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# Shear behaviour of large-scale rubberized concrete beams reinforced with steel fibres

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## HIGHLIGHTS

- Shear behaviour of large-scale beams with up to 35% CR replacement was studied.
- Different types of SFs (35 and 60 mm) were investigated.
- Using SFs can extend the possible structural applications for CR.
- Inclusion of 1% SFs improved toughness and shear capacity of CR beams.

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## ABSTRACT

The present work was conducted to investigate the influence of crumb rubber (CR) with/without steel fibres (SFs) on shear behaviour and cracking of large-scale self-consolidating and vibrated concrete beams with no shear reinforcement. Twelve beams were developed with variables including different replacement levels of fine aggregate volume by CR (0%–35%), SF volume fractions (0%, 0.35%, and 1%), and SF lengths (35 and 60 mm). The fresh and mechanical properties of the developed beams' mixtures were measured, and the performance of the tested beams was evaluated based on cracking behaviour, ultimate shear load, post-diagonal cracking resistance, and toughness. In general, increasing the CR content from 0% to 25% in self-consolidating concrete (SCC) showed a negative impact on their fresh and mechanical properties, ultimate shear load, post-diagonal cracking resistance, and toughness of the tested beams, but showed an improvement in the deformability and self-weight of concrete. However, optimizing acceptable SCC mixtures with CR and SFs alleviated the reductions in strength that resulted from adding CR and significantly improved the beams' toughness, ductility, and cracking behaviour. Since the challenge to optimize mixtures with high flowability and passing ability was not a factor in developing vibrated mixtures, it was possible to develop vibrated rubberized concrete mixtures with higher percentages of CR and SFs, providing beams with further improvement in ductility, ultimate shear load, deformability, toughness, and with further reduction in self-weight.

## 1. Introduction

During the last two decades, many studies have evaluated the possible usefulness of worn-out tyres in the concrete industry. This intensive work aimed to present the clean alternative of re-utilizing huge volumes of such waste materials, attempting to fix a significant environmental problem caused by the accumulation of millions of scrap tyres worldwide [1]. Most of the available research has been conducted on small-scale samples (i.e., cubes, cylinders, and prisms), focusing on using waste rubber as a replacement for fine and coarse aggregate in concrete [2–11]. In general, using rubber aggregate in concrete was beneficial to producing a new type of concrete with higher strain capacity, flexural toughness, ductility, energy dissipation, damping properties, and reduced self-weight [2,3]. The impact resistance of concrete was also found to be increased with the addition of rubber [4–7]. Other studies reported that the use of rubber aggregate appeared to enhance the resistance of concrete to abrasion, freezing-thawing action, and acid attack [8–11], while the resistance to water absorption and chloride ion penetration may negatively be affected [1,12]. However, the negative impacts of waste rubber on some durability aspects can be alleviated by adding SCMs such as silica fume and metakaolin (MK) [13–15]. The literature also stated that involving rubber in concrete can obviously improve its acoustic absorption capacity [16,17], providing a promising potential for

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**Nomenclature**

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| *CR* | crumb rubber | *FA* | fly ash |
| *SFs* | steel fibres | $f_c'$ | 28-day compressive strength |
| *SCC* | self-consolidating concrete | $f_{sp}$ | splitting tensile strength |
| *SCRC* | self-consolidating rubberized concrete | *ME* | modulus of elasticity |
| *VRC* | vibrated rubberized concrete | $T_{50}$ | the time to reach 500-mm slump flow diameter |
| *SFSCRC* | steel fibres self-consolidating rubberized concrete | *SR* | segregation resistance |
| *SFVRC* | steel fibres vibrated rubberized concrete | *ITZ* | interfacial transition zone |
| *C/F* | coarse-to-fine aggregate | *HRWRA* | high-range water-reducer admixture |
| *w/b* | water-to-binder ratio | *ASTM* | American Society for Testing and Materials |
| *MK* | metakaolin | | |

rubberized concrete to be used in applications, such as eliminating sound transmission through walls, floors, and ceilings. However, such types of concrete (with rubber) suffer from a weakness in the bonding between the rubber particles and surrounding mortar, which plays a significant role in decreasing the compressive strength, tensile strength, flexural strength, and modulus of elasticity [3,14,18]. In full-scale testing, Ismail and Hassan [19,20] investigated the flexural behaviour of reinforced self-consolidating rubberized concrete (SCRC) and vibrated rubberized concrete (VRC) beams. Their results indicated that using crumb rubber (CR) up to 20% by fine aggregate volume showed a reduction in the first crack load, ultimate failure load, and stiffness, but increased the concrete's strain, deformation capacity, ductility, and toughness. These observations are also in agreement with those reported by Najim and Hall [1]. Another study [21] investigated the influence of applying uniform vertical loading on masonry walls made from rubber-cement bricks. The results indicated that inclusion of rubber in masonry walls generally improved its toughness, deformation capacity, and capability to withstand post-failure loads. Ganesan et al. [22] also investigated the behaviour of SCRC beam-column joints that incorporated shredded rubber aggregates under monotonic and cyclic load. The authors observed that the SCRC beam-column joints showed higher energy absorption capacity, crack resistance, and ductility compared to specimens with no rubber. Similarly, Youssf et al. [23] stated that adding rubber to VRC columns showed an enhancement in the behaviour of rubberized concrete columns under seismic loading in terms of the hysteretic damping ratio and energy dissipation, but with a slight reduction in the ultimate lateral load. Although a number of investigations have studied the behaviour of full-scale SCRC, none have focused on the influence of the rubber aggregate on the shear behaviour of reinforced concrete beams. The drastic deterioration in the compressive and tensile strengths of concrete due to the addition of rubber highlights concerns that the rubber-mortar composite may not be strong enough, especially in resisting shear stress. In addition, the cracking behaviour and cracking mechanism, which influence the shear behaviour of concrete [24], may be affected by the inclusion of CR in the concrete mixture.

Using steel fibres (SFs) in rubberized concrete can be a promising technique not only to compensate for the reductions in the mechanical properties (especially the tensile strength) and capacity of structural elements resulting from the addition of rubber, but also to improve the toughness, impact strength, ductility, and limit the crack widths in concrete [25–28]. This type of concrete can be used in structural elements subjected to high impact loading or sudden forces caused by earthquakes. It can also be used in offshore structures exposed to impact loading from iceberg or ice sheets. Previous studies have also showed that using SFs in concrete beams could increase their shear strength and deformability, and the failure mode became more ductile [29–42]. For example, Ding et al. [40] concluded that 60 kg/m$^3$ of SFs (60 mm length and 0.75 mm diameter) can increase the shear capacity of beams without stirrups up to 82% compared to beam with no SFs. Tahenni et al. [41] also reported that the shear strength of high-strength concrete showed an improvement of up to 47% and 88% for a quantity of 0.5% and 3% SFs (35 mm length and 0.54 mm diameter), respectively. Their results also indicated that ductility of beams is significantly increased with the addition of fibres, in which the inclusion of 3% SFs increased the ductility factor by more than twice that of beams with no SFs. These improvements come from fibres' bridging action, which plays an important role in transferring stress across the cracked sections, and hence providing a residual strength to concrete [42].

The technical benefits of using SFs in rubberized concrete can be extended when self-consolidating concrete (SCC) is used. Such combination can generate a type of concrete that merges the beneficial effects of CR and SFs on enhancing the ductility, toughness, impact resistance of concrete, on the one hand, and the desirable properties of SCC in the fresh state, on the other hand. However, combining CR and SFs in SCC mixtures may present a potential challenge in terms of optimizing the fresh properties. Significant research has reported that using rubber in SCC decreased the flowability and passing ability, and increased the risk of segregation [43,44]. Similar negative impacts were observed for the inclusion of SFs in SCC, in which high blockage between SFs and coarse aggregates resulted in greatly reduced flowability and passing ability of mixtures [28,46,47].

The published research indicates that a limited number of studies have investigated the performance of rubberized concrete containing SFs in small- and full-scale testing, but there is no study looking at the influence of rubber with/without SFs on the shear behaviour of beams, especially when SCC is used. The main objective of this research, therefore, was to study the structural behaviour of large-scale reinforced SCRC, VRC, steel-fibre SCRC (SFSCRC), and steel-fibre VRC (SFVRC) beams under shear load. The investigation evaluated the effect of CR with/without SFs on the cracking behaviour, shear capacity, post-diagonal cracking resistance, and toughness of the tested beams. In this experimental work, CR in various volume fractions (0% to 35%), different SF volume fractions (0%, 0.35%, and 1%), and different lengths (35 mm and 60 mm) were used.

## 2. Research significance

The present work aims to understand the effect of CR with/without SFs on the shear capacity of concrete beams with no shear reinforcement. Combining waste rubber and SFs in concrete attempts to generate new types of sustainable concrete that have superior properties for structural applications requiring high-impact resistance, energy dissipation, and ductility. The mixtures