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Influence of the distribution and orientation of fibres in a reinforced concrete with waste fibres and powders

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HIGHLIGHTS

- The tensile strength is significantly affected by the addition of fibres and powder.
- The incorporation of both fibres and powders improve the uniaxial tensile strength.
- The orientation of the fibres showed that the incorporation of fibres is in 3D.
- The mechanical behaviour is slightly influenced by the mixing energy.

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ABSTRACT

This paper focuses on the incorporation of the sub-product materials based on the fibres and powders as used in the reinforcement of a cement matrix. These reinforcements (fibres and powders) were obtained from recycling by crushing of a thermoset composite based on unsaturated polyester/glass fibre. The mechanical and physical properties of Waste Fibre and Powder Reinforced Concrete (WFPRC) were investigated after optimising the composite. Regarding mechanical properties, the study focused on the effect of the volume of fibres and powders on the flexural, the uniaxial tensile strength and on different mixing energy. Regarding physical properties, the porosity, the orientation and distribution of fibres in a cement matrix were investigated. The results show that the tensile strength of WFPRC increased when both fibres and powders were added. The mixing energy influence strongly the fibres/powder content, the porosity, the distribution and fibres orientation regarding the loading direction of composite. However, the fibres distribution is an important factor for explain efficiency the mechanical behaviour of WFPRC. Fibre-orientation measurement by two-dimensional (2D) image analysis of polished cross-sections is a rapid and highly efficient method for determining the fibre orientation distribution over large sample areas. The results confirm that the rheology and fibre/powder content of concrete has an important influence on the orientation of the fibres and therefore the mechanical behaviour of composite reinforced fibres. The mixture reinforced with 4.4%, 6.2% and 11.54% of fibre/powder present an orientation coefficient ranging from 0.3 and 0.35 which indicate that the orientation of WFPRC is in 3D because the number of fibres is the same in three planes and confirm the poor workability of samples reinforced fibres.

1. Introduction

Although concrete is the most used building material on earth, this material has a still some serious problems related to the utilisation of this material: concrete possesses a good resistance against compressive stresses, but a very low tensile strength. Under tensile stress, concrete easily cracks and almost no ductility. The usual way to solve this problem can be the application of fibres reinforcement in concrete structures [1–3]. Other solution is the application of different types of fibres in the concrete, for example steel or synthetic fibres: this material is then called "fibre concrete". In the past, many types of fibre concrete have been developed. For many of them, the added value of fibres was rather low: no improvement of tensile strength could be achieved, only the ductility was somewhat higher compared to the plain concrete [3]. However, not only the type and quantity of fibres affect the tensile properties of composite, but also parameters as the number

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and orientation of fibres. Therefore, these parameters will be analysed in detail and linked to the tensile behaviour of fibre reinforced concrete.

Fibres are crucial for the tensile load bearing capacity of a fibre reinforced material and if more fibres are present and aligned in the loading direction, the crack bridging resistance and load bearing capacity will be higher [4]. Therefore, the fibres in the testing specimens have often been counted in order to quantify and evaluate the structural behaviour of fibre reinforced concrete [5]. The mechanical behaviour of fibre reinforced concrete is strongly influenced by the distribution and the fibres orientation of the composite.

Different methods can be used in order to count fibres in a test sample or a cross-section. These methods include wash-out tests [6], which fill a mould and place it over a sieve after mixing the concrete and it is still flowable. After washing out the coarse aggregates and fibres that remain on the sieve, the steel fibres can be separated from the aggregates with a magnet, and by counting and weighing them, the fibre concentration in the mixture can be evaluated. For other fibres such as glass fibres, and Carbon [29], other methods can be used such as X-ray diffraction or analytical analysis with image treatment. The image analysis is one of the most satisfactory techniques to determine the distribution and orientation of fibres in concrete [5,1].

The tensile behaviour for fibre reinforced concrete is strongly influenced by the fibres orientation. According to Wuest, in the case of self-compacting concrete, fibre orientation should be theoretically oriented in two-dimensions (2D) [7]. For this reason, the manufacture of fibres reinforced concrete or ultra high performance concrete reinforced fibres requires a high mixing energy to better scatter of fibres. This mixer also deflocculates the fine particles (e.g. silica fume) and the superplasticizer [8].

The principal aim of this work is to develop WFPRCs and determine the effect of fibre orientation on the mechanical behaviour of the concrete reinforced with waste fibres and powders. These reinforcements were recycled from thermoset composite parts (unsaturated polyester/glass fibre) from the automotive sector (iNoPLAST, France).

2. Theoretical expressions

2.1. Fibres orientation and distribution

Fibres in cross-sections will be generally visible with an elliptical form. In the ideal case, when the fibre is perpendicular to the cross-section, it will be visible as a full circle, otherwise as an ellipse. In the case of ellipse, the minor axis "b" corresponds to the fibre diameter, while the major axis "a" is the visible length of the fibre on that plane. Two angles characterise the fibre direction: the out-of-plane angle "θ" and the in plane angle "φ". Fig. 1 presents all the definitions.

2.1.1. The in-plane fibre distribution "φ"

The in-plane direction φ is equal to the orientation of the ellipse major axis "a" with respect to an arbitrary in-plane direction [9].

2.1.2. The out-of-plane direction "θ"

The out-of-plane angle "θ" gives an indication of the fibre alignment with regard to the loading direction; in that case, a perpendicular out of plane direction ($\cos\theta = 1$) would imply a perpendicular alignment to the loading direction and a preferable alignment with regard to the load bearing and crack bridging ability of the fibre. The out of plane angle "θ" can be determined from the major "a", and minor "b" axis length of the fibre in the cross-section (Fig. 1):

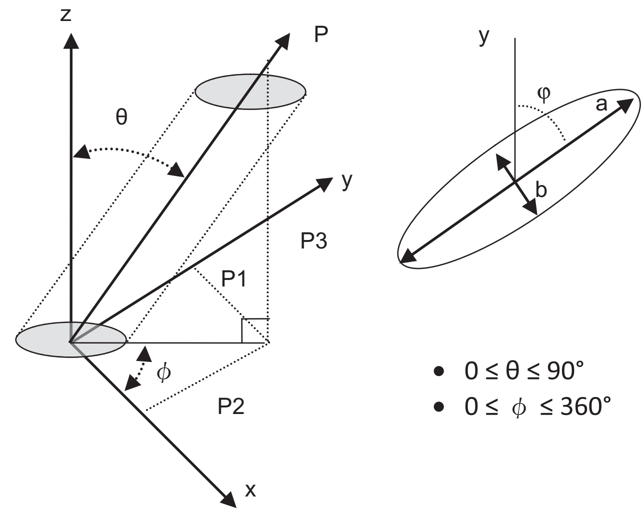

Fig. 1. Left: fibre in a 3D view; visibles are the in- and out-of-plane angles "φ" and "θ". Right: definition of an ellipse with its centre point, major and minor axis and in-plane angle [9].

$$\theta = arc \cdot \cos\left(\frac{b}{a}\right) \tag{1}$$

2.2. Determination of number and orientation of fibres in specimens

As previously stated, the tensile properties of any type of fibre concrete depend mostly on two parameters:

- the number of fibres in the cracking zone, and
- the orientation of fibres in the cracking zone, with respect to those of main tensile stresses.

Various common methods for quantifying fibres are based on images of sections of a specimen and not on the specimen itself; these images could be from X-rays [10,11], from microscopic images [9], or just photographs of cross-sections [12]. On these images, the fibres can again be counted manually, as it has been done by Grünewald on X-ray images, or digitally through digital image analysis [13,14]. For this research, photographs were taken from beam cross-sections which later were analysed with the image analysis software package Optimas [15].

The total number of fibres "N_f" in a cross section can be determined with all visible ellipses and circles. A dimension less orientation factor "η", giving an indication of the average orientation within a cross-section, can either be determined by comparing the number of fibres "N" with the theoretical number of fibres "N_f" (1/mm^2) that should be present according to the applied fibre volume fraction in the mixture, or via the out-of-plane angles determined for the single fibres in the cross-section.

The first method has been applied by Soroushian and Lee and the fibre orientation coefficient "C_{or}" is given by the following equation [16]:

$$C_{or} = N_f \cdot \frac{A_f}{V_f} \tag{2}$$

With A_f (mm^2) being the cross-sectional area of the fibres, $\pi d^2/4$, d (mm) the fibre diameter, and V_f (%) the volume fraction of fibres in the concrete.

The second method to determine the orientation factor, via the fibres out-of-plane angle, can be determined with the next equation [12]. This is the method applied in this study: