Construction and Building Materials 174 (2018) 466–473

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Pull-out creep mechanism of synthetic macro fibres under a sustained load

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HIGHLIGHTS

- Polypropylene and modified olefin macro fibres both show significant pull-out creep.
- This pull-out creep is a combination of fibre lengthening and end-slip.
- Embossed fibres has less pull-out creep than non-embossed fibres.
- X-ray CT scans show that the end-slip is far less than the fibre lengthening.

ARTICLE INFO

Article history:
Received 2 July 2017
Received in revised form 17 April 2018
Accepted 18 April 2018

Keywords:
Fibre pull-out
Fibre creep
Synthetic macro fibre
Macro-synthetic fibre reinforced concrete
Time-dependent fibre pull-out

ABSTRACT

The creep of cracked fibre reinforced concrete is still being investigated for incorporation into design guidelines. While the mechanism responsible for the time-dependent crack opening of steel fibre reinforced concrete has been associated with the fibre pull-out, a combination of pull-out creep and fibre creep have been reported for macro-synthetic fibre reinforced concrete. However, these phenomena are yet to be fully understood. In macro-synthetic fibre reinforced concrete, two possibilities exist: simultaneous occurrence of pull-out creep and fibre lengthening occurring within the matrix under sustained loading, or pull-out creep followed by fibre lengthening due to creep. This study investigates these phenomena. Single synthetic macro fibres were embedded into 50 mm cube cement-mortar samples and subjected to 50% of the average maximum pull-out load obtained from the single fibre pull-out tests. All tests were conducted in a controlled climate room. X-ray computed tomography (CT) images of samples were taken at different time intervals to assess the phenomena responsible for the increased crack widening in macro-synthetic fibre reinforced concrete. The results obtained have shown that the phenomena associated with the increased crack widening of cracked macro-synthetic fibre reinforced concrete are a simultaneous interplay of fibre pull-out and lengthening within the matrix. It is significant to note that fibre lengthening is a prominent mechanism.

1. Introduction

As the use of short, discrete fibres in concrete applications continues to see increased usage in the construction industry, research is also being intensified to fully understand the behaviour of fibre reinforced concrete (FRC), and the mechanisms associated with observed responses under different test conditions [1,2]. Fundamentally, fibres toughen concrete, thereby controlling crack propagation by bridging crack plane. Furthermore, the effectiveness of the fibres in crack control is hinged on several factors bordering around the concrete matrix, the fibre type (including geometry and orientation), and the fibre/matrix interface.

The failure mechanism in a cracked FRC element is primarily a result of the fibres pulling out or fracturing under load [3,4]. The failure mechanism is, however, dependent on the type of fibre and the fibre/matrix bond strength among others. With steel fibres, complete fibre pull-out is typically experienced [5–8]. The rupturing of steel fibre has been reported in some cases to be due to snubbing effect [9] and crimped configuration [10]. In an autoclave reactive powder concrete, images from the SEM photos revealed that steel fibre rupture occurred due to improved hydration reactions and the tobermorite gel congestion in the fibre-matrix interface [11]. Steel fibre rupture was also reported in an alkali-activated slag cements (AASC) based composites [12]. The rupture

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https://doi.org/10.1016/j.conbuildmat.2018.04.148
0950-0618/

was attributed to its high drying shrinkage values, different microstructure and fresh state properties. Furthermore, Khabaz [13] observed the rupture of corrugated steel fibre due to higher embedment length. The phenomena associated with the pull-out of steel fibres have been described by several authors [10,14]. On the other hand, for synthetic macro fibres, which are known to have a poor bond with cement/concrete matrix due to their hydrophobic nature, the failure mechanism is typically by complete fibre pull-out [15]. However, fibre rupture has been reported for synthetic micro fibres where a chemical bond is present [16].

Several studies have assessed the performance of macro-synthetic FRC, usually, in comparison to steel fibres [17–22]. Others have discussed the single fibre pull-out mechanism of synthetic fibres from cement matrix in a quasi-static test [15,23–29]. Since structures are subjected to time-dependent loading, creep becomes a necessary factor for consideration when dealing with FRC. When synthetic macro fibres are used to reinforce concrete elements, significant creep caused could be expected [30].

Some studies have been conducted at the single fibre level to understand the mechanisms responsible for the time-dependent crack opening of cracked synthetic FRC elements [30–32]. The two primary mechanisms have been identified as pull-out creep and fibre creep. The study by Boshoff et al. [31] revealed that the creep of polyvinyl alcohol (PVA), a micro synthetic fibre, had no significant contribution to the time-dependent crack opening of the cement-based composite tested. However, Babafemi & Boshoff [30] and Vrijdaghs et al. [32] have reported that the creep of macro synthetic fibre significantly contributes to the time-dependent crack opening of FRC elements under sustained loadings. There is a significant difference between the creep of crack synthetic fibre reinforced concrete compared to the use of steel fibres. As steel is known to have little to no creep, the main mechanism is fibre slipping/pull-out while with synthetic fibres, the main mechanism is the fibres lengthening combined with fibre pull-out [2,15,30].

Though these failure mechanisms (pull-out creep and fibre creep) are known, the creep failure of macro synthetic FRC is not yet fully understood. Some phenomena could be associated with the pull-out creep mechanism. The first is the fibre pull-out creep upon the application of sustained load followed by the creep of the pulled out portion of the fibre. Secondly, a simultaneous pull-out creep and fibre creep could occur within the matrix with the fibre also creeping outside the matrix. Still, fibre creep could occur upon the application of sustained load followed by pull-out creep and then creep of pulled out fibre. Whichever the case, the time-dependent lengthening is a function of the low elastic modulus of the fibre, while the pull-out creep could be a function of the fibre material, geometrical properties, surface configuration and shape if the matrix composition is kept constant.

In this study, an investigation of the phenomena associated with the time-dependent fibre pull-out of synthetic macro fibre from cement matrix has been carried out. The study has been conducted using three types of synthetic macro fibres with a different configuration and geometrical properties. Instantaneous single fibre pull-out tests were performed to determine the average maximum pull-out load. After that, pull-out creep tests of single fibres embedded in mortar matrix subjected to a fraction of the average maximum pull-out load were quantified. To gain further insight into the phenomena associated with the failure mechanisms, samples subjected to creep loads were subjected to X-ray computed tomography (CT) scans to relate the pull-out creep of the fibre from the external surface to the internal creep (within the matrix). The review of micro-CT scanning for applications in the materials sciences [33] and an example of porosity analysis in concretes is given in Du Plessis et al. [34].

2. Experimental programme

2.1. Materials and concrete mix

The concrete materials and proportion used for the preparation of the concrete mix are shown in Table 1. The cement, CEM I 52.5N, had a relative density (RD) of 3.14, while the crushed stone and natural sand, locally known as Greywacke stone and fine Malmesbury sand had relative densities of 2.72 and 2.62, respectively. The fine Malmesbury sand, passing through a 2.36 mm sieve, has a fineness modulus of 1.14, while the coarse aggregate passed through a 9 mm sieve size but retained on 4.75 mm. Since all tests for the investigation were performed at the single fibre level, no fibre was added to the concrete mixture. However, the mixture was designed as though fibres were to be added, and hence a superplasticiser, Chryso® Fluid Optima 206, supplied by Chryso, South Africa, was added to enhance workability.

After the preparation of the fresh concrete mix, the slump value was measured using Abrams cone according to the requirement of EN 12350-2 [35]. A slump value of 145 mm was obtained.

2.2. Synthetic macro fibres

Three types of synthetic macro fibres were used. The fibres and their properties are shown in Fig. 1 and Table 2. The equivalent diameter (d_{eq}) was calculated following the procedure outlined in EN 14889-2 [36]. Fibres 1 and 3 have continuously embossed surface configuration while Fibre 3 is crimped. A handful of each fibre type was added to the concrete mixture during mixing to simulate actual fibre condition as the aggregates in the mix damages the surface of the fibre during mixing [37]. This pre-damaging of the fibres during mixing was done for 3 min.

All fibres were added to the concrete mixtures at the same time for uniformity in mixing condition and time. The fibres were later handpicked during sieving (4.75 mm sieve) of the concrete mixture to obtain mortar paste. After that, the fibres were washed and marked to the required embedment length.

2.3. Sample preparation

Samples were prepared for two sets of tests: quasi-static fibre pull-out and fibre pull-out creep. The fresh concrete mixture was sieved to eliminate the stones using a 4.75 mm sieve to obtain only the mortar paste. Sieving off the stones aided the easy insertion of the flexible fibres into the paste. The samples for the quasi-static fibre pull-out test have dimensions of $40 \times 40 \times 100$ mm^3. The samples were obtained by using a wooden separator in a 100 mm cube size mould as shown in Fig. 2a). The paste was then cast into the moulds and vibrated using a vibrating table. On the other hand, the samples for the pull-out creep test were prepared by casting the mortar paste into 50 mm cube steel moulds. Pre-damaged fibres, which had already been marked to 20 mm, were then manually inserted into the midpoint of the surface area of each sample. The moulds were gently vibrated to ensure the closure of voids created during the insertion of the fibres. The fibres were adjusted manually and visibly checked to ensure they were perpendicular to the surface of the matrix. Cast samples are shown in Fig. 2b). All test samples were demoulded after 24 h and cured in water at a temperature of 25 °C until testing.

Quasi-static fibre pull-out tests were conducted on the 28-day, while the pull-out creep tests commenced on the 29-day after the samples were left in the climate-controlled room for 24 h. Ten numbers of 100 mm cube samples were also cast and tested for compressive strength. The compressive strength tests were performed according to the requirement of EN 12390-3 [38].

2.4. Single fibre pull-out test

Except for different sample size and fibre clamping device used in this study, the single fibre pull-out test setup has been previously reported in Babafemi & Boshoff [15]. A clamp was fabricated with two flat steel plates (40×40 mm^2) to grip the fibre. A 2 kN capacity load cell was attached to the setup to measure the applied load. The fibre portion protruding from the matrix was clamped as close as possible to the surface to eliminate any elastic elongation of the free length. Pull-out displacement during the test was measured using two 50 mm linear variable displacement transducers (LVDT), which were supported by polyvinyl alcohol (PVC) strip attached to the test setup as shown in Fig. 3. The pull-out tests were

Table 1
Mix composition and proportion of concrete materials.

Material type	Volume (kg/m^3)
Cement (CEM I 52.5 N)	370
Stone (Greywacke = 9 mm)	891
Sand (fine Malmesbury)	891
Water	204
Superplasticizer (0.8% by wt of binder)	2.96