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Influence of Steel Fibres on the Behaviour of RPC Circular Columns Under Different Loading Conditions

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ABSTRACT

An experimental program was conducted to investigate the effect of inclusion of steel fibres on the behaviour of Reactive Powder Concrete (RPC) columns. Three different types of steel fibre were used: micro straight steel fibre (MF), macro deformed steel fibre (DF) and waste steel fibre (WF) recovered from discarded tyres. In addition, a hybridization of steel fibres was made up to produce waste-industrial hybridization (WHF) (MF, DF and WF). Twenty reinforced RPC column specimens were prepared and tested under axial concentric, eccentric and flexural loading. Results of testing demonstrated that the ultimate axial load and the corresponding axial deformation increased effectively by the addition of steel fibres, especially at the presence of MF. For the flexural loading, the inclusion of WF and WHF increased the energy absorption of specimens by 470% and 453%, respectively, in comparison with the corresponding reference specimens. Axial load-bending moment (*P-M*) interaction diagrams were carried out. Results of testing show that WF is a promising material for enhancing the behaviour of RPC under different loading conditions.

1. Introduction

Reactive Powder Concrete (RPC) is known as concrete with superior characteristics and is being increasingly used. The strength of RPC comes from the utilization of highly refined admixtures, low water to binder ratio and the exclusion of the course aggregate. The RPC is rated as a concrete with excellent strength and durability [1,2]. This type of concrete enables the designers to reduce the size of structural members such us columns in lower stories and consequently reduces the self-weight of the structure. However, RPC is identified with its excessive brittleness. It was reported that the increase in the compressive strength of the concrete results in an increase in the brittleness of the concrete.

Helices are normally used to confine the core of the concrete columns. However, for high strength concrete, the transverse reinforcement confinement is less efficient than in normal strength concrete when used in columns [3–5]. Furthermore, the ACI 318-14 [6] set the limits for the degree of confinement by setting the pitch of the helices as minimum as 25 mm in order to avoid the congestion of the helices in the columns. As such, helices are less efficient when used in the RPC columns. The need to improve the properties of the RPC material is crucial to mitigate the brittleness issue.

The incorporation of steel fibre in the concrete enhances the tensile strength, flexural strength and the toughness of the concrete [7–10]. The way the steel fibre works is by bridging the developed cracks due to the applied compressive loads or shrinkage and prevents the widening of cracks. This action continues until the steel fibres debond from the concrete. As a result, the concrete that includes steel fibre exhibits higher strength and toughness compared to non-fibrous concrete [11–13]. Moreover, the geometry of steel fibres plays a key role in improving the properties of the concrete. For example, Olivito and Zuccarello [14] and Xia et al. [15] stated that length of the steel fibre greatly affect the post ultimate behaviour, toughness and the load carrying capacity of the normal strength concrete. Abbas et al. [13] stated that short steel fibres affects the flexural properties more than the long steel fibres. Nataraja et al. [16] and Wu et al. [17] reported that the configuration of the steel fibres affects the ultimate load and the flexural load-deflection behaviour of normal strength concrete and the effect of the deformed steel fibres is more than the effect of smooth steel fibres.

In order to obtain full benefit from the incorporation of steel fibres in the concrete, several researchers attempted to incorporate two types of steel fibres in the concrete in a process called hybridization. The hybrid steel fibres is obtained by mixing two types of steel fibres of different properties in order to make use of the advantages of each steel fibre in improving the properties of the concrete. For instance, Kang et al. [18] investigated including straight steel fibres (0.2 mm diameter and 16.3–19.5 mm length) hybridized with different types of synthetic fibres (basalt, polyvinyl-alcohol, and polyethylene) in Ultra-High

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Strength Concrete (UHSC). Results of testing showed that the inclusion of steel fibres and synthetic fibres effectively improves the tensile strength of UHSC due to the effect of fibres on the crack development in different stages. Park et al. [19] investigated the effect of including different types of steel fibres of different geometrical shapes on the tensile behaviour of UHSC. It was concluded that the tensile stress-strain behaviour, post-crack behaviour and the strength was noticeably enhanced by the addition of the hybrid steel fibres that included micro smooth and macro twisted steel fibres. Furthermore, Glavind and Aarre [20], Larsen and Krenchel [21] and Feldman and Zheng [22] have investigated the effect of hybridization between steel fibres and polypropylene on the behaviour of concrete. The reported results showed the hybridization of steel fibres and polypropylene fibres results in the enhancement of the tensile strength and the fracture energy. The enhancement was attributed to the action of the steel fibres in improving the ultimate strength while the polypropylene fibres improved the energy absorption of concrete. Banthia and Sheng [23] reported that the incorporation of two types of fibres of different materials and moduli of elasticity such as steel fibres and carbon fibres enhanced the strength and the toughness of the concrete. The steel fibres improve the strength while the carbon fibres improve the toughness of the concrete. Al-Tikrite and Hadi [24] investigated the inclusion of steel fibre on the mechanical properties of RPC in individual and hybrid forms. Al-Tikrite and Hadi [24] concluded that the hybridization of steel fibres affects the ultimate stress, the corresponding strain and the modulus of elasticity effectively. Also, the post ultimate behaviour of RPC and the energy absorption of RPC were improved noticeably.

On the other hand, the negative aspect of utilizing the industrial steel fibres to reinforce the concrete is the high cost of steel fibres compared to the materials used to produce the concrete. It is estimated that the cost of 1% by volume of steel fibres included in the Ultra-High Strength Concrete (UHSC) is higher than the cost of the material used in the mixture [25]. Also, if the consumption of the natural resources is taken into consideration, the estimated amount of the industrial fibres that are produced annually is about 60 million tonnes around the world [26]. Moreover, the cost of steel fibres in some countries may not justify using it in the concrete [27]. Consequently, to save the cost of steel fibre and to conserve the natural resources, the need for searching for alternatives to the industrial steel fibres or to reduce the amount of steel fibres to be added without affecting the properties of the concrete has become important.

As such, this study, as a complementary work of a study conducted by Hadi and Al-Tikrite [28], investigated experimentally the effect of the inclusion of steel fibre on the behaviour of RPC columns under different loading conditions. The emphasis of the current work is the investigation of the influence of the inclusion of different types of steel fibres of different geometry in individual form and in hybrid form on the behaviour of RPC specimens under different loading conditions. The geometry of steel fibres, type (industrial and waste) and volume content is the main parameters that were considered in this study. Also, the feasibility of the inclusion of the waste steel fibres (WF) recovered from discarded tyres either individually or hybridized with the industrial steel fibres in the RPC column specimens tested under different loading conditions was investigated. Three different types of steel fibres of different geometry and volume contents were used: straight micro steel fibre (MF), macro deformed steel fibre (DF) and waste steel fibre (WF) recovered from discarded tyres. A hybridization of steel fibres was made up to produce waste-industrial hybrid steel fibre (WHF). The RPC column specimens that included MF and DF had been investigated by Hadi and Al-Tikrite [28]. For comparison purposes, the above-mentioned two groups of column specimens were included in this research paper. A total of twenty RPC specimens of five groups were cast and tested in this study. Each group included four specimens, one tested under concentric loading, two were tested under eccentric loading (25 mm and 50 mm) and one tested under flexural loading (four-point bending).

2. Experimental program

2.1. Materials

Three different types of steel fibres of different geometries and volume contents were used: micro straight steel fibre (MF), macro deformed steel fibre (DF) and waste steel fibre (WF) recovered from discarded tyres. The ratio of MF, DF and WF used in this study were 4%, 2% and 3%, respectively. These ratios were shown to be the optimum ratios that improve the behaviour of RPC under loading based on an earlier study conducted by Al-Tikrite and Hadi [24] on RPC. A hybridization of steel fibre was made up by blending 50% of the best ratio of WF and 25% of the best ratios of MF and DF (1% MF, 0.5% DF and 1.5% WF) to produce the waste-industrial steel fibre (WHF) at 3%. The hybridization of WF, MF and DF was done after the waste steel fibre WF was measured and grouped into ranges of average diameters and ranges of lengths. Afterwards, randomly selected 1.5% of WF was hybridized with 1% MF, 0.5% DF to form WHF.

The micro straight steel fibres used was of a diameter ($D = 0.2$ mm), length ($L = 6$ mm) and nominal tensile strength of 2900 MPa [29]. The macro deformed steel fibre was of ($D = 0.55$ mm, $L = 18$ mm and nominal tensile strength = 800 MPa) [30]. The waste steel fibre recovered from discarded tyres was obtained from a local source.

The WF measurements were performed as follows [24]: waste steel fibres were randomly selected and distributed in ten groups of one hundred steel fibres. Measuring the length and the diameter of each steel fibre was done by a micrometre. The measurements were conducted on each steel fibre as follows: Three measurements for the diameter (one at each end and one in the middle) and one for the length. Also, a tensile strength test was conducted for two samples from each group. The WF was grouped into average diameters and range of lengths. The range of lengths and the percentage of WF were distributed according to the average diameters. The range of the average diameters and lengths measured with the percentage of each range is shown in Fig. 1. The average length was ($L_{average} = 22.2$ mm), the average diameter was ($D_{average} = 0.22$ mm) and the average tensile strength was 1900 MPa. Fig. 2 shows steel fibres utilized in this study.

The RPC mixture reported by Al-Tikrite and Hadi [24] was utilized in this study. The targeted compressive strength of RPC is 100 MPa. Table 1 presents the constituents of the RPC mixture.

2.2. Preparation of specimens, mixing and casting procedure

To investigate the effect of different types of steel fibre included in the RPC circular column, five groups of twenty RPC specimens of 200 mm diameter and 800 mm length were cast and tested. The first group was the reference specimens which were non-fibrous RPC specimens (NF). The second group was the RPC specimens that included 4% micro straight steel fibres (MF). The third group was the RPC specimens that included 2% macro deformed steel fibres (DF). The fourth group was the RPC specimens that included 3% waste steel fibre recovered from discarded tyres (WF). The fifth group was the RPC specimens that included 3% industrial-waste hybrid steel fibres (WHF). Each group included four specimens, one tested under concentric loading, two tested under eccentric loading (25 mm and 50 mm) and one tested under flexural loading.

To identify the RPC specimens, the specimens were labelled as follows: the first part of the label, NF, MF, DF, WF and WHF represents non-fibrous, micro steel fibre, deformed steel fibre, waste steel fibre and waste-industrial steel fibre, respectively. The second part of the label represents the loading conditions, E0, E25, E50 and PB, which represents concentric loading, 25 mm eccentric loading, 50 mm loading and flexural loading, respectively. For example, Specimen NF-E0 represents the RPC specimen which is non-fibrous specimen (reference) tested under concentric loading. Specimen MF-E25 represents the RPC specimen that included MF tested under eccentric loading at 25 mm.