Construction and Building Materials 64 (2014) 496–503

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Fibre distribution in macro-plastic fibre reinforced concrete slab-panels

Pablo Pujadas *, Ana Blanco, Sergio Cavalaro, Albert de la Fuente, Antonio Aguado

*Department of Construction Engineering, Universitat Politècnica de Catalunya, UPC, Jordi Girona 1-3, 08034 Barcelona, Spain*

## HIGHLIGHTS

- Specimens drilled from slabs are tested to qualitatively assess fibre orientations.
- Plastic fibres tend to be oriented parallel to the formwork walls.
- Plastic fibres tend to be oriented perpendicular to the flow direction for a free surface.
- CT-scan can be used to identify the dispersion and orientation of plastic fibres.

## ARTICLE INFO

*Article history:*
Received 31 December 2013
Received in revised form 21 March 2014
Accepted 4 April 2014
Available online 8 May 2014

*Keywords:*
Orientation
Fibre-reinforced concrete
Macro-plastic fibres
PFRC
Slabs
MDPT
CT-scan

## ABSTRACT

This paper focuses on the study of the influence of flowability and wall-effects of the formwork in the orientation pattern of macro-plastic fibres. In order to identify the preferential orientation of fibres caused by the geometry of slabs, pairs of specimens drilled from PFRC slabs with different width/length – ratio are tested using the multidirectional double punch test (MDPT). The results show that plastic fibres tend to be oriented parallel to the walls or surfaces of the formwork and perpendicular to the flow direction for a free surface flow. The side walls slightly redistribute the fibre orientation, as the transverse dimension of the slabs is reduced. Additionally, a computed tomography (CT-scans) was, for the first time, successfully applied to assess the amount of macro-plastic fibres as well as its distribution and orientation in a prismatic core.



## 1. Introduction

Fibre reinforced concrete (FRC) is one of the most relevant innovations in the field of special concretes. This composite has proven to be a competitive material in many types of structures [1,2]. In several of them, fibres are used for structural purposes substituting partially or completely the conventional reinforcement [3–7].

The addition of fibres provides enhanced properties to the composite cement-based material. In the hardened state, fibres modify the non-linear structural behaviour of concrete in tension increasing the post-cracking residual strength of the material. The bridging effect of the fibres contributes to the energy absorption capacity and crack control of structural elements, reducing the opening of cracks and counteracting its propagation.

This enhanced behaviour is particularly influenced by the amount of fibres effectively crossing a crack and its bond and strength properties [8]. Since all fibres cannot be aligned in the direction of the applied stress, the fibre effectiveness is dependent of the loading conditions (mainly on the directions of the principal tensile stresses) and the fibre orientation towards the active crack plane. Thereby, as proposed in the Model Code [9] the consideration of fibre orientation and dispersion is of great interest in the FRC design, as they significantly affect the post-cracking mechanical properties of the material [10–13].

The fibre orientation in the hardened-state is the final result of a chain of stages that FRC passes through from mixing to hardening inside the formwork (according to [14], mainly the fresh-state properties, the concrete pouring, the geometry of the formwork, the type of vibration and the production method). Among these factors, Refs. [8,15,16] consider that the most important ones are the fresh state properties (especially the flowability) and the wall-effects introduced by the formworks.

Examples of advantageous preferential orientations caused by the geometry are slabs and plates in which, given their low height to width ratio, the fibres tend to align in the perpendicular plane to the filling direction, being perpendicular to the failure planes that develop in such type of structures. This becomes more significant

* Corresponding author. Tel.: +34 93 401 7825; fax: +34 93 401 1036.
*E-mail address:* pablo.pujadas@upc.edu (P. Pujadas).

http://dx.doi.org/10.1016/j.conbuildmat.2014.04.067
0950-0618/

as the dimension of the element increases since the fibres flow through a longer path than in smaller elements. Similar results were obtained by [17,18] that identified the existence of a network effect in slabs reinforced with steel and plastic fibres, respectively.

This fact emphasises the need to understand and identify the preferential orientation of fibres caused by the geometry of slabs in order to consider its effects for structural design purposes. Some researchers have already reported the orientation of fibres in steel fibre reinforced concrete (SFRC) slabs using both non-destructive test [11,17,19] and indirect destructive methods by means of the post-cracking residual strength results [8,20]. However, no research has been conducted on the influence that the width of the slab has on fibre orientation.

Thus, the main objective of this paper is study the influence of both, the flowability and wall-effects of the formwork, in the orientation pattern of macro-plastic fibres in slabs. For that, the distribution/orientation of macro-plastic fibres in plastic fibre reinforced concrete (PFRC) slabs with different width/length – ratio was experimentally and qualitatively assessed using a simplification of the multidirectional double punching test (MDPT) developed by [13]. Furthermore, computed tomography was employed in a specimen to study the feasibility of this non-destructive method to be used with PFRC and at the same time verify the orientation of fibres obtained with the MDPT.

## 2. Experimental research

### 2.1. Specimens

The elements tested in this experimental program were 3 PFRC slabs of variable geometry without conventional reinforcement. The length ($b_{long}$) and the height ($h$) of the element were fixed at 3.00 and 0.20 m, respectively. In order to evaluate the influence that the flowability and wall-effects of the formwork have on the orientation of the fibres, slabs with three different widths ($b_{short}$) were produced: 1.5 m, 2.0 m and 3.0 m.

To distinguish between the different elements tested, the nomenclature L, M and S are used for slabs with dimensions of 3.0 m × 3.0 m, 2.0 m × 3.0 m and 1.5 m × 3.0 m, respectively.

### 2.2. Materials and concrete mixtures

Two batches with the same mix proportion were required to cast all the elements (the first batch has used to cast slabs L and M, and the second one to cast S slabs). The concrete mix was designed to obtain a fluid concrete with close to self-compactability characteristics.

The concrete was produced following the same mixing process. Initially the dried components were mixed for 1 min. Subsequently the water was added and the mixing proceeded for 2 min, afterwards the superplasticizer was added and finally the fibres were included. After that, the concrete was mixed for two additional minutes. For this study, a reference concrete mix with a water/cement – ratio of approximately 0.50 (see Table 1) and the plastic macro-fibre content of 9 kg/m$^3$ were used. The details of the concrete mix are presented in Table 1.

The plastic macro-fibres used in the tests were derived from polyolefin (specifically from polypropylene) with a continuously embossed surface texture to improve adherence. The main characteristics of the fibre used are presented in Table 2.

The casting of the slabs followed the same procedure in order to assure uniformity, due to its influence on the orientation of the fibres. The concrete was poured through a cupola from the centre of the slab at an approximate height of 1 m (Fig. 1). During the manufacturing, a vibrator table was used to ensure proper compaction. The concrete did not show signs of segregation and the plastic fibres were visible at the free-flowing edges of the poured mass.

**Table 1**
Mix proportions of concrete.

| Material | Characteristics | Content (kg/m$^3$) |
|---|---|---|
| Gravel (6/15 mm) | Granite | 520 |
| Gravel (2.5/6 mm) | Granite | 400 |
| Sand (0/3 mm) | Granite | 510 |
| Cement | CEM I 52.5 R | 350 |
| Filler | Marble powder | 300 |
| Water | – | 178 |
| Superplasticizer | Adva® Flow 400 | 12 |
| Fibres | | 9 |

**Table 2**
Fibre characteristics (data provided by the manufacturer).

| | |
|---|---|
| Length (mm) | 48 |
| Tensile strength (MPa) | 550 |
| Elasticity modulus (GPa) | 10 |
| Number of fibres per kg (fibres) | >35,000 |

### 2.3. Material characterization

For the mechanical characterization of each concrete batch in the hardened state, the following tests were conducted: compressive strength in 3 cylindrical specimens of ∅150 × 300 mm according with [21]; mean elastic modulus ($E_{cm}$) in 3 cylindrical specimens of ∅150 × 300 mm according with [22] and flexural tensile strength of 6 prismatic specimens of 150 × 150 × 600 mm according with [23]. All tests were performed at the age of 28 days.

Table 3 presents the average results at 28 days for the elastic modulus ($E_{cm}$) and the compressive strength ($f_{cm}$) tests as well as the coefficient of variation (CV) for the three studied series. The proportionality limits ($f_L$) and values of the residual flexural tensile strength $f_{R1}$, $f_{R2}$, $f_{R3}$ and $f_{R4}$ are also included in this table, which correspond to the different crack mouth opening displacement (CMOD) of 0.05 mm, 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm, respectively.

The bending test presents a relatively high dispersion, particularly for the series of slab S. However, this dispersion may be attributed to the test itself which according to [4,24–26] can reach values higher than 20%.

### 2.4. Procedure and test setup

The MDPT is an indirect tensile test method that allows assessing the toughness and residual tensile strength of FRC considering the distribution and orientation of fibres. The test setup is based on the double punch test applied to FRC or Barcelona test [25,27]. According to that, two cylindrical steel punches (see Fig. 2(a)) arranged concentrically above and below a FRC cubic specimen (with 150 mm of edge) transmit the load applied by the plates of the press that approach each other at a constant relative rate of 0.5 mm/min (Fig. 2(b)). The punch is a metallic cylinder with 24 mm of height and 35 mm of diameter (1/4 of the diameter of the largest circle inscribed in the face of the cube).

The test control is performed by means of the position of the loading plate. The correlation between the axial displacement and the total circumferential opening displacement (TCOD) for the Barcelona test [28] was applied to the MDPT to obtain an equivalent TCOD. Further details on the test and the analysis of its goodness to characterize the post-cracking response of FRC may be found in [13].

In the MDPT, the use of three cubic specimens allow three different loading directions, activating different groups of fibres in each case, and thus assessing three different toughnesses and residual tensile strengths. Unlike in the MDPT [13], in this paper only two directions could be tested. Consequently, based on the comparison of the post-cracking results obtained in two different specimens (drilled from different but analogous position in the slab), the orientation of fibres in the slabs was qualitatively assessed.

### 2.5. Core drilling strategy

In an effort to make a complete characterization of the fibre orientation in the slabs cylindrical ∅225 × 200 mm cores were drilled from the slabs: L; M and S (see Fig. 3).

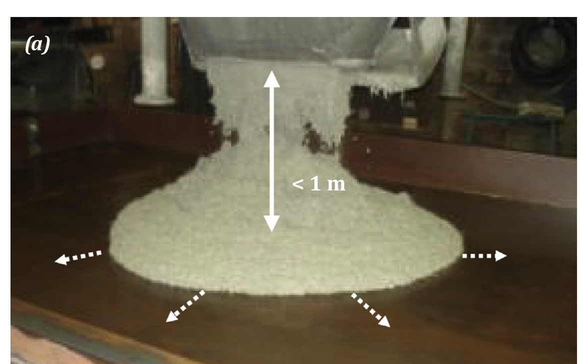


**Fig. 1.** Concrete poured from the centre of the slab and flow of concrete to the edges.