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Influence of the properties of polypropylene fibres on the fracture behaviour of low-, normal- and high-strength FRC

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HIGHLIGHTS

- The influence of the polypropylene fibres properties on fracture of FRC is analysed.
- Failure of fibres in FRC depend on its properties and the strength of concrete.
- The ductility of concrete depends on its strength and the properties of the fibres.
- The most suitable fibres for a particular strength of concrete are indicated.

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ABSTRACT

This paper describes a comprehensive experimental study of the influence of the geometrical and mechanical properties of polypropylene fibres on the fracture parameters and ductility of low, normal, and high-strength fibre-reinforced concrete. Three-point bending tests were carried out on 88 notched beams using the simplified boundary effect method of Abdalla and Karihaloo. The influence of the fibre reinforcement was especially felt on the tail of the load–displacement curve, and its effect on the size-independent specific fracture energy of concrete has been subsequently analysed. An analysis of the ductility of the concrete has also been carried out based on the Hillerborg's brittleness number. The increase in ductility due to the influence of the fibre reinforcement was conveniently analysed for the different mixes. From results, an analysis of the likeliest mechanisms of failure of the fibres reliant on their properties and the strength of concrete was completed. The results showed the most suitable fibres that were used to get the best fracture behaviour for a particular strength of concrete.

1. Introduction

Fibre reinforcement is a commonly used technique in cementitous materials to reduce the level of microcracking in the matrix of the material and to enhance the toughness and energy absorption capacity [1]. The strengthening effect of fibres in the matrix of concrete is due to the bridge effect that sews the lips of a propagating crack. There are three main mechanisms of failure of fibres. These are fibre pullout, fibre rupture and fibre/matrix debonding [2]. The properties of the fibres play an important role in determining the predominant mechanism of failure, and subsequently on the macroscopic behaviour of the cracked fibre reinforced concrete (FRC) [3,4].

Polypropylene (PP) fibres are widely employed in the reinforcement of concrete as they present some advantages including, higher durability of the FRC [5], they have a greater effect on reducing the shrinkage of concrete [6,7] and they reduce of the spalling effect in high-strength concrete subjected to elevated temperatures [8,9]. The utilisation of PP fibres in combination with steel fibres is also frequently used to achieve a hybrid FRC, which takes advantage of both the metallic and non-metallic fibres [10,11].

By considering the dosage of PP fibres usually employed in the construction industry (600–2400 kg/m^3) [12,13] and its low thickness (about 30 μm), the effect on the macroscopic behaviour of FRC is only marginally felt on the mechanical standard properties [14]. Nevertheless, the effect of PP fibres is more pronounced in the elastic modulus due to shrinkage cracking reduction and on the fracture behaviour of the FRC due to the bridge effect of the crack lips [6]. Using fracture mechanics tests, like the three-point bending test [15], the influence of the properties of PP fibres on the fibre/matrix interfacial bond and their main mechanisms of failure may be highlighted in a more evident way as the crack propagation in these kinds of tests usually occurs in a stable manner at a very low loading rate.

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Nomenclature

FRC	fibre reinforced concrete
FPZ	fracture process zone
G_f	size-dependent measured specific fracture energy
W_F	work of fracture
B	width of the specimens
D	depth of the specimens
a_0	initial notch depth
S	distance between supports at three-point bending tests
L	length of the specimens
P_{max}	maximum load during three-point bending test
β_H	Hillerborg's brittleness number
l_{ch}	characteristic length
f_t	tensile strength
g_f	local fracture energy
G_F	size-independent specific fracture energy
δ_{max}	maximum vertical displacement at the midspan at failure
BEM	boundary effect method
SBEM	simplified boundary effect method
CMOD	crack mouth opening displacement
m	mass of the specimen
g	acceleration due to gravity (9.8 m/s^2)
l_f	length of the fibres
t_f	thickness of the fibres
σ_{uf}	ultimate tensile strength of fibres
E_f	elongation of fibres
f_c	compressive strength of concrete
f_{st}	split tensile strength of concrete
f_{cf}	modulus of rupture of concrete

The current manufacturing processes used in the plastic industry makes it possible to obtain fibres with different geometrical and mechanical properties [16,17]. The differences between the properties of the fibres such as length of fibres, can show significantly different effects on the behaviour of the FRC [9]. A change in the properties of fibres can also alter its mechanisms of failure and its effect can be reduced even if the fibre content remains constant. The properties of the fibres characterise the fibre/matrix interfacial bonding [2].

On the other hand, the compressive strength of concrete is a clear indicator of the brittle/ductile behaviour of the material [18]. The stresses developed at the crack tip and in the cohesive zone during the crack propagation are different depending on the strength of concrete. The cohesive stress–opening curve (σ–ω) is an important fracture property of concrete [18]. High strength concrete presents a more brittle behaviour than ordinary concrete [19,20] with a higher level of stresses at the crack tip and with a lower level of deformation. Hence, the properties of the fibres can interact with the strength of concrete modifying the main mechanism of failure of the fibres [2]. In this way, the influence of the properties of the fibres on the macroscopic behaviour of concrete can be different depending on the strength of concrete.

This paper deals with the influence of the properties of PP fibres on the mechanical and fracture behaviour of FRC with different compressive strengths. A comprehensive experimental study consisting of three-point bending tests on notched beams containing either a very shallow or a deep starter notch referring to the simplified boundary effect method of Abdalla and Karihaloo [21] was carried out. The influence of the length, the thickness and strength of fibres for low-, normal- and high-strength concrete on the fibre/matrix interfacial bond was revealed by means of the analysis of the fracture parameters and ductility of the FRC. From the main results of this work the properties of PP fibres were optimised according to the strength of concrete.

2. Analysis of fracture behaviour

In the analysis of the fracture behaviour of concrete the most important parameters are the fracture energy, the tensile strength and the elastic modulus [18]. Furthermore, it is common to perform some additional analysis such as the study of the brittleness/ductility of concrete [20], especially in case of FRC.

2.1. Size-independent fracture energy of concrete

In order to measure the fracture energy of concrete, the work-of-fracture method recommended by the Technical Committee RILEM 50-FMC [15] consisting of three-point bend test on notched specimens is frequently applied. The fracture energy is defined as the energy necessary to create a crack of unit surface area projected in a plane parallel to the crack direction. As the specimen is split in two halves, the fracture energy is determined dividing the total work of fracture (i.e. total dissipated energy) by the total surface area of the crack (ligament area). This work of fracture in the case of the three-point bending tests according to the RILEM procedure is considered as the area under the load–displacement (P–δ) curve at midspan plus a self-weight compensation term, and the well-known RILEM fracture energy is given by

$$G_f = \frac{\int_0^{\delta_{\max}} P d\delta + \mathrm{mg}\delta_{\max}}{B(D - a_0)} \tag{1}$$

where B is the thickness, D is the depth, a_0 is the start notch depth of the specimen mg is the self-weight of the notched beam and $\delta_{\max}$ is the maximum vertical displacement at the end of the test.

The values determined by using the RILEM work-of-fracture method present a dependency on the ligament area (size and notch depth) of the test specimen, as demonstrated and analysed by several authors in the last decades [22–24]. In this sense, two methods have been proposed by Elices and co-workers [25–27] and by Hu and Wittmann [28] in order to obtain a size-independent value (G_F). The correction of the size-dependent G_f by the procedure proposed by Elices and his co-workers or by the boundary effect procedure of Hu and Wittmann result in nearly the same size-independent G_F irrespective of the size of the specimen and the notch to depth ratio [29].

Hu and Wittmann [30] argued that the effect of the free boundary is felt in the fracture process zone (FPZ) ahead of a real crack so that the energy required to create a fresh crack decreases as the crack approaches the free boundary. They represented the transition from the moderate decrease to the rapid decrease by a bi-linear approximation (Fig. 1). The bi-linear function consists of a horizontal line with the value of G_F and a descending branch that reduces to zero at the back surface of the specimen [31]. The intersection of these two straight lines is defined as the transition ligament size a_l [28]. According to this method, the RILEM fracture energy given by Eq. (1) represents the average value of the variable local fracture energy g_f. Considering the bi-linear approximation