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Fibre distribution and orientation of macro-synthetic polyolefin fibre reinforced concrete elements

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HIGHLIGHTS

- Fibres in PFRC-SCC specimens had better orientation factor poured from the side.
- PFRC-SCC positioning maps showed that there is not a constant flux along the mould.
- The fibre distribution in the VCC specimens was more uniform than in the SCC ones.
- In the vertical elements the coefficient of orientation was stable and around 0.60.
- The flux of SCC in the horizontal element raised the orientation factor.

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ABSTRACT

Fracture behaviour of polyolefin fibre reinforced concrete (PFRC) has proved to be suitable for structural design in construction elements. As in other fibre reinforced materials, the tensile behaviour is strongly affected by the positioning of the fibres. Previous research has assessed this influence by means of fracture tests, showing reliable results. These were obtained by changing the most influencing parameters: the fibre length, the pouring and compaction methods, the concrete type and specimen sizes. However, the influence of these factors in fracture results is merely limited to the fracture surfaces, while the positioning of the fibres in the rest of the piece may be a key factor for design in structural elements. Furthermore, examination of the orientation factor within the whole piece provides relevant information about the behaviour of the fibres during the pouring processes. It may also allow preparation of future models to predict the final positioning of the fibres. This paper examines the positioning and orientation of the fibres in elements which provided fracture results previously reported in the literature. In addition to counting the fibres located in the fracture surfaces, the specimens were divided in portions. The fibre-positioning maps obtained provide sound and useful conclusions that may be considered in future design of PFRC elements. The data gathered showed how the orientation-factor varied with the flux and vibration, absence of any tendency to float and the noticeable influence of the pouring point in fibre distribution. It also showed that this type of fibre is suitable for structural-size elements, improving the orientation factor for longer distances when using self-compacting concrete.

1. Introduction

The composite material formed by concrete and fibres is commonly termed fibre reinforced concrete (FRC). The properties provided by the fibres have enhanced one of the major drawbacks of concrete as a building material: its reduced tensile strength. Conventionally, the majority of uses of FRC have entailed a combination of steel fibres and concrete [1], forming what has been termed steel fibre reinforced concrete (SFRC). The improvement of the properties of concrete provided by the steel fibres has allowed its use in several applications, such as industrial pavements and tunnels, among others [2–4]. Furthermore, the contribution of the fibres has recently been considered in structural design [5–7] in the substitution of steel-bar reinforcement of concrete. Subsequently, codes and design standards [8–10] have specified mechanical requirements for structural use. Hence, those fibres capable of meeting residual strengths are the so-called structural fibres, and are typically macro-steel fibres with several shapes such as crimped or hooked-ended fibres.

However, the current concern of society as regards the environmental cost of materials, building processes and infrastructure refurbishment and rehabilitation has given rise to life spans of certain structures of up to 100 years. Therefore, the durability of

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materials has emerged as a key factor in the selection of building materials in civil construction. In this regard, the deleterious effects that the environment or soil might have on steel fibres, which may be corroded, have awakened an interest in fibres that are chemically stable and incremented the mechanical performance of concrete. As well as being highly corrosive in nature, steel is expensive to purchase, store and handle. In addition to this, the efforts of the plastic industry have allowed production of a new generation of polyolefin-based synthetic macro-fibres that are inert in an alkaline environment and provide concrete with structural capacities to substitute steel reinforcement [11,12]. Polyolefin fibres have good tensile properties, abrasion resistance and excellent resistance to chemical attacks, which when added to their relatively low cost places them as an alternative to steel reinforcing meshes or steel fibres [13]. Polyolefin fibre reinforced concrete (PFRC) has considerable residual tensile strengths [14–18] with lower weights in comparison with steel fibres. Both the scientific community and the construction industry have identified significant advances in the using plastic fibres to reinforce concrete [19]. Mainly due to the lower cost of the material and lack of corrosion when subjected to hazardous environments, the use of this type of fibres has become attractive [20,21]. PFRC entails multiple sustainability benefits. Recent research focussed on end-of-life cycles has shown the reduction of impact compared with the common practice of using steel reinforcing mesh or steel fibres [22]. The lower dosages in terms of weight needed to reach similar strengths reduce the transportation costs and the size of the carbon footprint. Derived from the production methods, significant decreases in carbon emissions compared with the production of steel can also be found in the literature [23]. Plastic fibres can be directly mixed with concrete without clustering problems and with reduced impact to the workability. Even when using ready-mix trucks the loss of fibres is limited compared with steel fibres [24]. In addition, the handling of this type of fibres is safer, involves less weight, and avoids time-consuming operations such as the preparation and placing of the wire mesh. These aspects permit continuous production of concrete setting with a reduction of labour costs to about half of those when using steel [25]. Hence, PFRC has become an appealing solution that has offered additional benefits if the complete life cycle was considered [26].

The increment of the mechanical properties of PFRC, as in other types of FRC, is significantly affected by a variety of factors, such as the constituent materials of the fibres, geometry and surface treatments. On another note, it is evident that fibre dosage influences performance due to the presence of more fibres acting at a certain surface. However, the action of such fibres varies with fibre inclination and the embedded length, as published research dealing with fibre pull-out has shown [27–29]. Therefore, the distribution and orientation of the fibres modifies the structural response because it entails variations of the number of fibres involved, the fibre angle and embedded length. In such a sense, the reliable use of the fibres is directly associated with knowledge about fibre final positioning in the concrete pieces. Some studies have analysed SFRC, both in conventional and self-compacting concrete, the positioning of fibres and their orientation by means of electromagnetic waves, X-ray radiographies, X-ray computed tomography and image-based analysis [30–34]. Such studies conclude that the rheology of concrete might be a key factor in the positioning of fibres and their orientation in the concrete bulk material. Some published research has evaluated the positioning of polyolefin fibres by means of a CT-scan or X-rays in limited portions of PFRC [35].

If one type of fibre is studied and its dosage is maintained at a steady rate, the main factors that influence fibre distribution and orientation are the concrete properties, pouring and compaction methods, and the formworks and mould sizes. This is of high importance due to the extrapolation of properties assumed when analysing the mechanical performance of any FRC. Moreover, the possible differences in the positioning of the fibres between the structural-size concrete elements and the laboratory specimens might be also influenced by the pouring processes and even by the size of the fibres used. It is possible to use the formwork and the wall effect with the aim of improving the mechanical response [36]. Some other pouring conditions, such as vertical pours have also been considered [37]. In addition, recent research has assessed the variations on fibre positioning in PFRC elements due to the concrete properties, pouring methods, fibres length and specimen size [38]. Focusing in this last issue, some other publications have assessed the distribution of the fibres in structural-size elements such as concrete slabs [39] or beam elements of more than 2 m-long and vertical elements 0.45 m-long [40]. Most of the discussion about the influence of the various factors involved comparison of the fracture results with the orientation factor at the fracture surfaces. In such a sense, at the time of writing there is few published research about the influence of such factors on the fibre positioning within the rest of the concrete piece. This is of significant interest for structural elements in which the critical section may be uncertain and where a decision as regards the setting processes and concrete type used is required. It may also be decisive for the final shapes of the pieces. The possibility of evaluating how the polyolefin fibres are distributed as a consequence of pouring processes, different formworks and compaction procedures may allow future modelling and a more reliable use of PFRC. This is particularly necessary for the structural-size elements that will become closer to reality.

This research offers an assessment of the distribution of the fibres in the pieces previously studied in Refs. [38,40], examining the effect on the final positioning of the polyolefin fibres by varying the concrete properties and setting processes and specimen sizes. The results provide relevant information for future orientation models that may consider use of synthetic macro-fibres. In addition, this study contributes to a better comprehension of the positioning of the fibres and provides notable data and design considerations for the structural use of PFRC. That is to say, this is studied with a systematic analysis of the positioning and orientation of 6 kg/m^3 of polyolefin fibres added with a variety of external differences. The evaluation was carried out in standard-size specimens ($150 \times 150 \times 600$ mm^3) of vibrated conventional concrete with 60 mm-long fibres (VCC6-60). In addition, it was assessed in SCC with 60 mm-long fibres poured in standardised moulds from one side (SCC6-60S) and in SCC with 48 mm-long fibres poured in standardised moulds both from one side (SCC6-48S) and from the centre (SCC6-48C). Moreover, elements similar to real applications were evaluated by manufacturing vertical concrete elements of $150 \times 450 \times 600$ mm^3 manufactured with vibrated conventional concrete with 60 mm-long fibres. Lastly, in a long horizontal element manufactured with SCC with an addition of 60 mm-long fibres, similar to a beam, of $2200 \times 250 \times 150$ mm^3 were analysed. The comparison of the elements with sizes similar to those typically found in building and civil structures with the standard specimens permitted evaluation of the use of laboratory specimens to determine the behaviour and distribution of fibres in PFRC. In addition, it could be argued that obtaining the distribution of fibres in such structural-size elements may provide relevant information about the reliability of the use of this type of fibres in structural elements.

2. Experimental programme

2.1. Materials and mix proportioning

The component materials included Portland cement type EN 197-1 [41] CEM I 52.5 R-SR 5 and a mineral admixture of limestone used as a micro-aggregate. This has a specific gravity and Blaine surface of 2700 kg/m^3 and 425 m^2/kg respectively.