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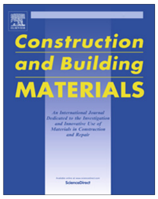

Friction and fracture characteristics of engineered crumb-rubber concrete at microscopic lengthscale

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HIGHLIGHTS

- Crumb rubber inclusions contribute to an increase in the effective friction behavior.
- Higher values of the fracture toughness are observed with the addition of crumb rubber particles.
- Crumb-rubber reinforced concrete is more resistant to surface lubrication with oil or water.

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ABSTRACT

Using small-scale depth-sensing techniques, we investigate the friction and hardness of engineered crumb rubber-reinforced concrete with applications into railway sleeper ties. The partial replacement of aggregates with crumb rubber particle leads to an increase in the friction coefficient and the fracture toughness, and a slight decrease in strength properties. Moreover, improper bonding at the cement/rubber interface is shown to result in poor strength characteristics. Furthermore, crumb rubber particles contribute to a higher durability as evidenced by sustained high values of the friction coefficient even in presence of surface lubrication with water or oil.

1. Introduction

Crumb rubber concrete is an alternative way to reuse rubber waste and prevent pollution of the environment [1]. Up to 12 million tons of rubber waste are disposed annually in both the US and Europe [2,3]. Recycling rubber into advanced construction materials provides a way to alleviate the pressure to landfills. A byproduct of the petroleum engineering industry, tire wastes are estimated at 75 million tons per year in the United States alone [4]. Tire wastes are problematic because (i) they are non-biodegradable, (ii) they require a significant amount of space, (iii) they pose a fire hazard [5], and (iv) they serve as a breeding ground for mosquitoes and larvae. A highly-explored strategy to recycle waste tire consists in embedding crumb rubber in cement mixtures for structural applications such as railway concrete sleepers [6,7], asphalt pavements [8], or precast concrete [9].

Although previous studies have focused on the strength characteristics of rubber-reinforced concrete [5,10], the friction characteristics have received little attention. For instance, Liu et al. recorded the mechanical and durability properties of the crumb rubber concrete from the macro level [2]. A negative correlation was observed between the compressive strength and the rubber content [11]. Taha et al. investigated the mechanical and fracture properties of rubber concrete using quasibrittle fracture mechanics models. They concluded to the existence of an optimal replacement ratio for tire rubber particles to enhance fracture toughness without compromising strength [12]. Ganesan et al. studied the flexural fatigue behavior of self-compacting shredded rubber concrete and showed that a 15 percentage or 20 volume percentage replacement of rubber would significantly improve the distribution of the fatigue life. [13]. Ganesan et al. studied the strength and durability characteristics of self-compacting rubberized

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concrete with or without steel fibers. They found that the addition of steel fibers can compensate the loss of strength due to rubber addition [14]. Nevertheless, in the aforementioned studies, the tribological behavior was not considered. The impact of tire particle/cement matrix bonding was not studied. Finally, the effect of surface treatment on the mechanical performance was not investigated. As friction and wear are important measures of the durability of railway tracks, new studies are needed. To this end, we rely on micro-tribology tests such as scratch testing to gain a fundamental understanding at the micro- and meso-scale.

In order to understand the friction and fracture response, we rely on scratch testing. Other methods such as atomic force microscopy (AFM) [15] and lateral force microscopy (LFM) [16] have been suggested in the past to measure the friction. However, the AFM/LFM techniques present several drawbacks such as tedious force calibration procedure, and unknown probe tip geometry which makes it challenging to gather valuable quantitative information regarding the friction and fracture behavior. Another challenge is the resolution which remains at the nanoscale. In practice, AFM/LFM methods have been used to yield qualitative data regarding the topography and morphology of cementitious materials. For instance, atomic force microscopy (AFM) and lateral force microscopy (LFM) techniques have been employed to investigate the nanostructure and microstructure of cement hydration products [17–19]. Herein, we select constant-load and progressive-load scratch testing for improved accuracy, reliability and rigor.

Scratch tests consist in pushing a sharp diamond probe across the surface of a weaker material. Scratch tests are frequently used to characterize the friction behavior of metals, polymers, thin films, coatings, and ceramics [20–24]. Very recently, scratch tests have been applied to characterize the tribology of cementitious materials and geomaterials, which exhibit a large degree of heterogeneity [25]. To our knowledge, scratch tests have not yet been applied to crumb rubber-reinforced concrete. A major challenge is the large range of length-scales between the whole concrete at the meso and macroscopic scale and the micro-constituents at the micro-scale. Herein, we apply fracture analysis and friction analysis to scratch testing in order to understand the tribological behavior of crumb-rubber concrete at different length-scales and under different loading conditions and surface treatment options.

2. Materials and methods

Four different types of crumb-rubber reinforced concrete were synthesized at the Birmingham Centre for Railway Research and Education at the University of Birmingham. The mix design is summarized in Table 1. Mix 1 is the control material, which consists of cement, water, fine aggregate, and coarse aggregate. Table 2 provides the gradation of the aggregates used in this study. In order to compensate for the potential loss in mechanical resistance due to the addition of crumb-rubber particles, fume silica was introduced in Mix 2–4 at a ratio of 10% in weight with respect to the mass of fine aggregates. Mix 2 was reinforced with silica fume whereas both Mix 3 and Mix 4 were reinforced with rubber with a mass fraction of respectively 5% and 10% with respect to the mass of fine aggregates. Silica fume, grade 940, was utilized for Mix 2–4 with the chemical and physical properties of silica fume given in Table 3. Two different sizes of crumb rubber were used: 425 μm with a specific gravity of 1.14 ± 0.02 for Mix 3, and 75 μm with a specific gravity of 1.14 ± 0.03 for Mix 4. For each design, 5.5-in.×2-in.×1-in. specimen blocks were manufactured. The specimens were subsequently aged for 28 days prior to microscopic examination and testing.

Table 2
Aggregate gradation table.

Serial No.	Sieves (mm)	% retained	Cumulative retained	% fine
1	20	0	0	100
2	16	0	0	100
3	10	21	21	79
4	6.7	67.5	88.5	11.5
5	4.75	9	97.5	2.5
6	Base	2.5	100	0

Table 3
Chemical and physical properties of silica fume.

Properties	Specification	Unit
SiO_2	>90	%
Retention on 45 μm sieve	<1.5	%
H_2O (when packed)	<1.0	%
Bulk Density (U)	200–350	kg/m^3
Bulk Density (D)	500–700	kg/m^3

2.1. Material peparation

In order to ensure accurate measurements, a rigorous specimen preparation procedure was devised so as to yield a low surface roughness relative to the maximum penetration depth [26]. The specimens were machined using a top-table bandsaw and later embedded under vacuum in an epoxy resin. A linear-precision diamond saw was later utilized to yield 5-mm thick cylindrical specimens with rigorously flat top and bottom faces. The resulting specimens were mounted onto metal disks using cyano-acrylate adhesive. The mounted specimens were then ground and polished using a semi-automatic grinder/polisher. Grinding occurred using silicon carbide abrasive discs of different gradations, consecutively 240, 400, 600, 800, and 1200. Afterward, polishing took place using colloidal suspensions of polycrystalline diamond with particle size consecutively 3 μm, and 1 μm. In between each steps of the grinding and polishing phases, the specimens were rinsed in N-Decane using an ultrasonic bath. The quality of the polished surface was assessed via optical microscopy and surface profilometry. After grinding and polishing, the specimens were stored in a vacuum desiccator at room temperature to prevent water-induced degradation [27].

2.2. Micro-structural characterization

Scanning electron microscope (SEM) was used to image the polished crumb-rubber cement specimens. A JEOL JSM-6060LV Low Vacuum Scanning Electron Microscope (SEM) was utilized at the

Table 1
Design of crumb-rubber reinforced concrete systems considered in this study.

Material	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Silica fume (kg)	Rubber (kg)
Mix 1	530	233	630	986	0	0
Mix 2	477	233	630	986	53	0
Mix 3	477	233	599	986	53	32
Mix 4	477	233	567	986	53	63