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Behaviour of fibre-reinforced RPC columns under different loading conditions

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HIGHLIGHTS

- Behaviour of non-fibrous and fibrous RPC column is investigated.
- Effect of steel fibre type, volume content and geometry on RPC column is reported.
- Effect of single and hybrid steel fibre on the behaviour of RPC column is reported.
- Micro steel fibre greatly increased the peak axial load of RPC column.
- Hybrid steel fibre has enhanced the ductility of RPC effectively.

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ABSTRACT

This paper investigates experimentally the influence of steel fibres inclusion on the behaviour of Reactive Powder Concrete (RPC) columns. Micro steel fibre (MF) and deformed steel fibres (DF) were used. Steel fibres were hybridized to produce hybrid steel fibre (HF). Sixteen RPC specimens were cast and tested under axial loading, eccentric loading (25 mm and 50 mm) and four-point bending. Results of testing demonstrated that RPC specimens that included MF exhibited 8–58% higher load carrying capacity compared to the reference NF specimens. Moreover, RPC specimens that included HF showed 29–408% higher ductility under different loading conditions compared to the reference specimens (NF). Also, the RPC specimens containing steel fibres exhibited 2–32% higher axial deformation under different loading conditions compared to NF specimens. Finally, it was observed that the RPC specimens reinforced with HF showed delayed spalling of concrete cover more than the RPC specimens that included MF and DF.

1. Introduction

Reactive Powder Concrete (RPC) is a special type of ultra-high performance concrete characterised by its strength, durability and toughness. The excellent performance is attributed to the utilization of admixtures, very fine sand and low water/binder ratio in addition to the exclusion of the coarse aggregates. Also, RPC is considered as 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 addition, utilization of RPC in structural applications such as in columns increases the design efficiency through decreasing the dimensions of the concrete elements and reducing the concrete volume of the entire structure. The RPC, however, is a very brittle material which requires more confinement than the normal strength concrete to achieve the ductility improvement which is limited by the design codes due to the possible congestion of reinforcement. Also, the sudden failure due to the excessive brittleness limits the wide spread utilization of RPC especially in seismic activity zones. Therefore, the inclusion of steel fibre is necessary to mitigate the brittleness and to increase the strength and toughness of RPC.

Hsu and Hsu [6], Mansur et al. [7] and Campione et al. [8] reported that the inclusion of steel fibres in the High-Strength Concrete (HSC) results in a significant increase in the strength of HSC. In addition, the fracture energy of the concrete was effectively improved after the addition of steel fibres to the concrete [9,10]. The action of steel fibre in concrete bridges the cracks that may

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result from lateral expansion of columns under compression and resists crack widening via pull-out of fibres from concrete. Moreover, the addition of steel fibres to concrete in columns delays the spalling phenomenon of the concrete cover and increases the ductility noticeably. Steel fibre content in the concrete plays a key role in strength and ductility. Hadi [11] explored the inclusion of steel fibres in the high strength concrete columns. Results of testing demonstrated that steel fibres content effectively increases the maximum load of the HSC columns and delays the cover spalling phenomena noticeably. Ikponmwosa and Salau [12] investigated the influence of short steel fibre inclusion on the behaviour of the normal strength concrete column. Results showed that increasing the volume fraction of steel fibre leads to an increase in the maximum column strength and the first crack load. Aoude et al [13] reported that the inclusion of steel fibres in the concrete columns markedly increased the peak axial load and improved the post peak behaviour of the column effectively. Moreover, Tokgoz et al. [14] reported that the incorporation of steel fibres in the high strength columns noticeably improves the confinement, deformability and the ductility of the column.

To maximize the enhancement due to the addition of steel fibres, past studies stated that the inclusion of different types of steel fibres can improve the performance of the concrete effectively. For instance, the inclusion of the microfiber of different diameters enhances the tensile behaviour of the concrete due to the influence of the fibres on the crack initiation and growth at different stages at failure [15,16]. Also, it is reported that the hybridization between steel fibres results in an increase in the strength and toughness of the concrete in comparison with the strength and the toughness of the concrete when one type of steel fibres was added [17]. This is attributed to the action of the steel fibres in controlling the formation of cracks which affects the tensile strength of the concrete. Several attempts were made to specify the interaction of hybridization of fibres to obtain the full advantage of steel fibre's action. For instance, it was reported that the ultimate compressive strain and the fracture energy was increased when a hybrid steel and polypropylene fibres were hybridized and added to the concrete [18–20]. Furthermore, Feldman and Zheng [21] stated that the hybridization of fibres such as steel fibres and polypropylene fibres increases the ultimate strength and toughness of concrete. Moreover, the hybridization of different types of fibres having different properties is more efficient due to different actions of each fibre. Banthia and Sappakittipakorn [22] concluded that the addition of crimped steel fibre of different diameters and sizes results in an improvement of the toughness of the hybrid fibre concrete in comparison with the toughness of the concrete when one type of concrete were used. Yao et al. [23] investigated the inclusion of steel fibres, polypropylene (PP) and carbon fibres in a hybrid form in the concrete. Yao et al. [23] concluded that the inclusion of two different types of steel fibres, especially steel fibres and carbon fibres, in the concrete considerably improved the strength and toughness of the concrete.

The inclusion of hybrid straight steel fibres in the Ultra-High Performance Concrete (UHPC) was investigated by Kang et al. [24]. Macro and short fibres of different tensile strengths 1100–2700 MPa and different lengths 12–19.5 mm were hybridized and added to UHPC. The hybridizations were in different ratios. It was concluded that the addition of hybrid fibres effectively improves the tensile behaviour of the UHPC. Park et al. [25] investigated the inclusion of the hybrid steel fibre in the UHPC. Macro, micro and twisted steel fibre were utilized in different ratios. The conclusion was that the geometry, the shape and the content of the steel fibre influence the tensile behaviour, strain hardening and the post-cracking strength of the concrete. Yu et al. [26] reported that the inclusion of hybrid steel fibres that included long and short steel fibre has increased the flexural and compressive strength of the UHPC markedly.

This paper presents experimentally the influence of steel fibres' inclusion in an individual form and in a hybrid form on the characteristics of RPC specimens. Two types of steel fibres having different properties were selected which are micro steel fibres (MF) and deformed steel fibres (DF). Hybridization (HF) between these two types of steel fibres was performed in this study by blending 50% of the optimum ratio of each steel fibre to be hybridized. Hybrid steel fibre (HF) was obtained from 2% MF and 1% DF to form 3% HF. Four groups of specimens were cast and tested. Each group include four specimens tested under concentric loading, eccentric loading (25 mm and 50 mm) and four-point bending.

1.1. Research significance

The utilization of RPC by itself in structural members is not well desired due to the lack of toughness and its brittle behaviour compared with the normal strength concrete. In addition, increasing the strength of the concrete utilized in structural members requires more confinement which may interfere with ACI design code (ACI 318-14) which limits the minimum spacing between the confining helix to 25 mm [27]. In addition, increasing the confinement by reducing the pitch of the helices results in early spalling of the concrete cover due to the formation of separation plane between the confined core and the surrounding concrete cover [28,29]. Therefore, enhancing the ductility behaviour of RPC is necessary in order to cope with the steel reinforcement design. Consequently, steel fibres are added to the RPC specimens in individual form and in hybrid form to investigate the contribution of steel fibres in improving the behaviour of the column and the influence of the steel fibres hybridization on the performance of RPC column. For this purpose, 16 specimens divided into four groups of four specimens according to the variation in steel fibres type were cast and tested under different loading conditions. The steel reinforcement for all specimens was kept the same for all specimens to investigate the influence of the steel fibres on the behaviour of RPC specimens.

1.2. Preliminary study

An investigation was conducted to optimise the optimum ratio of steel fibres to be utilized in RPC that enhances the performance of RPC in regards the strength and ductility under compression. Different ratios were utilized of the micro steel fibre (MF) and deformed steel fibre (DF). Results of testing demonstrated that the addition of 4% MF and 2% DF individually has improved the mechanical properties of the RPC. Moreover, the hybridization between 50% of the optimum ratio of MF (4%) and 50% of the optimum ratio of DF (2%) which forms 3% HF (2% MF and 1% DF) resulted in enhanced behaviour of RPC under compression.

2. Experimental program

2.1. Specimen design and preparation

In order to investigate the influence of each steel fibre on the behaviour of the RPC specimens under different loading conditions, 16 specimens of 200 mm in diameter and 800 mm in length were cast. Twelve specimens were tested under concentric and eccentric loadings and four specimens were tested as beam under four-point bending. All specimens were reinforced longitudinally with six deformed steel bars of 12 mm diameter (6N12). Smooth steel bar of a 10 mm diameter was used as helix (R10). The pitch of the