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The effect of mixing on the performance of macro synthetic fibre reinforced concrete

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ABSTRACT

Concrete suffers from brittle failure due to its low tensile strength. This drawback can be compensated for by adding reinforcement bars and/or steel fibres, and more recently, macro synthetic fibres. When mixing concrete with these fibres the aggregates could damage the fibres. This paper presents work done on the effect of mixing on the performance of macro synthetic fibre reinforced concrete. Single-fibre pull-out tests were conducted on various fibres in both the original and mixed state. Furthermore, flexural tests were performed to investigate the influence of mixing time and mixer type on the performance. It can be concluded that mixing is beneficial for flat type fibres, but the performance of crimped or embossed fibres remains the same. Furthermore, longer mixing times (> 10 min) in a pan mixer are detrimental to the performance, while the performance in a tilting drum mixer remains unchanged even after a mixing time of 60 min.

1. Introduction

Even though concrete is globally the most widely utilised building material, it still has certain shortcomings. These include low tensile strength in comparison to compressive strength, as well as its brittle failure in uni-axial or flexural tension. This results in structural design models not including the tensile strength of concrete [1,2]. In order to compensate for this, high tensile strength steel reinforcing bars are typically included. However, due to disadvantages regarding steel reinforcing, such as durability issues in corrosive environments [3–5] and being labour and time-intensive, fibre reinforced concrete (FRC) has been developed as a partial alternative [6–8].

FRC is becoming more widely used in the civil engineering field due to its favourable mechanical properties [6–9]. In particular, fibres increase the toughness of concrete, i.e. providing concrete with a significant residual tensile strength in the cracked phase, due to fibres bridging across crack surfaces [10–12]. Recently, more work is also done on the tensile creep of cracked FRC sections as this creep can increase deflections of structures where fibres are used as the primary reinforcement [13–16]. For most structural applications of FRC, steel is preferred as a material for fibre reinforcement, however, macro synthetic fibres have been developed and successfully introduced to the construction industry [17–19]. The use of macro synthetic fibres in concrete slabs-on-grade has become one of its primary applications [20]. However, the addition of fibres to concrete slabs-on-grade is only beneficial if a yield-line design approach is followed [21,22].

Properties of synthetic fibres are crucial to their performance in cement-based composites such as concrete. As the fibre contents are relatively low (normally < 1% by volume), fibres should possess strength characteristics exceeding that of the surrounding cement matrix as well as have a high aspect ratio [23,24]. Due to fibres working in tension, lateral fibre contraction occurs as a result of longitudinal fibre elongation, ultimately breaking the bond between the fibre and the surrounding concrete matrix. Mechanical interlock can be used to increase the bond characteristics between the fibres and the surrounding matrix. Synthetic fibres have shown to perform worse than steel fibres in the tensile creep of cracked sections [15,25], however, this is only a problem with high, long term loading of a cracked section, which is typically not the case for slabs-on-grade.

Previous research [26] to determine an optimal fibre shape using single-fibre pull-out tests on different existing macro-synthetic fibre geometries, concluded that crimped fibre geometries produce the most promising results. More recent studies [27,28] indicated that the type of fibre deterioration and the degree of deterioration experienced during mixing of fresh FRC is dependent on the parent material, production technology, fibre coating, size and the surface of the fibre. The study also established that the tensile strength of macro-polymer fibres decrease as mixing time increases and that the post-cracking flexural performance of FRC decreases as the mixing time increases for the same fibre type and dosage. Finally, the study concluded that the degree of mechanical deterioration of fibres and the number of deteriorated fibres increase as the mixing time increases.

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To the authors' knowledge no work has been published on the effect of mixing on the single-fibre pull-out behaviour of macro synthetic fibre reinforced concrete. In this paper an in depth study is done on the effect of damage caused by mixing on the single-fibre pull-out behaviour of macro synthetic fibres as well as the effect of the mixing time and type of mixer on the flexural behaviour of macro synthetic fibre reinforced concrete.

2. Methodology and experimental framework

In order to investigate the effect of mixing on the performance of macro synthetic fibre reinforced concrete, single-fibre pull-out tests and flexural tests were performed. The single fibre pull-out tests were conducted to compare the single-fibre performance of different macro synthetic fibres with various geometries in their virgin and mixed fibre state. Flexural tests were conducted to investigate the flexural performance of macro synthetic fibre reinforced concrete for one macro synthetic fibre type by taking account of different mixing times and two different mixer types.

2.1. Materials

A concrete mix yielding a compressive cube strength of 38.2 MPa was used for all single fibre pull-out tests. A CEM II/A-L 52.5 N Portland composite cement was used as binder with a natural pit sand (locally known as Malmesbury sand) and Greywacke crushed stone as coarse aggregate with a nominal size of 13 mm. The mix proportions and constituents are shown in the left-hand side of Table 1.

In order to facilitate the manual insertion process of the macro synthetic fibres, the fresh concrete was sieved (2.36 mm sieve) directly after mixing in order to retain a mortar. For fibres with 50 mm length three insertion depths were chosen (with denotations in brackets), i.e. 12.5 (L12.5), 25 (L25) and 37.5 mm (L37.5). Fibres with lengths other than 50 mm were also additionally embedded one half of the respective fibre length (LH).

The fibres used were either embedded in a virgin state, referring to the original condition as received by the suppliers, or in a mixed state. Mixed fibres were subjected to 5 min of mixing in a rotating pan mixer, followed by a rinsing process using water to firstly separate the fibres from the concrete and then remove any form of debris or surface deposits on the fibres. The fibre characteristics, as given by the suppliers, are listed in Table 2. All the fibres in Table 2 were used for the single fibre pull-out tests, except the CHRYSO fibre which was used for the flexural tests investigating the mixing time and mixer type.

For the flexural performance evaluation of macro synthetic fibre reinforced concrete after prolonged periods of mixing, a different mix design was used to be more representative of concrete mixes typically implemented for industrial flooring applications. A CEM II/A-L 52.5 N Portland composite cement was used as binder with a water/binder ratio of 0.55. The fine aggregate comprised of a 60:40 ratio by mass between a dune and crusher sand while the coarse aggregate was a Greywacke crushed stone with a nominal size of 19 mm. The mix design is shown on the right-hand side of Table 1.

Table 1
Concrete mix proportions and constituents.

Single-fibre pull-out test		Three point flexural test	
Constituent	Mass [kg/m^3]	Constituent	Mass [kg/m^3]
CEM II/A-L 52.5 N	319	CEM II/A-L 52.5 N	309
Potable water	204	Potable water	170
13 mm Greywacke Stone	996	19 mm Greywacke Stone	1088
Natural pit sand	873	Dune sand	512
		Greywacke crusher sand	356
		Fibre	4.0
		Plasticiser (CPO134)	2.3
		Superplasticiser (CFR)	max 5.15

A water reducing agent (plasticiser) with trade name CHRYSO Plast Omega 134 (CPO134), which is a hybrid PCE/Lignosulphonate, was added to provide suitable workability. Due to the mixing process, especially for prolonged mixing times, a slump revival admixture with tradename CHRYSO Fluid Rescue (CFR), which is a modified phosphonate polymer, was incorporated. CFR is a high range water reducing agent (superplasticiser) and results in plastic conditions being maintained for an extended time period. The dosage of the slump revival admixture was adjusted for each mixing time as required. The target slump was a value between 50 and 160 mm, workable enough to ensure good compaction. The slump readings were always taken just before the specimens were cast.

For investigating the flexural performance of macro synthetic fibre reinforced concrete, only one macro synthetic fibre type was considered at a constant fibre content of 4.0 kg/m^3 corresponding to a volume fraction (V_f) of 0.43%. This polypropylene fibre, an experimental fibre by CHRYSO, was supplied in a collated, fibrillated form, with a twisted profile and a rectangular cross-section. Table 2 provides the properties of the fibre, as obtained from the supplier.

2.2. Single-fibre pull-out test

Single fibre pull-out tests were conducted to evaluate the interfacial bond achieved by different macro synthetic fibres with various geometries and surface deformations, as well as the effect of damage on the fibre surface caused by mixing.

A 100 mm cube mould was used by inserting a wooden cross to divide the mould into four samples with dimensions of 39 × 39 × 100 mm^3 each. One sample is shown in Fig. 1a). After filling the voids with a sieved mortar, the fibres were carefully inserted to the correct length and re-vibrated slightly to ensure good packing around the fibre. Samples were placed in water at 25 °C at around 24 h after casting and then cured until an age of 28 days.

The concrete sample was held in place at the bottom of the Zwick Z250 universal testing machine by pneumatic operated steel grips. The fibre portion protruding from the mortar matrix was gripped using a clamp consisting of a steel plate fastened to the gripping device, as shown in Fig. 1b) and c). The fibre was gripped as close as possible to the mortar surface in order to eliminate any elastic fibre elongation of the free length. The load cell used has a capacity of 500 N while two 50 mm spring Linear Variable Differential Transformers (LVDTs) were used to measure the actual fibre pull-out displacement. The tests were controlled by the crosshead displacement at a rate of 0.2 mm/s. The rate does influence the pull-out behaviour [14], therefore it is important that all tests are done at the same rate to enable objective comparison between the different fibres.

All the fibres in Table 2 except the CHRYSO fibre were tested using the single fibre pull-out tests. Eight fibres were tested of each fibre type in the virgin state while twelve fibres of each were tested in the mixed state. More fibres in the mixed state were tested to account for potential variability in the test results caused by the additional surface roughening.

2.3. Flexural tests

To investigate the effect of mixing time on the performance of macro synthetic fibre reinforced concrete, flexural tests were performed according to EN 14651 [29]. The adopted flexural test setup is shown in Fig. 2. The setup consists of two supporting rollers, 500 mm apart and one loading roller located at mid-span. A load cell of 250 kN was used together with a crack opening displacement extensometer, which was used to measure the crack mouth opening displacement (CMOD). The extensometer was mounted along the longitudinal axis at mid-width of each test specimen using two knife edges glued to the bottom surface.