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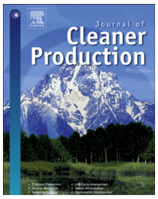

Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes

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ABSTRACT

Investigations and research into the recent use of rubber particles in concrete has been well documented. However, information on the rubber particle sizes or their distributions within concrete which may also influence the concrete properties is still limited. In this study, three groups of singly-sized rubber particle samples (3 mm, 0.5 mm and 0.3 mm) and one sample of continuous size grading (prepared by blending the three singly-sized samples to form the same particle distribution curve of sand) were used to replace 20% of the natural fine aggregate by volume. The reference concrete containing 100% sand was also prepared to compare its properties with those of the samples in terms of workability, fresh density, compressive strength, tensile splitting strength, flexural strength and water permeability. The experimental results demonstrated that the rubber particle size affects the concrete's workability and water permeability to a greater extent than the fresh density and strength. Concrete with rubber particles of larger size tends to have a higher workability and fresh density than that with smaller particle sizes. However, the rubber aggregates with smaller or continuously graded particle sizes are shown to have higher strengths and lower water permeability.

1. Introduction

Waste tyres have presented a pressing global issue for the environment, as a result of a growing use of road transport vehicles. Discarded waste tyres often create 'black pollution' because they are not readily biodegradable and pose a potential threat to the environment (Nehdi and Khan, 2001). Several means of reusing or recycling tyre rubber have been proposed, including the use of lightweight fill in the asphalt pavement, fuel for cement kilns, the feedstock for making carbon black, and the artificial reefs in marine environments (Prasad et al., 2009; Raghavan et al., 1998). However, some of these proposals are economically or environmentally unviable.

In the past twenty years, many attempts have been made to utilise recycled waste tyre rubber as an aggregate substitute in concrete. Together with other recycled aggregates, such as recycled concrete (Marie and Quiasrawi, 2012; Yang et al., 2011), and recycled glass (Ling and Poon, 2014; Castro and Brito, 2013), the recycling of scrap tyres has become a viable option for sustainable construction. A great number of applications have been reported on the use of waste rubber aggregate since an early study by Eldin and Senouci (1993). Most researchers have confirmed that there is a decrease in compressive strength and an increase in ductility with an increasing proportion of rubber phase in the mixture (Bignozzi and Sandrolini, 2006). To the authors' best knowledge, limited research work studies the effect of the size of rubber particles on the properties of resulting concrete, such as workability, strength and durability, as indicated by the literature review (Albano et al., 2005; Ali et al., 1993; Eldin and Senouci, 1993; Fattuhi and Clark, 1996; Fedroff et al., 1996; Li et al., 2009; Topçu, 1995). Furthermore, the conclusions from the reported studies are quite inconclusive due to the wide variations in the reported results.

In an early study, Eldin and Senouci (1993) reported that there was around 85% reduction in compressive strength and a 50% reduction in tensile strength when the coarse aggregates were fully replaced by coarse rubber chips. On the other hand, when fine aggregates were fully replaced by fine rubber, specimens lost up to 65% and 50% of their compressive strength and tensile

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Abbreviations

BS	British standard
CCSR20	concrete with combined-size rubber, 20% fine aggregate by volume
CRA20	concrete with rubber sample A, 20% fine aggregate by volume
CRB20	concrete with rubber sample B, 20% fine aggregate by volume
CRC20	concrete with rubber sample C, 20% fine aggregate by volume
CSR	combined-size rubber
EN	European norm
PSD	particle size distribution
RA	rubber sample A
RB	rubber sample B
RC	rubber sample C
REF	reference mix without rubber
SSD	saturated surface dry

Variables in formulae

m_{ec}	mass of empty container
m_{fc}	mass of filled container
m_{OD}	mass of oven dried aggregate
m_{SSD}	mass of saturated surface dried aggregate
v_c	volume of container
v_{SSD}	volume of saturated surface dried aggregate

strength respectively. Topçu (1995) reported the decrease of about 50% in the cylinder and cube compressive strength, and of 64% in the tensile strength observed in the concrete mixed with fine rubber particles. Introducing coarse rubber particles reduced the cylinder and cube compressive strengths by nearly 60% and 80%, respectively and the tensile strength by nearly 74%. These results indicate that the coarse rubber aggregates have a more significant negative effect than the fine rubber aggregates. However, the results of tests carried out by Fattuhi and Clark (1996) indicated the opposite trend. They found that adding graded fine rubber granules lowered the compressive strength of concrete more than the graded coarse granules. This was in agreement with Ali et al. (1993), but not with the findings of Eldin and Senouci (1993) or Topçu (1995).

In a recent study, Li et al. (2009) reported that using rubber particle sizes between 0.25 and 1 mm has less effect on the tensile splitting strength than on the compressive strength, and finer rubber was particularly beneficial for reducing the tensile splitting strength loss. These results partially disagree with the findings of Albano et al. (2005) who found that a decrease in the rubber particle size from 0.59 mm to 0.29 mm resulted in a lower workability and density at the fresh stage, as well as the weaker compressive and tensile splitting strengths at the dry stage. It is difficult to directly compare the results from various resources, as the nature of the raw materials, the test specimens and test methods were different. Hence, there remains a need to carry out further studies.

The aim of this study is to further the understanding of the effects of rubber particle size on the properties of the resulting concrete. To this end, three types of rubber particle samples with singly-sized rubber particles, and a fourth with rubber particles of varying sizes were used as part of the fine aggregate in concrete. A series of tests, including workability and density at the fresh stage, the cube compressive strength, the tensile splitting strength, the flexural strength and water permeability at the hardened stage were conducted according to relevant standards. Test results were analyzed and discussed, leading to the conclusions informing the tyre recycling industry to rationally design the particle size distribution (PSD) of rubber particles as the recycled aggregates.

2. Preparation of concrete

2.1. Materials

The materials used for preparing the test specimens comprised cement, water, coarse aggregate, fine aggregate and different sizes of rubber particles.

2.1.1. Cement

Ordinary Portland cement with a characteristic strength of 42.5 MPa was used in accordance with BS EN 197-1. This cement contains 30% of pulverised fly ash which was taken into account in the mix design process. It was stored in airtight packages before use.

2.1.2. Water

Tap water that is reasonably free from contamination in the laboratory was used to hydrate the cement in the mixtures.

2.1.3. Coarse aggregate

Crushed gravels with a nominal maximum size of 10 mm were used as the coarse aggregate. Water absorption of the coarse aggregates used in this study under SSD condition was measured by immersion in water for 24 h, followed by removing excess surface water with wet cloth after they were moved out of water. At the time when there was no free water on the surface, aggregates were assumed to be under the SSD condition. The sampled aggregates with saturated water under the surface-dried condition were weighed and recorded as m_{SSD}. After 24 h oven-drying at a temperature of 105 °C, aggregates were weighed and recorded as m_{OD}. The SSD water absorption was calculated by the formula of $(m_{SSD} - m_{OD})/m_{OD}$. The volume of the sampled aggregates under the SSD condition was measured by using the water displacement method and recorded as v_{SSD}. The SSD density of gravels was calculated by the formula of m_{SSD}/v_{SSD}. The results of SSD water absorption and SSD density of gravels are presented in Table 1.

2.1.4. Fine aggregate

Natural river sand with a maximum particle size of 5 mm was used as the fine aggregate. The procedures for measuring the sand's SSD water absorption and SSD density were the same as those for gravels, and results are presented in Table 1. A sieve analysis test was carried out in accordance with BS EN 933-1. As shown in Fig. 1, the sand used in this study presented continuous grading.

2.1.5. Rubber

Three different granular samples of waste tyre rubber particles, RA (cut to 3 mm), RB (grounded to 0.5 mm) and RC (grounded to

Table 1
SSD density and SSD water absorption of natural and rubber aggregates.

Item	Sand	Gravel	RA	RB	RC	CSR
SSD density (kg/m^3)	2512	2581	1111	909	909	973
SSD water absorption (%)	1.37	1.26	4.49	10.70	10.09	8.46

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