The Effect of Industry Waste Material and Steel Fibers on the Fracture Characteristics of Self-compacting Concrete

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http://doi.org/10.29227/IM-2024-02-08

Submission date: *09.07.2024.* | Review date: *23.07.2024*

Abstract

The work aims to examine the effects of incorporating industry waste material and steel fibers on the fracture toughness properties of self-compacting concrete (SCC). A set of twenty-four specimens, comprising notched SCC beams with different shapes of steel fiber, each measuring 100 × 100 × 500 mm, those beams were tested under a three-point bending test. The red mud (RM) in this study is a by-product derived from Bayer's aluminum manufacturing industry, which was used as a partial (20%) of ordinary Portland cement. This study investigates five different fibers distinguished by their diverse shapes and aspect ratios. The fiber types encompassed in this study consist of the hook-end fiber, characterized by lengths of 60 and 30 mm, the straight fiber, characterized by lengths of 21 and 13 mm, and the flat-end fiber with lengths of 50 mm. The study investigates six distinct concrete combinations, all of which contain fibers constituting 1% of the total volume. An additional aim of the research is to examine the mechanical and fresh properties of concrete. The results demonstrate that the use of steel fiber negatively impacts the fresh concrete properties of SCC. The inclusion of steel fiber in a material leads to improved mechanical characteristics and fracture toughness in SCC. An increase was recorded in the peak loads, deflection at the point of failure, and crack mouth opening displacement.

Keywords: *Crack mouth opening displacement, Fracture Characteristics, Mechanical properties, Red mud waste, Self-compacting concrete, Steel fiber*

1. Introduction

The propagation of ground-borne vibrations into buildings is a multi-faceted process with ramifications that extend far beyond surface-level structural concerns. While the immediate worry often revolves around the risk of physical harm and accelerated deterioration of buildings, the impact of these vibrations is profound and wide-reaching. They not only pose a threat to the structural integrity of the built environment but also significantly influence the overall habitability of these structures. This influence transcends the realm of physical repercussions, delving into the psychological and physiological well-being of the individuals who occupy these spaces. From inducing feelings of discomfort and unease to potentially affecting sleep quality and overall health, the effects of ground-borne vibrations on building occupants are diverse and profound, warranting careful attention and consideration in architectural and urban planning endeavours.

Self-compacting concrete (SCC) is a unique type of concrete that possesses special characteristics. This sort of concrete mixture has unique flow characteristics. SCC undergoes compaction under its own weight, effectively spreading throughout the designated area, filling the formwork, and enveloping the reinforcement. This process ensures that segregation and excessive bleeding do not occur, and mechanical consolidation is not required [1]. Moreover, SCC typically has substantial amounts of powdered constituents that are essential for maintaining an appropriate yield value and preserving a viscous consistency in the fresh mixture. Based on the literature, the incorporation of fine elements such as fly ash, silica fume, and ground granulated blast furnace slag in industrial waste is deemed essential for the manufacturing of SCC, aligning with the European Guidelines for SCC [2]. Despite the numerous benefits of SCC, it is crucial to know that the cement industry stands as one of the three primary contributors to carbon dioxide (CO2) emissions [3]. Researchers have proposed many strategies to mitigate the emission of CO2 during the production of cement and concrete. In the field of concrete production, various waste materials are being used as either partial substitutes or complete replacements for cement, based on their weight. One example of a waste substance is red mud (RM). RM is a remarkable waste material that is generated in aluminum production facilities worldwide by the utilization of Bayer’s technique on bauxite. The substitution of a portion of RM with ordinary Portland cement effectively meets the requirements for concrete’s strength and durability, while also ensuring the proper disposal of RM [4]. The investigation conducted on the cementitious content of RM reveals that a replacement of 20% of RM for cement by weight leads to alterations in the characteristics. According to a study cited in reference [5], replacing more than 20% of RM in concrete considerably reduces its compressive strength and stiffness. However, SCC exhibits similar characteristics to conventional concrete, which indicates a low tensile strength and minimal resistance to crack propagation. The occurrence of concrete cracking has the potential to reduce the serviceability and durability of concrete elements [6]. The incorporation of steel fibers has the potential to enhance the post-peak characteristics of SCC. The utilization of SCC with fibers (SCFs) addresses two contrasting weaknesses, specifically, the limited workability observed in fiber concrete mixtures and the cracking resistance of conventional concrete. Therefore, the incorporation of fibers in SCC is considered a comparatively innovative composite material. This unique amalgamation offers the advantage of incorporating SCC technology alongside the benefits associated with utilizing fiber for a robust cementitious matrix. Numerous investigations have endeavored to enhance the mixture proportion of SCC through the incorporation of fibers (e.g., [7-9]). In summary, while certain researchers have conducted investigations into the fracture energy of conventional concrete compositions, comprehensive studies relating to the fracture toughness of unique concrete compositions remain lacking. Moreover, research on improving the fracture toughness of SCC using steel fibers is limited. Hence, a systematic investigation into the fracture toughness of SCC that contains RM and steel fibers must be conducted. The concept of including steel fibers and RM has been derived as a means of enhancing the fracture toughness of SCC and as an environmental solution to the disposal of waste materials. This study aims to investigate the effect of integrating RM waste and different types of steel fibers on the fracture toughness characteristics of SCC. A total of 24 specimens consisting of notched SCC beams with various steel fibers (measuring 100 × 100 × 500 mm) are subjected to a three-point bending test. This study examines five various fiber types characterized by varying shapes and aspect ratios. These fiber types include the hook-end fiber with lengths of 60 and 30 mm, the long straight fiber with lengths of 21 and 13 mm, and the flat-end fiber. Six concrete mixtures, each incorporating fibers with 1% of the volume percentage, are examined. RM is used at a replacement rate of 20% of the mass of cement. The slump flow, compressive strength, splitting tensile strength, and load–displacement/crack mouth opening displacement (CMOD) curves, and the fracture toughness parameters, were experimentally evaluated for all SCC mixtures.

2. Materials and Methods

The first control mixture was a simple SCC without adding RM or fibers. The SCC1 mixture was created by using RM as a partial (20%) regular Portland cement type-1 substitute. The coarse aggregate utilized in this study consists of limestone rock that has been crushed to a maximum size of 12.7 mm. The desert's natural sand is also used. Sand and gravel are used in accordance with ASTM C33 [10], with specific gravities of 2.67 and 1.70, and water absorption rates of 1.1% and 1.6%, respectively. The RM in this study is a by-product derived from the Bayer's aluminum manufacturing industry. The RM that was acquired underwent a filtration process using a 150 mm sieve to eliminate larger particles. Subsequently, the sample underwent a refinement process utilizing a ball mill, producing fine RMs characterized by an average diameter of 4.96 μm, as shown in Fig. 1.

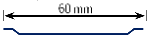
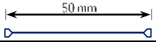
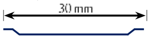
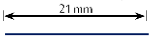
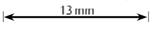
Fig. 1. RM in this study.

Table 1 displays the characteristics of RM and cement. The chemical characteristics of the fine RMs were found to be consistent with the standards stated in ASTM C618 [11]. The SCF mixtures were created using five different types of fibers: SF1, SF2, SF3, SF4, and SF5. These fiber types include the hook-end fiber with lengths of 60 and 30 mm, the long straight fiber with lengths of 21 and 13 mm, and the flat-end fiber. Moreover, 0.2% of hybrid fibers were included in each type of fiber. In this investigation, the volume proportion of SFs was 1% of the volume of concrete. Table 2 provides information on the fibers' characteristics.

Tab. 1. Properties of RM and Cement.

Material	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	CaO	TiO_2	L.O.I.	Average diameter (μm)	Surface area (m^2/kg)
RM	18	12	36	5.3	9	0.3	12	6.3	397
Cement	20.1	4.9	3.9	0.08	61.6	0.24	2.1	9.2	353

Tab. 2. Physical characteristics of steel fibers

Fiber Shapes	SF1 (Hooked end) 	SF2 (Flat end) 	SF3 (Hooked end) 	SF4 (Micro) 	SF5 (Micro) 
Diameter (mm)	0.92	0.9	0.55	0.35	0.2
Tensile strength (MPa)	1160	1160	1160	1100-1300	1100-1300
Aspect ratio	65	56	55	60	65

For improved workability, polycarboxylate superplasticizer (SP) was added to the SCC and SCF mixtures during production. The ACI 211.1–91 [12] criteria were followed in the creation of the concrete mixture. After the completion of the SCC mixture, steel fibers at a volume fraction of 1% added to create the SCFs. The concrete mixture proportions are presented in Table 3. In accordance with the EFCAA specifications [2], a slump flow test was conducted to determine the SCC characteristics of the fresh concrete. The compressive and splitting tensile tests were conducted on standard cylinders according to ASTM C39 [13] and ASTM C496 [14], respectively. In accordance with the RILEM 50-FMC [15] and the Karihaloo [16], the three-point bending test procedure was applied. The notched beams used in this study had dimensions of 100 × 100 × 500 mm and a notch depth of 30 mm, as shown in Fig. 2. The load-displacement/CMOD curves and fracture properties (i.e., fracture energy and fracture toughness) were used to assess the influence of different steel fiber types in accordance with the analysis conducted by Reda et al. [17], Al-Tayeb et al. [18], Alwesabi et al. [19].

Tab. 3. Concrete mixture compositions (kg/m3)

Mix ID	Water	Cement	RM	Sand	Gravel	SF1	SF2	SF3	SF4	SF5	SP
SCC	220	500	-	820	801	-	-	-	-	-	6.5
SCC1	220	400	100	795	801	-	-	-	-	-	6.5
SCF1	220	400	100	795	801	78.4	-	-	-	-	6.5
SCF2	220	400	100	795	801	-	78.4	-	-	-	6.5
SCF3	220	400	100	795	801	-	-	78.4	-	-	6.5
SCF4	220	400	100	795	801	-	-	-	78.4	-	6.5
SCF5	220	400	100	795	801	-	-	-	-	78.4	6.5
SCF6	220	400	100	795	801	15.68	15.68	15.68	15.68	15.68	6.5

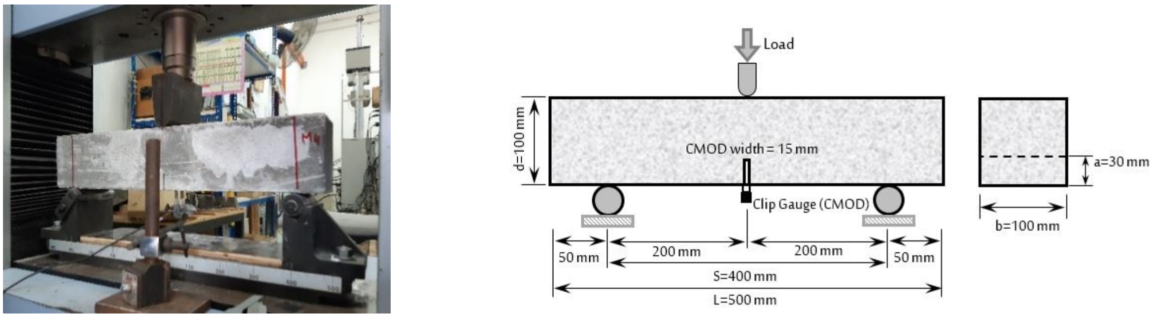


Fig. 2. Test setup.

3. Results and Discussion

Slump flow. Table 4 displays the slump flow, compressive strength, and splitting tensile strength results of the concrete mixtures. The SCC slump flow value exhibited a range of 500–700 mm, conforming to the standards specified by EFNARC [2]. The slump flow of mixes consisting of SCC, SCC1, SCF3, SFC4, and SCF6 showed a similar range. By contrast, the combinations of SCF1, SCF2, and SCF5 exhibited a lower flow that fell below the minimal threshold of 500 mm, showing a slight decrease in ratios ranging from 2% to 8%. The findings indicate that the incorporation of RM and steel fiber has an adverse effect on the fresh concrete characteristics of SCC, as shown in Table 4. This result agrees with the findings of Zeyad [20], which indicate that the incorporation of steel fiber has a detrimental effect on the fresh characteristics of SCC mixtures.

Compressive strength. The compressive cylinder specimens undergo a curing process lasting 28 days and testing in accordance with ASTM C39 [13]. The average compressive strength of SCC1, which has been partially substituted with 20% RM, shows an 11.6% higher ratio compared with that of the SCC mixture. The observed phenomenon can be attributed to the enhanced bonding and reduced air voids in the concrete paste. The incorporation of the various types of steel fiber exhibited a higher compressive strength compared with the SCC mixtures. This result is consistent with the findings published by [21, 22]. The increased ratios ranged from 16.2% to 35.9%, as shown in Table 4. SCF3, which refers to the smaller hooked fiber, exhibited the highest compressive strength when compared with the other SFC mixtures. Among all the combinations containing fibers, SCF6 (i.e., hybrid fiber) exhibited the lowest compressive strength.

Splitting tensile strength. The splitting tensile test was conducted on cylinder specimens after a curing process lasting 28 days and testing in accordance with ASTM C496 [14]. The same trend was observed regarding splitting tensile strength results. The average splitting tensile of SCC1, which has been partially substituted with 20% RM, shows a 6.2% higher ratio compared with that of the SCC mixture. The incorporation of the various types of steel fiber exhibited a higher splitting tensile strength compared with the SCC mixtures. The increased ratios ranged from 33.1% to 51.5%. The inclusion of fiber content in concrete enhanced its tensile strength properties. This improvement can be attributed to the ability of fibers to impede and span the fractures that form within the concrete matrix [23, 24].

Tab. 4: Slump flow, compressive strength, and splitting tensile strength results.

Mix ID	SCC	SCC1	SCF1	SCF2	SCF3	SCF4	SCF5	SFC6
Slump flow (mm)	730	690	460	490	530	500	490	520
Compressive Strength (MPa)	28.4	31.7	36.2	35.9	38.6	36.5	35.1	33.0
Splitting Tensile Strength (MPa)	2.60	2.76	3.56	3.46	3.68	3.94	3.77	3.69

Load–displacement characterization. The load–displacement/CMOD curves of the notched beams are shown in Figs. 3 and 4, respectively, and were used to calculate the fracture energy and toughness parameters as shown in Figs. 5 and 6. As the applied load progressively increased (Fig. 3), the deformation of the concrete matrix reached the strain at which early cracking occurred, resulting in the production of micro-cracks. The load–displacement curves exhibited an increasing linear pattern until the peak loaded. The steel fibers functioned by establishing a connection between the concrete elements along the existing fissures to delay the crack's expansion. The inclusion of fibers in the SCF mixes resulted in enhanced ductility and improved stress transfer capacity across cracks. The observed situation was marked by heightened peak loads, as well as the ultimate deflection of all SFC mixes. After reaching the peak loads, the SFC curves exhibited a gradual decline in loads without a sudden drop, as in the SCC and SCC1 specimens (Fig. 3), leading to a proportional increase in overall performance. Regarding the effect of the hooked fiber lengths (i.e., SF1 and SF3), SF3 (i.e., shorter fiber) resulted in a greater total area under the curve when compared with that of the SF1 (i.e., larger fiber). The incorporation of steel fibers resulted in an increase in the CMOD of the concrete matrix. Fig. 4 illustrates the load–CMOD curves of all SCF beams. The CMOD of the SCC and SCC1 beams mostly followed a straight line before it reached its highest point of load, and then it dropped quickly, as shown in Fig. 4. The initial stage of load application on the SCF beam exhibited linear elasticity. The steady increase in applied load showed that the plastic phase had begun, which is known for a different kind of cracking than what was seen in the SCC beam. The steel fiber has the potential to disengage gradually from the concrete, establishing a connection across the cracks. The bridging effect was enhanced by the incorporation of the hybrid steel fiber (i.e., SFC6), as shown by the continuum increase in CMOD with a slight decrease in loads, as presented in Fig. 4. The SCF6 specimen exhibited a satisfactory level of ductility.

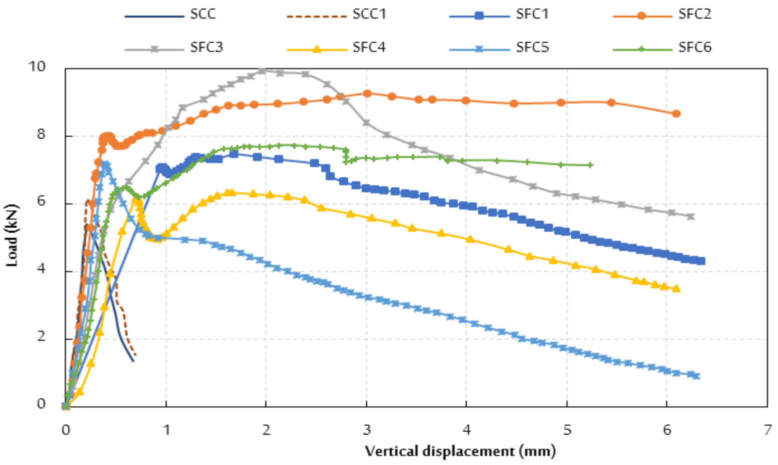


Fig. 3. Load-displacement curves of the various concrete compositions' notched beams.

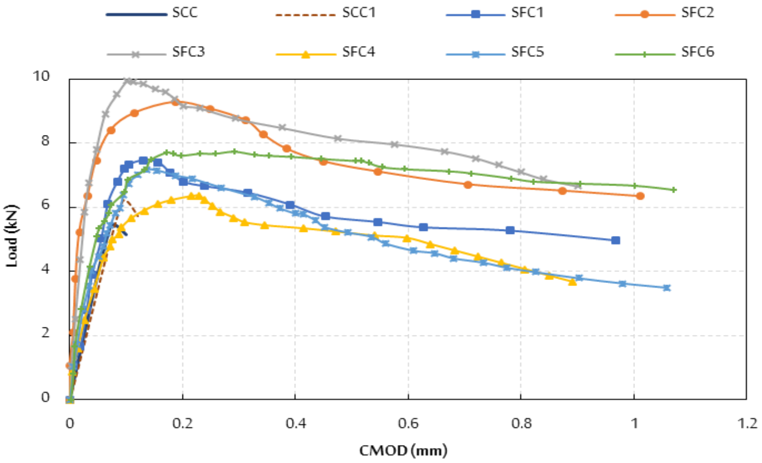


Fig. 4. Load-CMOD curves of the various concrete compositions' notched beams.

Flexural toughness parameters. Fig. 5 illustrates the influence of steel fibers on the fracture energy of the SCC and SCF mixes. The inclusion of steel fibers in the SCC matrix resulted in a considerable enhancement of fracture energy in comparison with the SCC and SCC1. The increased ratios ranged from 7.1 to 11.4 times when compared with the SCC and from 5.2 to 8.5 times when compared with the SCC1. The flat-end fiber (i.e., SCF2) demonstrated the maximum fracture energy compared with all other mixes, as shown in Fig. 5. Regarding the effect of longer fibers (i.e., SCF1 and SCF4), their combinations exhibited lower fracture energy in comparison with the shorter fibers (i.e., SCF3 and SCF5). The utilization of steel fiber led to the effective elongation of the trajectory of cracking, hence impeding its propagation and enhancing the fracture energy [25]. Fig. 6 illustrates the influence of various steel fiber types on fracture toughness. The fracture toughness of SCF mixtures showed remarkable improvement when compared with SCC and SCC1 mixtures. The increased ratios ranged from 17.1% to 82.9% when compared with the SCC and 3.4% to 61.3% when compared with the SCC1. The small hook-end fiber (i.e., SCF3) demonstrated the maximum fracture toughness compared with all other mixes, as shown in Fig. 6. The same trend was noticed regarding the effect of longer fibers (i.e., SCF1 and SCF4); their combinations exhibited lower fracture toughness in comparison with the shorter fibers (i.e., SCF3 and SCF5). The SCF's beams retained some of their integrity because they did not split in two entirely. During the examination of the SCF specimen, audible sounds of fiber pulling out or breaking could be discerned. Similar findings have been reported by [26, 27].

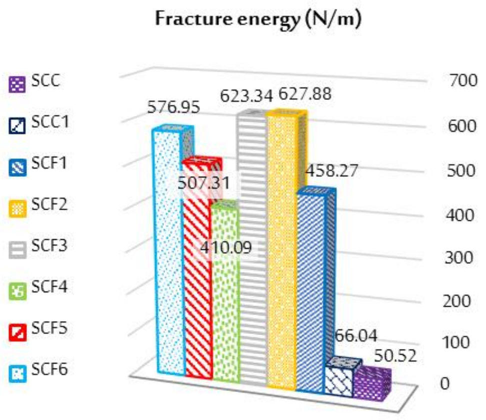


Fig. 5. Fracture energy results.

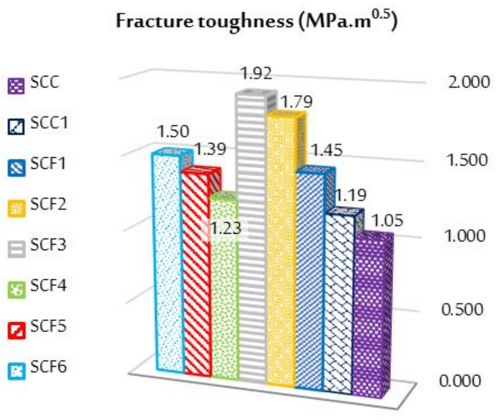


Fig. 6. Fracture toughness results.

4. Conclusion

The conclusions presented in this study can be summarized as follows:

1. The incorporation of RM and steel fiber has an adverse effect on the fresh concrete characteristics of SCC.
2. The cement partially substituted with 20% RM led to increased compressive and splitting tensile strengths of 11.6% and 6.2%, respectively, compared with the SCC mixture.
3. The inclusion of fibers resulted in enhanced peak loads, ultimate deflection, and ductility of the SCF mixtures.
4. Steel fiber has the potential to establish a connection across the cracks and delay total collapse, as demonstrated by the continuum increase in CMOD with a slight decrease in loads.
5. The inclusion of steel fibers in the SCC matrix resulted in a considerable enhancement of fracture energy and toughness as compared to the SCC and SCC1.

Recommendations for Future Study

On the basis of the findings of this study, potential areas for future research have been identified, as follows:

6. Investigate the fracture toughness of SCC with cement partially substituted with various ratios of RM.
7. Conduct an extensive investigation on the microstructure of SCC mixed with RM and steel fiber.
8. Evaluate the incorporation of RM and steel fiber in SCC’s dynamic characteristics.

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