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Assessment of the shear behaviour of polyolefin fibre reinforced concrete and verification by means of digital image correlation

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HIGHLIGHTS

- A major contribution of polyolefin fibres involves the replacement of shear stirrups.
- Steel fibres have been shown as effective but there is a lack regard to polyolefin fibres.
- Shear strength of PFRC is assessed by means of push-off tests.
- Shear cracking nucleation and growth are studied by means digital image correlation.
- Assessment of shear contribution of polyolefin fibres is compared with existing codes.

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ABSTRACT

Given that remarkable structural applications of fibre reinforced concrete have been successfully developed in the last 60 years, modern concrete codes and fib Model Code have included requirements and formulations for considering the fibre contributions in structural design. In recent times, polyolefin fibre reinforced concrete (PFRC) has been shown as an attractive alternative to steel fibres, with it being chemically stable and having a lower dosage in terms of weight to reach similar residual strengths. It is worth noting that fibre contributions are attained from flexural tensile strengths tests. However, one of the major contributions provided by fibres in rebar substitutions has involved use in replacing shear stirrups. In such a sense, while the use of steel fibres has been shown as effective there is a lack of published literature with regard to PFRC. In this study, push-off tests in specimens obtained from the remaining halves after three-point bending tests have been performed. In addition to the mechanical results obtained, digital image correlation has allowed the cracking processes of the specimens to be identified. This paper offers a significant contribution to the field, given that it relies on the assessment of the shear contributions of polyolefin fibres and comparison with the requirements of the existing codes. Moreover, it supplies notable information about residual shear strengths and the cracking processes that take place.

1. Introduction

Concrete is the leading construction material in the fields of civil engineering and building materials. In order to improve the structural capacities of such a material, various methods have been successfully applied, with the combination of concrete with steel-bar reinforcing being the most archetypal solution. Attention should also be drawn to the modern use of fibre reinforced concrete (FRC), which has entailed experience being obtained over more than 50 years. Moreover, practice is supported by several outstanding recent applications such as tunnels [1,2], pavements, a wide range of precast pieces [3] and even footbridges in combination with other types of high-performance concrete [4]. Among the benefits of adding fibres to structural concrete are the improvements obtained in flexural and tensile performance [5,6]. Most advances have been achieved by means of steel fibres with several shapes. In such a sense, the emergence of macro-polymer fibres that are chemically stable and with structural capacities has provided an attractive alternative [7–10]. Some other added benefits of polyolefin-based fibres have been published, such as lower environmental impact, lower weight, and reduced relative cost in comparison with steel fibres [11–13].

The behaviour of FRC depends on several factors, such as the fibre shapes, constituent materials, fibre dosage and the final distribution and orientation of the fibre located in the concrete element [14–17]. In order to consider the contribution of such fibres in structural design, the existing regulations, such as Model Code

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(MC2010) [18] and the Spanish Structural Concrete Code [19], require certain demands to be met. Such structural requirements have led to extensive research that includes both steel fibre reinforced concrete (SFRC) [15,20,21] and polymer fibres [7,22,23]. The main advantages of polyolefin fibres rely on the structural nature with a reduction or substitution of steel weights included in the structural elements [24] that gives place to the benefits of saving weight and reducing cost [25]. In addition, the good performance in fresh state of polyolefin fibres and their structural capacities has been shown to reduce time and labour costs in certain applications [26].

Given that the structural requirements are based on the results of three-point bending tests [27–29], research in structural polyolefin fibre reinforced concrete (PFRC) has been focused on assessing the residual tensile strength by standard tests. Once the post-cracking residual strengths are obtained in such tests, constitutive relations may be found in the standards [30] or be accurately obtained by cohesive models and direct [31,32] or inverse analyses [33], allowing structural design. However, there is still a lack of research that deals with the behaviour of PFRC under shear stresses.

Various studies about the shear behaviour of SFRC have shown that remarkable improvements, and considerable reduction or even total substitution of steel stirrups, may be obtained by considering the contribution of steel fibres as shear reinforcement [34–37]. Nonetheless, there still remain uncertainties in determining and quantifying with accuracy the resistant mechanisms of FRC under shear stress when optimising the reinforcements in each structural problem [38,39]. In order to address this task, the mechanisms that are mobilised in a cracked element may well be identified as follows: tangential stresses in the area of un-cracked concrete (the area under compression in the cross-section of the beam), engagement of the aggregates (aggregate interlock or shear friction at the crack), a pin effect of the longitudinal reinforcement (dowel action), an arch effect and residual tensile stress across cracks [40].

The published research dealing with shear strength of fibre reinforced concrete has focused on testing concrete elements subjected to bending and shear loading [41–43,36]. There is a lack of scientific literature about pure shear, probably due to the absence of a standard test. Some of the proposed methods are as follows: the JSCE-SF6 shear test [44], double shear specimen test [45], Iosipescu shear test [46], tests where shear is mixed with bending [47,48] and the push-off test [49–52], among others. While all of them have been adopted for SFRC, this has not been the case for PFRC.

The significance of this research lies in the evaluation of various types of concrete with several amounts of polyolefin fibres under shear stresses by means of push-off tests and digital image correlation (DIC) methods. The use of various types of concrete was adopted for showing the performance of such a procedure when applied to distinct types of concrete. The finite element method (FEM) also supported the conclusions obtained by discussing the results of both techniques by means of numerical calculations in the elastic regime. The results supply relevant information about the fracture processes in Mode II in concrete and the involved mechanisms. As a clarification it should be noted, depending on the shape of the loading, that there are three fracture modes: Mode I, where the displacement of the faces of the crack is perpendicular to the plane of the crack, leading to the opening of this; Mode II, where the displacement of the faces of the crack occurs at the level of the crack and perpendicular to front of crack; and Mode III, in which the relative displacement of the faces of the crack is produced in the direction of the front of the crack [53].

With the aim of analysing the deformations and identifying the cracking processes, conventional measuring devices were supplemented with additional techniques, with the most interesting ones being those found in published research, the use of the acoustic emission technique [54], the sensitive fibre technique [55] and the digital image correlation technique [54,56]. They allow the generation of deformation maps in a given area and display the fracture behaviour of the quasi-brittle material accurately [57]. One outstanding advantage of the use of the digital image correlation technique is that it entails the absence of physical contact with the specimen and, therefore, avoidance of any influence in the boundary conditions of the test.

The starting point of the experimental campaign was the use of the remaining halves obtained from three-point bending tests shown in previous published research [58,59]. The so-called push-off tests consist of performing two horizontal notches, generating a surface of vertical ligament through which a shear force is transmitted [51]. This seeks to generate a shear stress concentration in the ligament surface up to the failure of the specimen. PFRC specimens were subjected to pure shear tests and relevant information obtained regarding the cracking deformation and loss of the initial stiffness of the specimens. Three types of concrete were used: moderate compressive strength (MSC) with 6 kg/m^3 and 7.5 kg/m^3 of polyolefin fibres, self-compacting concrete (SCC) and vibrated conventional concrete (VCC) with 10 kg/m^3 polyolefin fibres.

2. Materials and mix proportioning

The constituent materials included Portland cement type EN 197-1 CEM II 32.5 B-M for MSC with an absence of any other admixture. In the case of the SCC and VCC mixtures, EN 197-1 CEM I 52.5 R-SR 5 was used, as well as limestone powder with specific gravity and Blaine surface of 2700 kg/m^3 and 400–450 m^2/kg respectively. The calcium carbonate content of the limestone powder was higher than 98% with less than 0.05% being retained in a 45 μm sieve. A polycarboxilate-based superplasticizer named Sika Viscocrete 5720 with a solid content of 36% and 1090 kg/m^3 density was employed in the SCC and VCC. MSC and VCC reached compaction on a vibrating table. The SCC specimens were poured in a single load from one side to the other of the mould, reaching compaction by only the action of its own weight. The mixtures were made with siliceous aggregates composed of two types of gravel with a size of 4–8 mm and 4–12 mm and sand of 0–2 mm. The maximum aggregate size was 12.7 mm. Polyolefin straight fibres with an embossed surface were employed with two lengths of 48 mm (MSC) and 60 mm (SCC and VCC) and named, respectively, PF48 and PF60. Table 1 shows a 48 mm-long fibre and the main characteristics, their properties and the geometrical patterns of both fibres. In MSC, 6 kg/m^3 or 7.5 kg/m^3 of fibres were added. In SCC and VCC 10 kg/m^3 of fibres were added. Table 2 shows the mix proportioning and fibre dosage of the concrete types used.

The most relevant mechanical properties of the concrete types were assessed in previous research [58,59] and are shown in Table 3. The SCC and VCC specimens were characterised in hardened state with compressive and, indirect tensile strength tests, as well as modulus of elasticity [60–62]. In the case of the MSC specimens, only compressive strength was measured. Three cylindrical test specimens with a 300 mm height and diameter of 150 mm, and four prismatic specimens with dimensions of $600 \times 150 \times 150$ mm^3, were used in all the concrete types. The residual tensile strength of PFRC was obtained according to EN 14651 [29]. The results obtained can be seen in Table 3.