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Pull-out response of macro synthetic fibre from concrete matrix: Effect of loading rate and embedment length

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HIGHLIGHTS

- Pull-out load of synthetic macro fibre from a cementitious matrix is rate sensitive.
- The fibre pull-out load increases as the fibre embedment length increases.
- Major failure mode of synthetic macro fibre is by complete pull-out from matrix.
- Uniform bond model is not valid for crimped synthetic macro fibres.

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ABSTRACT

The single fibre pull-out response of macro synthetic fibre from concrete matrix has been investigated and reported in this study. Particular attention has been given to the response of the interfacial shear resistance between the matrix and fibre to loading rate at different fibre embedment length. One mix design and one fibre type have been used throughout the experiment while four orders of magnitude of loading rate and three embedment lengths are the variables evaluated. The effect of loading rate on the tensile strength of the macro synthetic fibre under four order of magnitude of loading rates is also reported. All tests were conducted in a controlled climate room at a temperature of 23 ± 1 °C and a relative humidity of 65 ± 5%. Experimental test results have shown that the ultimate tensile strength of the fibres is dependent on the loading rates. Pull-out behaviour from concrete matrix is shown to be slip softening and sensitive to loading rate and embedment length. All fibres pulled out of the concrete matrix without fracturing. Pull-out load increases as the loading rate and the embedment length increases.

1. Introduction

It is now a common knowledge that fibres' bridging activity is triggered only after a cementitious material deforms and a crack is formed. The increase in the energy absorption capacity and ductility of a fibre reinforced cementitious composite after crack initiation is dependent on the interaction between the fibre and the cementitious matrix. The vicinity of this interaction between the fibre and the matrix has been described as the interfacial transition zone (ITZ). In fibre reinforced concrete (FRC), several factors influence the bonding between the fibre and matrix at the ITZ; those related to the fibre properties – fibre type, fibre geometry, fibre surface deformation, fibre strength, fibre diameter, fibre length, elastic modulus, fibre aspect ratio, and those related to the properties of the cement matrix. These factors ultimately influence the overall deformation behaviour of the composite material under load. The failure of the ITZ between the fibre and the cementitious matrix dictates the failure of the composite material leading to either a complete fibre pull out or fibre rupture. Whereas chemical and frictional bonds are formed between fibre-matrix interface using hydrophilic fibres, with steel and hydrophobic fibres, only frictional bond exist at the ITZ [1].

When dealing with synthetic fibre reinforced concrete, the frictional bond is independent of the grade of concrete but majorly dependent on the type and properties of the fibre [2,3]. For steel fibre reinforced composites, good bonding property (load transfer ability) with cement matrix resulting in improved energy absorption capacity under load has been reported [4–8]. Steel fibres with deformed and hooked end configuration have particularly resulted in slip-hardening responses under pull-out load from the cement matrixes in certain cases. Though synthetic macro fibre is increasingly being used for reinforcing concrete in ground slab, precast members and shotcreting, however, due to its hydrophobic nature,

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low elastic modulus and tensile strength compared to steel, straight synthetic macro fibre has been reported to have poor bond strength with cement matrix [9]. In a bid to improve the bonding characteristics of synthetic macro fibre with its cement matrix, different geometric shapes have been investigated [9,10]. Modification to the surface geometry of such fibres from straight to a deformed configuration has been reported to increase the fibre-matrix interface shear resistance [8,11–13]. The interface shear resistance has become accepted as one of the major property for characterising the fibre-matrix adhesion level of fibre reinforced composites [14]. This is because it reflects the stability of a propagating crack in the fibre reinforced composite.

While few studies on the synthetic fibre pull-out behaviour from cement matrix have been undertaken under static loading [9,15–17], the effect of loading rate and embedment length on the interfacial shear resistance have not been fully investigated. Steel fibres have been reported not to be sensitive to rate effects and the fibre-matrix interface less sensitive in steel fibre reinforced composites [1], though this is dependent on whether it is straight or has hooked end [18]. The same cannot be said of hydrophobic fibres which are quite sensitive to rate effects [1,15] due to their viscoelastic nature, and this response is expected to influence the interfacial shear resistance of the ITZ.

With the development of new geometrical shapes and surface configurations of synthetic macro fibres to enhance the energy absorption capacity of fibre reinforced composites, the need for more experimental investigations cannot be overemphasised. The synthetic macro fibre used in this study has an X-shaped cross-sectional area profile with a slightly crimped configuration, and it has been designed to enhance the mechanical bond between the fibre and the matrix. The fibre is also known to be resistant to alkaline environment and does not corrode in the cement matrix. A study of the fibre-matrix interface using the single fibre pull-out test will help to simulate the crack bridging capability of this fibre. Again, an understanding of the pull-out response can be correlated to the composite material behaviour at both macro and structural levels.

This study has investigated the response of the interfacial shear resistance of synthetic macro fibre pulled out from concrete matrix to different loading rates at varying fibre embedment lengths. After the single fibre pull-out tests were performed, pulled out fibres have also been subjected to scanning electron microscopy (SEM) to assess the effects of the pull-out rate on the surface of the fibres.

2. Experimental investigation

2.1. Materials and concrete mix

To investigate the pull-out response of the fibre from concrete matrix by observing the effect of loading rate and embedment length, one type of synthetic macro fibre (polypropylene) and concrete mix design has been used. The properties of the fibre (as received from supplier) and the mix design reported elsewhere [19] are presented in Tables 1 and 2.

Table 1
Properties of polypropylene macro-fibre.

Specific gravity	0.88–0.92
Modulus of elasticity	4.3 GPa
Colour	Translucent
Elongation at yield	15–25%
Tensile strength	400 MPa
Melting point	150–170 °C
Length (l_f)	40 mm
Nominal diameter (d_f)	0.8 mm
Aspect ratio (l_f/d_f)	50

Table 2
Mixture proportion of concrete.

Material type	kg/m^3
Cement (CEM I 52.5)	395
Stone(Greywacke = 6 mm)	800
Sand(locally known as Malmesbury)	990
Water	190
Superplasticizer (0.2% by weight of binder)	0.79

Most fibre pull-out investigations available in literature were carried out using mortar as the matrix. However, concrete matrix with finely grained coarse aggregate (6 mm) has been used for this study rather than mortar. The finely grained coarse aggregate was used to simulate a mixture that allows for good fibre distribution according to the Kobayashi and Cho [20]. It is acknowledged though that larger coarse aggregate sizes could also be used to achieve good fibre distribution. It should be remarked that fibres were not added to the concrete mix except for the embedded fibres. As earlier mentioned, the fibres used for this investigation have an ‘X’ profile and slightly crimped along its length (Fig. 1).

2.2. Specimen preparation

The test specimens were prepared from 100 mm cube moulds. The moulds were divided into two halves with a wooden block measuring 100 × 100 × 40 mm^3, giving two specimens from each mould. The fresh concrete mix was cast into the moulds and vibrated on a vibrating table for about 60 s. Thereafter, fibres were carefully inserted by hand into the matrix at mid-point of the cross-sectional area of each specimen to the designated embedment length. The moulds were then gently vibrated again to close up the voids created during the insertion of the fibres. Adequate care was taken throughout the exercise to ensure verticality of the fibres. Specimens were then moved to a safe place in the laboratory where samples were undisturbed until demoulding after 23 ± 1 h. The demoulded specimens were transferred to the curing tank where they were cured in water at 21 °C for additional 27 days by complete immersion. The test specimens with inserted fibres are shown in Fig. 2.

2.3. Single fibre pull-out test

For ease of testing and repeatability of the experiment, a simple test setup was developed (Fig. 3). All tests were performed in a Zwick Z250 universal testing machine. The specimens were held

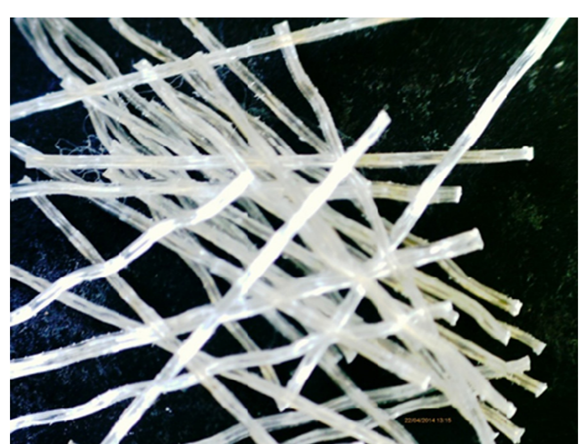

Fig. 1. Polypropylene macro fibres showing crimped configuration.