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An experimental study on flexural behaviour of large-scale concrete beams incorporating crumb rubber and steel fibres

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ABSTRACT

Twelve self-consolidating and vibrated concrete mixtures were developed to investigate the effect of crumb rubber (CR) with/without steel fibres (SFs) on flexural behaviour of large-scale beams. The main parameters were the percentage of CR (0–35% by volume of sand), volume of SFs (0%, 0.35%, and 1%), and length of SFs (35 mm and 60 mm). The performance of some code design equations was evaluated in predicting the cracking moment and flexural capacity of the tested beams. The results showed that increasing the CR appeared to narrow the crack widths, reduce self-weight of concrete, and improve deformability at a given load. On the contrary, the addition of high percentages of CR (above 15%) showed a significant reduction in the ductility, toughness, first crack moment, and ultimate flexural capacity of the tested beams. However, adding 1% SFs (35 mm) helped to increase the possible safe content of CR to 35%, achieving concrete beams with further reduction in self-weight and with sufficient flexural capacity, ductility, and toughness for multiple structural applications. The results also indicated that the investigated design equations conservatively predicted the flexural capacity of the tested beams but overestimated the first cracking moment.

1. Introduction

In recent years, significant research has been conducted on the application of waste rubber in the development of concrete as an alternative for conventional fine and coarse aggregates. This research is particularly aiming to present an eco-friendly, environmental alternative to the accumulated millions of waste tyres [1,2]. Such an approach, therefore, can greatly contribute not only to limiting the serious environmental problems that result from the disposal of worn-out tyres by burning or piling up in landfills, but it also reduces the consumption of natural aggregates. Consequently, involving waste rubber in the construction industry helps to promote the development of green buildings and implement the concept of sustainable production [3].

In small-scale testing (i.e., cubes, cylinders, and prisms), numerous studies have been performed to investigate the influence of rubber on the properties of concrete composite. The conducted studies indicated that using rubber aggregate appeared to improve the strain capacity, energy dissipation, damping ratio, and impact resistance of concrete [4–8]. The low density of rubber particles compared to conventional aggregates also helped to reduce the unit weight of concrete, achieving a more economical building design. However, the low modulus of elasticity of rubber particles compared to cement-mortar and the poor strength of rubber-mortar interface negatively affected the mechanical properties of concrete composite [9,10]. In large-scale testing, a limited number of investigations have studied the performance of structural members made with rubberized concrete. For example, Ganesan et al. [11] studied the effect of shredded rubber on the behaviour of self-consolidating rubberized concrete (SCRC) beam-column joints under monotonic and cyclic load. They stated that using rubber increased the crack resistance, energy absorption capacity, and ductility of concrete. Similar effects were observed by Youssf et al. [12], in which the addition of crumb rubber (CR) appeared to improve the hysteretic damping ratio and energy dissipation of concrete columns when cyclic loading was applied. Another study reported that masonry walls made with rubber-cement bricks exhibited higher toughness, deformation capacity, and capability to withstand post-failure loads compared to those made with conventional concrete bricks [13]. However, these studies reported a decrease in the ultimate capacity of the investigated structural members due to inclusion of rubber, which resulted from decaying the compressive and tensile strength of concrete composite.

In terms of materials, many researchers focused on alleviating the reduction in the mechanical properties by pre-treating the

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List of notation

CR	crumb rubber
SFs	steel fibres
SCC	self-consolidating concrete
SCRC	self-consolidating rubberized concrete
VRC	vibrated rubberized concrete
SFSCRC	steel fibres self-consolidating rubberized concrete
SFVRC	steel fibres vibrated rubberized concrete
C/F	coarse-to-fine aggregate ratio
w/b	water-to-binder ratio
MK	metakaolin
FA	fly ash
ASTM	American Society for Testing and Materials
HRWRA	high-range water-reducer admixture
M_{cr}^{exp}	experimental first cracking moment
M_{cr}^{theo}	theoretical first cracking moment calculated by design codes
M_{u}^{exp}	experimental ultimate moment capacity
M_{u}^{theo}	theoretical ultimate moment capacity calculated by design codes or empirical equation

surface of the rubber using different chemicals such as sulfur compounds and sodium hydroxide [14–16] or by pre-coating the rubber particles using mortar/cement paste [15]. Those techniques aimed to improve the adhesion between rubber particles and surrounding mortar. Other researchers compensated for the reduced mechanical properties by using supplementary cementing materials with high pozzolanic activity such as silica fume and metakaolin (MK) [17,18].

The inclusion of steel fibres (SFs) can also be an effective technique for alleviating the reduction in the tensile strength of rubberized concrete. The fibres' bridging mechanism allows tensile stress to transfer across the cracked sections, which provides a residual strength to concrete [19–22]. Moreover, the fibres' stitching action has an effective role in controlling the development of cracks and limiting the crack openings [23,24]. Using SFs was also found to boost the impact strength, toughness, and stiffness of concrete [25–27]. Combining CR and SFs in self-consolidating concrete (SCC) can develop new types of mixtures that have the desirable properties of SCC in the fresh state, such as high flowability, passing ability, and self-compactability, and those properties result from the addition of SFs and CR in the hardened state. However, optimizing the fresh properties of SCC incorporating CR and SFs is considered to be a significant challenge. Previous studies have indicated that including CR in SCC increased the inter-particle friction, which in turn decreased the flowability and passing ability of mixtures [28–30]. In addition, the low density of rubber makes it easy for particles to float toward the concrete's surface during mixing, causing segregation and hence reducing the stability of SCC mixtures. The problem becomes more significant when CR and SFs are combined: the presence of SFs increases the interference and blockage in mixtures, which leads to a significant decrease in the flowability and passing ability of SCC [31,32].

By reviewing the literature, it is obvious that a limited amount of research has studied the behaviour of rubberized concrete incorporating SFs in small- and full-scale testing, and no study has covered the combined effect of CR and SFs on the flexural behaviour of full-scale beams, especially when SCC is used. Accordingly, this research was conducted to study the flexural performance of large-scale reinforced SCRC, vibrated rubberized concrete (VRC), steel fibre SCRC (SFSCRC), and steel fibre VRC (SFVRC) beams. The behaviour of the tested beams in terms of load-deflection response, stiffness, ductility, toughness, first cracking moment, flexural capacity, and cracking characteristics was covered in this study. The research also evaluates the performance of code design equations in predicting the cracking moment and flexural capacity against the results obtained from the conducted experiments. Such comparisons are absent from the literature due to the novelty of this concrete type. The main purpose of the research is to extend the possible applications of CR with/without SFs in the concrete industry. The tested beams were developed with varied percentages of CR (0–35%), different volumes of SFs (0%, 0.35%, and 1%), and different lengths of SFs (35 mm and 60 mm).

2. Experimental program

2.1. Materials properties

Type GU Canadian Portland cement similar to Type 1 ASTM C150 [33], metakaolin (MK) conforming to ASTM C618 Class N [34], and fly ash (FA) similar to Type F ASTM C618 [34] were used as binders for all developed mixtures. Natural crushed stone, with a maximum size of 10 mm, and natural sand were used for the coarse and fine aggregates, respectively, with a specific gravity of 2.6 and water absorption of 1%. In this study, the fine aggregate was partially replaced by CR aggregate, which had a maximum size of 4.75 mm, a specific gravity of 0.95, and negligible water absorption. The aggregate gradations of the 10-mm crushed stones, natural sand, and CR are presented in Fig. 1. Two types of SFs with hooked-ends (Dramix 3D) were used in this study. The first type of SFs had a length of 35 mm, 65 aspect ratio, and a 0.55 mm diameter; while the second type of SFs had a length of 60 mm, 65 aspect ratio, and a 0.9 mm diameter. Each type of SF had a 1050 MPa tensile strength, 210 GPa Young's modulus, and 7.85 kg/m^3 density. A polycarboxylate-based high-range water-reducer admixture (HRWRA) similar to ASTM C494 Type F [35] with specific gravity of 1.2, volatile weight of 62%, and pH of 9.5 was used to achieve the required workability of the tested mixtures. The steel bars used in the constructed beams had an average yield stress of 417 MPa and an average tensile strength of 725 MPa.

2.2. Concrete mixtures

The developed mixtures were chosen from a comprehensive investigation implemented by the authors on optimizing the fresh and mechanical properties of SCRC, VRC, SFSCRC, and SFVRC mixtures [36]. This investigation indicated that to ensure SFSCRC mixtures achieved self-compactability with no visual sign of segregation, a total binder content of at least 550 kg/m^3 with a minimum water-to-binder (w/b) ratio of 0.4 should be used. The binder content (550 kg/m^3) included 50% GU Canadian Portland cement, 30% FA, and 20% MK, amounts which were found to be optimum choices for adjusting the mixtures' viscosity and, hence, reaching a good particle suspension with reasonable flowability. In particular, 20% MK [37] was used to compensate for the reduction in the mechanical properties of concrete (due to the addition of CR), which achieved compressive strengths suitable for multiple structural applications. The coarse-to-fine aggregate (C/F) ratio was kept constant at 0.7 in this investigation for all tested mixtures.