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Pull-out behaviour and interface critical parameters of polyolefin fibres embedded in mortar and self-compacting concrete matrixes

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HIGHLIGHTS

- The parameters that describe polyolefin fibres pull-out behaviour are reported.
- The critical length of polyolefin fibres was close to 20 mm in a concrete matrix.
- The results obtained can be used as benchmark for modelling or design assumptions.
- Micrographies showed sound interface between polyolefin fibres and cement paste.
- Pull-out work and load of polyolefin fibres were similar to those of steel fibres.

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ABSTRACT

Polyolefin based macro-fibres have proved their good performance for the structural reinforcing of concrete with fracture behaviour comparable to that of steel fibres but being chemically stable. Their adhesion to cementitious matrix is enhanced by surface treatments and embossed shapes. However, there is a lack of research about their pull-out behaviour and microstructural interface property. In this study, pull-out tests were designed by synchronising the testing machine with a video-extensometer device. The tests were performed with polyolefin fibres embedded on mortar and self-compacting concrete specimens. Six embedded lengths were used, with their inclination varying from 0° to 60°. The results provided significant information about the pull-out load and the energy absorbed in the process. Microstructural analyses provided a detailed view of the interface between polyolefin fibre and cement paste. The continuity between CSH gel and polyolefin fibres exhibited a sound interface between polyolefin fibres and cement paste, without either voids or discontinuities.

1. Introduction

Among the significant developments in concrete technologies during the last decades, fibre reinforced concrete (FRC) has been one of the most relevant fields for research [1]. Considering that concrete is a composite material with a wide variety of advantages but for its low tensile strength, it is not surprising that both research and practice have added fibres of sizes of the same order of the aggregates to improve its tensile response. During the fracture processes in FRC, the crack is intercepted by randomly oriented fibres that, in the case of having enough embedded length, prevent crack growth. Such fibre bridging depends on the efficiency of the fibre–matrix interface property [2]. Regarding this inter-relationship, the shape of the fibre has been widely used in order to provide mechanical anchorages that increase the energy needed to extract the fibre from the matrix. However, the general effects that govern the process of pull-out are the bond adhesion and interfacial shear stress along the fibre–matrix interface. Some other significant effects are also needed to assess pull-out behaviour, such as the influence of the inclining angle and the achievement of the critical embedded length in which the fibre acts in all its tensile capacity [3,4]. Enhancement of fibre-pull-out has been at the centre of research, especially given that the possibilities to improve the post-cracking response of FRC are directly related. While research has encompassed a large variety of shapes and constituent materials of the fibres [5], it is possible to obtain relevant information by means of pull-out tests applied either to ease the selection of the fibre type or improve the fibre-performance and interface [6]. Moreover, with the data obtained from pull-out tests, even numerical models for the tensile behaviour of the material have been developed [7,8].

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One of the major challenges that FRC has faced in recent years has been the use of their residual post-cracking strengths to reinforce concrete which has enabled partial or total substitution of the traditional steel-bar reinforcement [9,10]. Steel-hooked fibres have been the most commonly used for structural purposes, as can be seen in the quantity of research and practical applications [11,12]. The mechanical anchorage and energy needed to rectify the hook have been shown to be highly effective [13]. However, with the development of synthetic macro-fibres with a structural capacity to reinforce concrete with lower overall material costs and which are chemically stable, some new considerations should be made. While it is true that the first developments on polyolefin fibres were focused on their interface properties [14,15], those fibres were cylindrical and with lower mechanical capacities. Nowadays, polyolefin-based macro-fibres have improved mechanical properties and a surface treatment that provide analogous results in fracture tests of polyolefin fibre reinforced concrete (PFRC) [16]. Nevertheless, the conclusions obtained in research performed in steel fibres are not directly applicable [17]. Even though PFRC has proved to meet the requirements [16,18] (in terms of residual strength) of the existing standards [19–21] based on steel fibre reinforced behaviour, their performance has distinctive features. In previous studies, the capital influence of the orientation of synthetic fibres in the behaviour of the structural element has been addressed [18]. The anchorage of the steel hooked fibres or embossed macro-polymer fibres together with their remarkable distinct mechanical properties allows each type of fibres to show advantages in different deformation states. The latter has even enabled studies to be made with the aim of exploiting the advantages available through combining both short steel-hooked and longer polyolefin fibres [16]. Moreover, the combination of PFRC with self-compacting concrete has been shown to be well-suited for structural uses as in recent research has reported [22]. However, at the time of writing, there is a lack of research on the pull-out mechanisms of the polyolefin based structural macro-polymer fibres.

In this study, two types of test configuration have been used with distinct purposes. The first one was carried out with the main aim of achieving the value of the critical length, placing polyolefin fibres inside a conventional mortar cube. In addition to this, it also assessed frictional stresses that appear when pulling out the fibre. The second line of work was performed by means of performing pull-out tests of polyolefin fibres embedded in several lengths and by varying the angle of incidence in a specimen made of self-compacting concrete (SCC) produced with the same mix as that examined in [16,22]. Given that matrix composition influences pull-out behaviour [23], the use of a standardised mortar allowed both comparison with other works [24] and assessment of the influence of the cementitious matrix when compared with SCC. This was carried out with digital image analysis (DIC) that allowed the initial elastic deformation of the fibre to be considered in order to acquire the real pull-out curve once the displacement inside the matrix had started. Additionally, a qualitative analysis was completed by means of scanning electron microscopy (SEM) to analyse the microstructure of the interface fibre–matrix. The conclusions showed that tests performed with digital analysis provide accurate results. The polyolefin fibre–matrix interactions were found to be especially suitable in terms of microstructure, with the pull-out results showing that polyolefin fibres outperformed steel straight fibres and had remarkable performance inside the cementitious matrix. It was also found that performance was better when the fibre was embedded in the real concrete than in tests carried out with mortar. Given that the inclining angle affects the pull-out behaviour [3,8,25], the concrete specimens not only had six embedded lengths ranging from 5 to 30 mm but also an incidence angle that was configured from 0° to 60°. The peak load reached the maximum with an inclination of 45° and the maximum work to produce debonding occurred with 30° of inclining. The critical length was close to 20 mm of the embedded length.

It should be noted that one of the main challenges of this study was to obtain firm and reliable results with the aim of feeding future fracture models for polyolefin fibre reinforced concrete. The varied configurations used for the tests were performed to evaluate the fibre bridging mechanisms that may occur in a crack surface of a concrete piece. In such a surface, fibres can be positioned in any embedded length or at any inclined angle. The results obtained permit the future development of such models to assess the fracture properties of polyolefin fibre reinforced concrete in considering both the embedded length and inclination of the fibres.

This study fills the gap in the use of new types of macro synthetic fibres which are of increasing interest due to their good performance in the post-cracking behaviour. Although the behaviour of PFRC in the meso-scale has been addressed before, there was a lack of knowledge about the pull-out behaviour of the fibres embedded in a cementitious matrix. The significance of this research is that it provides for the first time a complete study on the pull-out behaviour of this type of fibres. In addition, the use of DIC has been shown to be especially suitable for fibre pull-out tests.

2. Experimental details

2.1. Materials and specimens

The production methods of each mixture and configurations chosen are described in this subsection. Two types of cementitious matrixes were produced: mortar specimens and SCC specimens. Inside each piece, a polyolefin fibre was embedded (the properties provided by the manufacturer are summarised in Table 1).

The mortar specimens were cubes of dimensions 40 × 40 × 40 mm^3, with the fibre crossing them with an incidence angle of 90° at one of the faces. The mortar composition was performed according to the standard EN 196-1 [26]. The proportions in weight of the mortar used are 3:1:0.5 normalised sand, cement and water respectively. The mixing process stated in the aforementioned recommendation was followed. The test setup was similar to that used in tests performed in prestressed concrete elements where the local surface effect that can appear was avoided by placing a covering in the most superficial part of the steel element [27]. In accordance with this test setup, a plastic cylinder sheath with the fibre inside was positioned across the mould from one side to the other. In order to assure orientation and embedded length, the plastic sheaths were placed with only exposed the length designed. The visual aspect of one specimen and the pouring

Table 1
Outlook and properties of the polyolefin fibre (fibre properties provided by manufacturer).

Density (g/cm^3)	0.91
Length (mm)	60
Eq. diameter. (mm)	0.92
Modulus of elasticity (GPa)	>9
Tensile strength (MPa)	560