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Properties of high-performance cementitious composites containing recycled rubber crumb

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HIGHLIGHTS

- Addition and replacement mix design schemes lead to comparable material properties for high-performance cementitious composites containing recycled rubber crumb.
- Drying shrinkage is neglectable after hot water curing and the 28 days' dry shrinkage can be reduced by introducing submerge curing at early ages.
- The compressive strength reduction can be mitigated by pre-treatment of rubber crumb using $Na(OH)$.
- Excellent resistance to chloride penetration was not compromised by the amount of rubber crumb up to 40% of the volume of the fine sand.

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ABSTRACT

Concrete containing rubber crumb from waste tyre has been investigated previously and enhancement of material performance, for example, energy absorbing, has been observed. However, at the same time, the degradation of compressive and flexural strength, as well as some other physical properties are also inevitable. In this study, physical, mechanical properties and durability of High Performance Cementitious Composites containing rubber crumb (HPCC-R) were assessed. Moreover, 2% volume fraction of micro steel fibres were added to form High Performance Fibre Reinforced Cementitious Composites (HPFRCC-R) to increase its integrity. Experimental results were then compared to those of the base material without rubber crumb. The impact of different mix design methodologies, grading of rubber particles, and different curing conditions were investigated.

It was observed that the drying shrinkage is neglectable after hot water curing at either 90 °C or 60 °C for HPCC-R. Under normal curing condition, drying shrinkage development follows the similar trend as the base material but end up with approximately 20% higher shrinkage at 28 days' age. The compressive strength and flexural strength of both HPCC-R and HPFRCC-R decrease significantly with the increase of the amount of rubber crumb. Applying hot water curing at 90 °C and pre-treatment of rubber crumb using $Na(OH)$ were identified as effective approaches to compensate the compressive strength loss. However, it was observed that impacts of different curing conditions are insignificant on the flexural strength development. The rapid chloride permeability test (RCPT) results of HPFRCC-R material under different curing conditions were at the same level, and as good as that of the base material. Mixing scheme of using rubber crumb as filler material instead of replacement of fine sand lead to better material performance regarding its compressive strength versus density ratio at a relatively high replacement ratio of 40% by volume. It is recommended to use "Addition" mixing scheme when a large amount of rubber crumb being used in HPFRCC in the future.

1. Introduction

The amount of annually discarded tyres is estimated to be up to 1200 million by the year of 2030 [1]. Disposal of waste tyre rubber as a part of solid management results in a significant environmental issue. In most cases, these discarded tyres are inadequately disposed of, which causes potential damages to human health. In most countries, landfill and incineration are primary treatment methods of used tyres, which are not optimal due to the limitation of space and long-term pollutants generated in the environment. In order to solve this environmental issue, the recycling of discarded tyre rubber has been investigated and take into practice. The

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recycled tyre rubber has been used for manufacturing new tyres, for agricultural purpose [2], or to be used as a raw material for various civil engineering materials, such as asphalt and concrete.

Recycled rubber particles were used in sustainable concrete products, such as paving blocks [3], road side barriers [4], pervious concrete [5], rigid pavements [6], composite beams [7], metal deck composite slabs [8], concrete column in seismic zone [9], and external building cladding [10], etc. In the majority of the investigations, the rubber crumb is used as a replacement for fine aggregates. Sometimes, they were also used to replace coarse aggregates if the rubber particle size is big enough [11]. The concrete containing rubber crumb exhibits excellent energy absorbing characteristics and is usually lighter than conventional concrete [12]. Use recycled rubber as aggregates can be an economical and environmentally friendly solution. However, the property degradation of concrete is expected because the modulus of elasticity and strength of rubber crumb are usually much smaller than those of nature aggregates.

It is widely reported that the compressive strength of concrete decreases when rubber crumb is incorporated as replacement of sand. This conclusion was confirmed for concrete materials with a wide range of water cement ratio [13–15]. The degree of strength degradation with regard to the replacement percentage is greatly affected by the mix design scheme. For equivalent weight replacement, the compressive strength decrease is report to be 31% for 5% weight replacement rate [16] and 25% for 7.5% weight replacement rate [10], respectively. However, for equivalent volume replacement scheme, 5% sand replacement cause insignificant compressive strength reduction (less than 5%) as stated by Youssf [17] and Guo [18]. For high strength concrete, the volume replacement also leads to high strength reduction and was approximately 57% for 20% replacement rate according to [19]. Different replacement schemes investigated in previous researches are shown in Table 1. It can be seen that the density of rubber crumb affects the actual amount of rubber material used in the mix design even if equivalent volume replacement percentage is used. The compressive strength of concrete containing rubber particle is also affected by the size of the rubber. Usually, the concrete with fine rubber particles shows higher compressive strength than those with same amount but larger rubber particle size [20]. In addition, adding silica fume into the mix design usually lead to much higher compressive strength [21]. Finite element models built in Abaqus were used to simulate the compressive strength of concrete containing rubber crumb and good correlation was observed for rubber concrete with 20% replacement rate [22]. Thomas [15] and Xie [23] observed that flexural strength is also decreased when adding rubber crumb into concrete. Guo [18] and Gesoglu [5] observed that rubber aggregate can increase both fracture energy and fracture toughness when rubber content does not exceed 10%.

In order to improve the interface bond between rubber particle and hydrated cement paste, various surface treatments were investigated including water washing, limestone powder coating [24], and cementitious silane coupling agent [25]. While the compressive strength increase by 5% when coating the rubber particle by limestone powder under a 15% volume replacement scheme, the compressive increase was reported to be around 10–20% by using silane coupling agent. The pretreatment using $Na(OH)$ solution for 30 min is also used in previous researches [17], which is aiming to remove the zinc stearate layers from the rubber surface and thus improve the bond between particles and cement paste.

According to the investigation of Thomas [15] and Gupta[13], the concrete with rubber crumb has higher resistance to carbonation. The resistance to abrasion of the concrete with rubber crumb is increased according to the test conducted by Thomas [26] and Su [20]. Similar results are achieved in chloride penetration test conducted by Azevedo [16] and Thomas [27]. The resistance to chloride penetration increases when rubber crumb is used as aggregates. With regard to the volume stability, the drying shrinkage for concrete with a 25% volume replacement of rubber is reported to be around 502 ± 151 microstrain at 28 days, which increases around 10% when compared to the base group without rubber. Meanwhile, the durability of concrete containing rubber crumb is reported as acceptable with volume replacement up to 20% with regard to its carbonation depth, acid attack resistance, and chloride penetration depth [28]. In general, although mechanical properties and some of the durability properties of concrete with rubber crumb generated from recycled tyres are degraded, this material does have relatively high energy absorption, low density, improved heating insulating and acoustic properties. Therefore, such concrete is considered to be a promising material for construction industry [24,29,30].

Table 1
Summary of sand replacement rate and rubber particle usage.

Literature	Specimen ID	Sand (kg/m^3)	Rubber (kg/^{m}3)	Rubber/Sand
Azevedo et al. [16]	C_5RW_15	1132	60	1
	C_10RW_15	1073	119	
Holmes et al. [10]	2A	570	0	1
	1A	527.3	42.7	
Youssf et al. [17]	L0	628	0	0.33
	L5-P	597	10.2	
Guo et al. [18]	RC-R0	645	0	0.40
	RC-R4	625	7.9	
Onuaguluchi et al. [21]	R	820	0	0.41
	A5	779	16.8	
Mohammadi et al. [6]	T/0.35/00CR	695	0	0.44
		556	61	
Xie et al. [23]	RC-R0	626.2	0	0.41
	RC-R4	601.2	10.2	
Al-Tayeb et al. [42]	Plain	797	0	0.25
	FrT	638	39.7	
Gesoglu et al. [5]	Control	1594	0	
	10TC	1434.6	59.8	0.38
	10CR	1434.6	48.6	0.30
	10FCR	1434.6	28.1	0.18