min.

2.2. Mould and specimen preparation

It is acknowledged in the literature that performing a uniaxial tensile test is a difficult exercise [17,23]. In this study, to enable the ease of gripping and testing of uniaxial tensile specimens, specially designed steel hooks with eye-like connectors, which serve as anchors for positioning in the testing machine and tensile creep frame, were embedded into conventional 100 × 100 × 500 mm^3 steel moulds. A detailed description of the assemblage of the hooks into the moulds can be found in Babafemi & Boshoff [17]. A diagram of the finished mould and the casting procedure of the steel fibre concrete mixture is shown in Fig. 1.

Table 2
Mixture composition for SFRC.

Material type	kg/m^3
Cement (CEM I 52.5N)	395
Water	190
Sand (Malmesbury)	990
Stone (Greywacke, 6 mm nominal size)	800
Superplasticiser (0.5% by weight of binder)	1.975
Fibres (0.5% by volume)	39.25

After casting, specimens were demoulded after 24 ± 2 h, moved to a curing tank where they were cured by complete immersion in water at a temperature of 23 °C until an age of 28 days when testing commenced.

The single fibre pull-out test specimens were prepared from 100 mm cube moulds. The mould was divided into two halves with a wooden block to give a specimen size of 100 (L) × 40 (B) × 100 (H) mm as described in Nieuwoudt & Boshoff [20] and Babafemi & Boshoff [24]. It should be noted that concrete mix cast into the moulds have no fibres in it. Each of the three fibre types was carefully inserted to the pre-marked embedment length in the middle of the specimen. Thereafter, the moulds were gentle vibrated to ensure closure of void created during the fibre insertion. The fibres that were embedded at certain orientation angles were bent before the insertion of the fibres at the specific embedded orientation angles to be tested. All specimens were tested after curing in water for 27 days.

2.3. Test setups and programmes

In this study, four major categories of tests were performed: uniaxial tensile strength, uniaxial tensile creep, single fibre pull-out and pull-out creep tests. The compressive strength of concrete mixtures was also tested. The uniaxial tensile, uniaxial tensile creep and drying shrinkage tests are classified as macro level tests, while the single fibre pull-out and pull-out creep tests are the single fibre level tests. A summary of all tests conducted, fibre type used, main variables, number of specimens and specimen size is shown in Table 3. The specific details of each test are further described in subsequent sub-sections.

2.3.1. Compressive strength tests

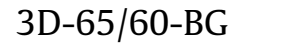
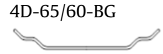
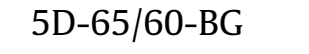
The compressive strength of concrete mixtures, with (Type A fibre only) and without fibres, were carried out according to the requirements of EN 12390 [25] using 100 mm cube specimens. The test was performed at a loading rate of 0.3 MPa/s using a Contest Materials Testing Machine with a capacity of 2000 kN. Thirty specimens from eight mix batches were tested for the plain concrete, while sixteen specimens from three batches were tested for the SFRC.

2.3.2. Uniaxial tensile test

Several indirect tests exist to determine the tensile properties of concrete. However, the uniaxial tensile test is believed to be the most appropriate method for obtaining the tensile properties of concrete [26–28]. Wille et al. [29] report a review of some existing test methods. For this study, the setup for obtaining the post-cracking behaviour of the SFRC regarding stress-crack width, σ-w, relationship, is shown in Fig. 2. This test was performed in a Zwick Z250 Universal Testing Machine that has a capacity of 250 kN. Note that only Type A fibre was used in the uniaxial tensile tests.

Prior to testing specimens on the 28-day, a circumferential notch, with a depth of 10 mm, was made with a 3 mm diamond blade at the centre of the specimens, giving an effective cross-section area of 80 × 80 mm^2. The displacement reading of the crack width was acquired with two HBM Linear Variable Displacement Transducers (LVDTs), placed on adjacent to each other on two planes of the specimen. The LVDTs were attached to the specimen using a removable aluminium frame with a gauge length of 100 mm. The specimens were pre-loaded to 1 kN to stiffen the

Table 1
Properties of hooked-end steel fibre.

Fibre type	A	B	C
Trade name: DRAMIX	3D-65/60-BG	4D-65/60-BG	5D-65/60-BG
Profile			
Tensile strength (on the wire) [MPa]	1160	1500	2300
Relative density	7.85	7.85	7.85
Modulus of elasticity [GPa]	210	210	210
Length (l_f) [mm]	60	60	60
Diameter (d_f) [mm]	0.9	0.9	0.9
Aspect ratio (l_f/d_f)	67	67	67