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Scrap tire steel fiber as a substitute for commercial steel fiber in cement mortar: Engineering properties and cost-benefit analyses

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ABSTRACT

Utilization of recyclates in the construction industry is hamstrung by perceptions of lower quality, uncertain performance benefits and high cost. Thus, in this study, the mechanical performance and cost implications of using scrap tire steel fiber (SSF) with a hitherto limited reuse value as a partial or full substitute for virgin commercial macro hooked-end (HE) steel fibers in cement mortar are investigated. Mechanical properties, especially the post-crack average residual strength (ARS) and abrasion resistance of mixtures reinforced with 0.35% and 0.5% total fiber volumes were evaluated. Cost-benefit analyses based on derived ARS/abrasion performance enhancements and HE: SSF material cost ratios ranging from 1:0.2 to 1:0.7 were also performed. Results indicate comparable compressive and splitting tensile strength for all the mixtures investigated. However, fifty percent replacement of HE fiber with the SSF yielded a 39% increase in ARS relative to that of the 0.35% singly reinforced HE mortar. Similarly, the abrasion resistance of mortar mixtures singly reinforced with the SSF or fifty-fifty combination of the SSF and HE fibers was higher than those of mixtures reinforced with just HE fibers. Cost – benefit analyses indicate that for both ARS and Abrasion resistance, mortar mixtures singly reinforced with 0.35% SSF gave the best performance – cost benefit, up to four times that of the HE fiber at HE: SSF cost ratio of 1:0.2. Conversely, once HE: SSF cost ratio exceeds 1:0.5, the use of the SSF as a fiber reinforcement in mortar gave only marginal cost benefits, especially for 30% substitution of HE fibers with the SSF.

1. Introduction

The construction industry and its material manufacturing sub-sector not only consume large quantities of finite natural resources and energy, the waste generation and environmental pollution arising thereof are also humongous. Horvath (2004) reported that the construction industry has been the largest consumer of materials in the United States for more than a century. It was also estimated that more than 3 billion tons of materials are consumed in the manufacture of construction materials across the world annually (Saghafi and Teshnizi, 2011). A study on the energy use during the life cycle of buildings by Adalberth (1997) showed that approximately 15% of the total building energy use was utilized during the manufacture of virgin construction materials. Conversely, a related study by Gao et al. (2001) indicated that this energy consumption would be reduced if recycled materials are used in lieu of virgin materials. Therefore, in response to the growing concern about the activities of the construction industry and the clamor for material and environmental sustainability in recent years, the industry has been making efforts to mitigate its negative environmental footprints by embracing waste minimization and reuse concepts. Hence the reuse of thermal generation by-products, construction and demolition wastes and etc. as constituents in the manufacture of cement composites have gained traction in most developed countries. Development of cement-based applications for post-consumer goods from other sectors of the economy, such as the tire manufacturing industry has also received attention.

Several cement and concrete research studies have explored value-added applications for end-of-life tires (ELTs) by-products in the construction industry, such as the utilization of crumb rubber and rubber chips for soil improvement and the production of controlled low strength soil-based material (Edinçliler et al., 2010), the use of crumb rubber as aggregate in cement composites (Yilmaz and Degirmenci, 2009; Aiello and Leuzzi, 2010; Onuaguluchi and Panesar, 2014; Onuaguluchi, 2015; Thomas et al., 2015). Unfortunately, compared to investigations on crumb rubber modified cement composite in the literature, just a few studies have examined the recycling potential of steel which constitutes about 14–15% by weight of ELTs (CalRecycle, 2003), as a construction material. Therefore, given that approximately one billion ELTs are generated annually across the world (WBCSD, 2010), and this figure is expected to continue increasing as the world

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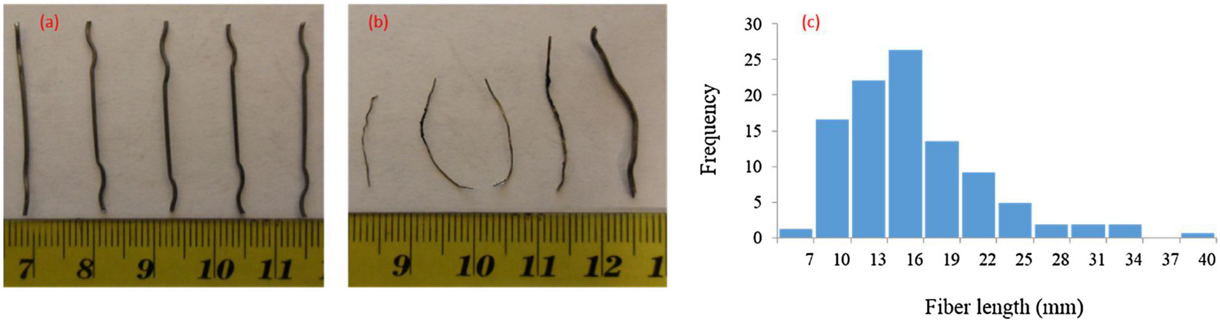

Fig. 1. (a) 30 mm HE fibers (b) Typical pieces of SSF (c) SSF length distribution.

population and vehicle usage become higher, a potential utilization option for micro scrap tire steel fiber (SSF) which has been largely limited to its meagre reuse value as a raw material in steel manufacturing plants and as an iron feedstock in cement plants is as a discrete fiber reinforcement in cement composites.

Previous studies have confirmed that macro steel fibers improve the plastic shrinkage crack resistance and mechanical strength, especially the post-crack flexural toughness of cement composites (Banthia et al., 1994; Banthia and Sheng, 1996), hence a large volume of virgin macro steel fibers of varying dimension and geometry is used as reinforcements in cement-based materials annually. A limited number of studies on mechanical strength properties of SSF reinforced cement-based materials (Tlemat et al., 2006; Aiello et al., 2009; Centonze et al., 2012; Sengul, 2016) and the effect of the SSF on the corrosion performance of composites (Graeff et al., 2009; Onuaguluchi et al., 2017) highlighted the potentials of the SSF as a discrete reinforcement in cement composites. However, compared to the performance of commercial macro steel fiber reinforced mixtures containing the same volume fraction of fiber, the mechanical properties of SSF reinforced cement composites reported in some of the previous studies were lower (Graeff et al., 2012; Martinelli et al., 2015; Sengul, 2016). This reduced mechanical strength performance is understandable, given the very short dimension of the SSF. Fiber hybridization which is a concept utilizing either the differences in fiber dimension or stiffness to synergistically enhance the mechanical properties of fiber reinforced cement-based materials could be used to ameliorate the aforementioned drawback of the SSF. Research findings on commercial steel fiber hybridization (Nehdi and Ladanchuk, 2004; Banthia and Soleimani, 2005; Banthia and Sappakittipakorn, 2007) showed that while micro fibers bridge and delay micro-cracking, macro fibers inhibit macro-crack propagation thereby enhancing the toughness of cement composites. Therefore, it is possible that the synergistic effect from a hybrid combination of macro steel fiber and micro SSF which would provide a higher number of individual short-sized fibers per unit volume of the matrix could also enhance the mechanical performance of cement-based materials.

It seems that the absence of a large body of information on the performance of SSF reinforced cement composites contributed to the limited interest in its use as a reinforcement in cement composites. According to Oyedele et al. (2014), the paucity of information about the effectiveness and durability properties of recycled materials are some of the reasons for the ambivalent attitude of the construction industry towards recycled by-products. However, the main factor seems to be the presumed lower quality and higher cost of SSF in comparison to virgin commercial macro steel fiber. Therefore, to engender the interest of the construction industry, the performance of SSF reinforced cement composites needs to be enhanced substantially at minimum costs. Hence, there is a need for studies highlighting cost ranges for maximizing performance benefits accruable from the use of the SSF in place of commercial macro steel fiber in cement-based materials, especially simple and easy to understand cost-benefit analyses that are unencumbered by regional variation in material costs.

Therefore, given the dearth of information in the literature on the engineering properties of single and hybrid SSF/commercial steel fiber reinforced cement composites, this study is aiming to provide additional insights on the abrasion resistance and mechanical strength, especially the post-crack residual flexural strength of mortar mixtures containing the SSF as a complete or partial substitute (hybrid combination) for hook-end (HE) steel fibers in repair mortar. Moreover, globally applicable cost-benefit analyses based on derived performance enhancements and HE: SSF material cost ratios were also used to further assess the economic viability of the SSF as a substitute to macro HE fiber as a discrete reinforcement in mortar.

2. Experimental methods

2.1. Materials

Ordinary Portland cement (OPC) and natural sand, fine aggregate having a specific gravity of 2.65 were used. Pictorial descriptions of the fibers used in this study are given in Fig. 1a–c. The SSF used were obtained from a scrap tire processing plant in Canada. The average length and diameter of the HE fiber was 30 mm and 0.65 mm, respectively. While the average diameter of SSF was about 0.2–0.3 mm, its average length was approximately 15 mm, with two predominant length classes of 10–13 mm and 13–16 mm as shown in Fig. 1c. Scanning electron microscopy (SEM) photomicrographs highlighting typical surface characteristics of the SSF are shown in Fig. 2, and it indicates the presence of largely smooth, but twisted, deformed and partly shredded fibers, with attached rubber residue in some instances.

2.2. Methods

2.2.1. Mortar mixture proportion

To ensure that all the mixtures are workable with similar consistency, mortar mixtures with a constant water-to-cement (w/c) ratio of 0.50 and sand-to-cement (s/c) ratio of 2.0 was prepared, and singly reinforced with 0%, 0.35% and 0.5% volume fractions of HE and the SSF, respectively. Thereafter, a second batch of mixtures where each volume of HE fiber was partially replaced by 30 wt% and 50 wt% of the SSF was also prepared. A total of nine mixtures as shown in Table 1 were investigated. Mortar mixtures were prepared using a rotary pan mixer, and according to the ASTM C192 (2016) specifications. The total mixing time used was six minutes. Cast specimens were de-molded after 24 h, and thereafter kept in the curing room at a temperature of 23 ± 0.5 °C and relative humidity of 95 ± 5% for 14 days.

2.2.2. Compressive and splitting tensile strength

Three 75 mm × 150 mm cylindrical specimens were used to determine the compressive strength of the plain and fiber reinforced mixtures in accordance with ASTM C39 (2017). The loading rate used was 0.24 MPa/s. The splitting tensile strength of three 75 mm × 150 mm specimens obtained from each mixture was also