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Mechanical properties of reactive powder concrete containing industrial and waste steel fibres at different ratios under compression

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HIGHLIGHTS

- Influence of industrial and waste steel fibres on RPC is investigated.
- Micro steel fibre has greater influence on the strength of RPC.
- Hybrid steel fibre improved the ductility of RPC significantly.
- Waste steel fibre effectively enhanced the strength and ductility of RPC.
- Waste steel fibre is comparable to industrial steel fibre in RPC.

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ABSTRACT

This paper investigates experimentally the influence of type, content and geometry of steel fibre (industrial/waste) on the mechanical properties of reactive powder concrete (RPC) in terms of compressive strength, tensile strength, modulus of elasticity and stress-strain behaviour under compression. Three types of steel fibres were used: industrial micro steel fibre (MF), industrial deformed steel fibre (DF) and waste steel fibre recovered from discarded tyres (WF). Steel fibres were added to RPC at 1%, 2%, 3% and 4% of the total volume. Two forms of steel fibres' hybridizations were explored: industrial hybridization (HF) and waste-industrial hybridization (WHF). Results of testing demonstrate that the addition of DF and WF up to 3% and 4%, respectively, significantly affected the flowability of RPC. The addition of 4% MF achieved the highest increase in the compressive strength, tensile strength, modulus of elasticity, peak stress and the corresponding strain. The inclusion of HF increased the RPC toughness by 245%. Moreover, the inclusion of the waste steel fibre as full replacement (WF) or partial replacement (WHF) was comparable to the industrial steel fibre in enhancing the mechanical properties of RPC in addition to the increase in the toughness of RPC by 158.8% and 211%, respectively. Finally, WF is considered as a promising material in the structural applications and can fully or partially replace industrial steel fibres in RPC.

1. Introduction

Reactive powder concrete (RPC) is a special type of concrete characterised by its strength, durability and toughness. The excellent performance is attributed to the utilization of the admixtures, very fine sand and low water/binder ratio in addition to the exclusion of the coarse aggregates. The RPC is a promising construction material for civil engineering and military applications due to its superior properties. The first structure constructed from RPC in the world was Sherbrooke Bridge in Canada in 1997 [1–5]. In Turkey, the manhole covers are made of RPC [6]. However, RPC is a brittle construction material and the inclusion of steel fibre is significant to enhance the ductility of RPC. Moreover, steel fibre plays a key role in decreasing the crack initiation, spalling of the concrete cover and to increase the strength [7]. The inclusion of steel fibres in the concrete results in improving the mechanical properties of the concrete under different loading conditions [8,9]. Steel fibre increases the tensile and flexural strength effectively and increases the compressive strength marginally [10]. However, the size of steel fibre has an impact on the compressive strength of the concrete. For instance, Xia et al. [11] reported that short steel fibres influences the compressive strength more than long steel fibres. In addition, size of steel fibres may affect the feasibility of utilizing steel fibre in thin cross sectional structural members. Olivito et al.

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[12] stated that fibres' length influences the post cracking behaviour and the tensile strength while it has a little effect on the compressive strength. Also, the geometry of steel fibres has an impact on the toughness and the compressive strength simultaneously. Moreover, Ou et al. [13] stated that long hooked end steel fibre has a little effect on the compressive strength and modulus of elasticity of the concrete. However, the effect on the strain corresponding to the peak stress was noticeable especially when 2% were added to the mixture. Furthermore, Song and Hwang [14] reported that the inclusion of the hooked end steel fibre in the concrete significantly improves the tensile and flexural strength of the concrete when the steel fibre were added to the mixture up to 2% of the total volume. On the other hand, Nataraja et al. [15] investigated the inclusion of crimped steel fibre in the concrete and reported that the inclusion of the crimped steel fibre in the concrete increases the toughness of the concrete while it has little effect on the compressive strength. Also, these increases are proportional to the length, diameter and ratio of the steel fibre. Therefore, some researchers suggested incorporating two types of steel fibres in concrete in order to make use of the function of each steel fibre to improve the engineering properties of concrete. The incorporation of two or more types of steel fibre in the concrete is called steel fibre hybridization.

Steel fibre hybridization plays a key role in enhancing the mechanical properties of concrete. The inclusion of two or more types of steel fibre in the concrete effectively enhances the properties of the concrete as reported in previous studies. Yu et al. [16] reported that the hybridization between long and short steel fibres results in good workability and improves mechanical properties. However, long steel fibre has more influence on the behaviour of the concrete under impact loading than short steel fibre. Kang et al. [17] reported that the tensile behaviour of the Ultra-High Strength Concrete (UHSC) was noticeably improved when various types of steel fibres were included. Furthermore, Feldman and Zheng [18] investigated the hybridization of two types of fibres (polypropylene and steel fibres). Their results showed that steel fibres effectively improved the strength of the concrete while the polypropylene improved the toughness and the post peak behaviour of the concrete. Banthia and Sheng [19] studied the influence of blending low modulus carbon fibres and high modulus steel fibres. Results demonstrated that steel fibres enhanced the strength of the concrete while the carbon fibres enhanced the toughness of the concrete. Therefore, the inclusion of different types of fibres has different impacts on the mechanical properties of concrete. Attempts continue to find a combination of steel fibres that achieve the maximum advantages of including steel fibres in concrete.

In addition, in recent years, several studies attempted to include waste fibres from waste materials to investigate their functionality in concrete. In addition, the inclusion of various kinds of by-products in concrete has become a widespread practice [20–22]. The utilization of the waste fibres as an alternative to the industrial steel fibre is due to its environmental and economic advantages. In particular, the incorporation of waste steel fibre recovered from waste tyres in normal strength concrete was widely explored. The outcomes were the waste steel fibres (WF) effectively improved the behaviour of normal strength concrete after the peak-load was reached and that WF is similar to the industrial steel fibre in enhancing the energy absorption, pull-out behaviour and post cracking behaviour of normal strength concrete. Also, WF is comparable to the industrial steel fibres in enhancing the properties of concrete and it is a promising material for structural applications [23,24]. Aiello et al. [23] stated that WF was similar to the industrial steel fibre in improving the flexural and post cracking behaviour of the concrete. Papakonstantinou and Tobolski [25] concluded that WF greatly increases the toughness of concrete. Also it was concluded that WF has not influenced the workability of concrete noticeably. Furthermore, Centonze et al. [26] reported that the inclusion of WF in the normal strength concrete has effectively improved the post peak behaviour of the concrete and WF is comparable to the industrial steel fibres when incorporated in the concrete.

Accordingly, this paper investigates experimentally the mechanical properties (compressive strength, tensile strength and stress-strain behaviour and modulus of elasticity) of RPC that includes different types of steel fibres at different amounts under compression. Industrial micro steel fibre (MF), deformed steel fibres (DF) and waste steel fibre (WF) were utilized at 1%, 2%, 3% and 4%. Also, this paper explores the influence of steel fibre hybridization on the mechanical properties of the RPC. Two proportions of hybridization were used based on the optimum ratio of steel fibre to be added to the RPC that were experimentally obtained in this study. Industrial steel fibre hybridization (HF) includes the hybridization between 50% of the optimum ratio of each MF and DF (2% MF and 1% DF) which forms 3% of the total volume of the mixture. Waste-industrial steel fibres hybridization (WHF) includes replacing 50% of HF with WF by blending 50% of the optimum ratio of WF and 25% of the optimum ratio of each MF and DF (1.5% WF, 1% MF and 0.5% DF) to form 3% of the total volume of the RPC mixture. The conventional casting and curing methods were used in this study.

2. Experimental investigation

2.1. Materials and proportions

General purpose cement [27] was used in this study at 955 kg/m^3. The silica fume utilized was amorphous high grade densified silica fume powder [28] at 229 kg/m^3. The chemical composition of the cement and the silica fume are shown in Tables 1 and 2. The fine sand was from local natural resources and sieved to a size less than 600 μm. The specific gravity of the sand was 2.65 and the proportion in RPC was 974 kg/m^3. Silica flour of a grade 200 was utilized at 10 kg/m^3. The water reducer and retarder (superplasticiser) was used at 52.6 L/m^3. Three different types of steel fibres were utilized. Micro steel fibre (MF) of 6 mm in length, 0.2 mm diameter and 2500 MPa tensile strength [29]. Deformed steel fibre (DF) of 18 mm in length, 0.55 mm diameter and 800 MPa the tensile strength [30]. Waste steel fibres recovered from waste tyres (WF) were utilized from a local source. The dimensions of WF were measured by using the following procedure:

Ten groups of WF were selected randomly. Each group contained one hundred fibres. The diameter and length of the fibres were measured by a micrometre. Four measurements were taken for each fibre, two diameter measurements at each end, one diameter measurement in the middle and one length measurement. Based on the measurements, the ranges of diameters and lengths and the percentage of each range of WF utilized are shown in Fig. 1(a) and (b), respectively. Types of steel fibres used are shown in Fig. 2. The volume fraction of each steel fibre was 1%, 2% 3% and 4%. The water/binder ratio was 0.133. The mixture utilized in this study is based on a proposed mixture by Richard and Cheyrezy [5] and modified to maintain the flowability within the allowable limits.

2.2. Methodology

The conventional casting and curing methods were utilized for the RPC specimens in this study. The procedure followed for mixing the constituent of RPC is based on the mixing procedure proposed by Bonneau et al. [31]. Some amendments were performed in order to suit the mixed constituents. The mixing process was performed by mixing the dry materials first (cement, silica fume, silica flour and the natural river sand) in the vertical mixer's pan shown in Fig. 3 for about four

Table 1
The chemical composition of cement [27].

Composition (mass)	Content (%)
Portland Cement Clinker	<97
Gypsum ($CaSO_4$ $2H_2O$)	2–5
Limestone ($CaCO_3$)	0–7.5
Calcium Oxide	0–3
Hexavalent Chromium Cr (VI)	<20 ppm
Crystalline Silica (Quartz)	<1