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Physico-mechanical, microstructural and dynamic properties of newly developed artificial fly ash based lightweight aggregate – Rubber concrete composite

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ABSTRACT

The use of industrial by-products in concrete would increase the sustainability of the construction industry. In this study, the potential use of scrap crumb rubber as fine aggregate in lightweight (Lytag) concrete was experimentally investigated. The effects of replacing natural sand by crumb rubber particles on the physico-mechanical, micro-structural and dynamic properties of the Lytag concrete were evaluated. When the rubber was introduced, the reduction in compressive strength of the Lytag concrete was experienced due to the less than perfect bond between the cement paste and the rubber as confirmed by the micro-structural observation. Additionally, there was flocculation of some of the crumb rubber particles and the packing of the rubber particles contributed to pockets of voids resulted in anisotropy in the concrete. The results also showed that the rubber not only meliorated the resistance of the cementitious Lytag composite to cracking from impact load but overall impact strength was also improved as the rubber particles acted as impedance to crack initiation and propagation.

1. Introduction

Use of light-weight aggregates (LWA) can offer many advantages such as reduction of dead load (i.e. lower density), lower cost of handling and transporting materials, higher thermal insulation, and enhanced fire resistance. LWA can be either naturally occurring low-density materials such as pumice or diatomite or they can be formed from coarse grade bottom ashes that self-sinter during the combustion process such as incinerator bottom ash [1–3]. They can also be artificially manufactured from the expansion or pelletisation of clay (e.g. Leca©) or from industrial by-product such as fly ash (e.g. Lytag©) [4]. Such aggregates, due to their process of formation, have a high pore volume which has the potential to provide concrete with a lower thermal conductivity and density. Research has shown that the thermal conductivity of light-weight concretes (i.e. concretes produced with LWA) is considerably lower than that of normal concretes [5,6]. In this study, sintered pulverised fuel ash lightweight aggregate (provided by Lytag Ltd) was used due to its relatively high strength compared to the other LWA [4]. The raw material used in the manufacture of Lytag is fly ash, which is the waste material produced from electricity production in coal-fired power stations.

Approximately 37 million scrap tyres were annually produced in the United Kingdom in 2002 [7]. For many countries, burning the tyres and using as fuel is still the most preferable strategy which leads to serious environmental hazards [8] which could be reduced if scrap rubber could be used in concrete. Rubber tyre particles are manufactured by processing (i.e. mechanical shredding) of the non-reusable tyres from the automotive industry, and can be classified into three categories: shredded or chipped tyre to replace gravel; crumb rubber to replace sand and ground rubber that may partially replace cement.

Apart from deliberate impact loads, concrete & structures in practice can frequently subjected to a range of accidental impact such as columns in underground car parks, overpass bridges and medium to low rise buildings located close to major roads and intersections or rock falls on the roadways in mountain areas [9]. In the literature, many research studies have been performed for investigating the impact behaviour of conventional and fibre-reinforced concrete [10–12] while the behaviour of concrete

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produced with unconventional aggregates is almost scarce. Topcu and Avcular [13] studies the behaviour of concrete barriers with and without rubber aggregates under collision impact and concluded that the barriers manufactured with rubberized concrete reduced the impact damages more effectively as it absorbs plastic energy easily and yields more displacement. In a more recent work, Rao et al. [14] investigated the behaviour of recycled aggregate concrete (RAC) beams under drop-weight impact and found out that the RAC is more sensitive to the high strain rate of loading and its impact resistance reduces with the increase in percentage of recycled concrete aggregates.

The general aim of the proposed study is to achieve a concrete with good mechanical and physical properties, and impact resistance; while maintaining adequate strength.

2. Materials, mix design and sample preparation

The control mix for concrete comprised a 10 mm single size Lytag and 4 mm down natural sand in compliance with BS EN 12620 [15] with high-strength Portland cement (CEM I class, 52.5 N/mm^2). The natural sand in the control mix was replaced with 20 wt% and 50 wt% of crumb rubber; particle size is 2–4 mm, as shown in Table 1.

Five 100 mm cubes per mix were used for the determination of compressive strength at 28 days according to BS EN 12390-3 [16]. Three 100 × 100 × 500 mm prisms were used for the determination of four-point flexural strength for each of the concrete mixes, according to BS EN 12390-5 [17]. Ultrasonic Pulse Velocity (UPV) was determined for each prism specimen using a PUNDIT device according to BS 1881-203 [18].

Apparent porosity (AP) of specimens was assessed using the following expression:

$$AP(\%) = \frac{w_s - w_o}{w_s - w_w} \times 100 \quad (1)$$

w_s is the weight of the specimen at the saturated condition, w_w is the weight of the specimen in water under saturated conditions and w_o is the dry weight of the specimen when dried to constant mass at 105 ± 5 °C for 24 h. Concrete density was determined according to BS EN 12390-7 [19].

Based on the suggestions in the ACI Committee 544 [20], a new, versatile and economical type of repeated drop-weight impact testing equipment developed by Erdem et al. [21] was used in this paper. In this method, a 5 kg cylindrical steel mass with a hemispherical head is repeatedly dropped from a height of 1 m on the specimen under the guidance of a polyvinyl chloride (PVC) tube. The guide system, which ensures a controlled drop path, had a length of 3 m and a diameter of 110 mm. A 100 mm cube specimen was placed on a steel base plate that rested upon the concrete laboratory floor. There was a rubber sheet with a thickness of 3 mm between the specimen and the base plate to prevent stress concentrations at the bottom. Four steel lugs were also welded to each corner of the base plate to prevent excessive rotation of the mass after the impact. A steel plate, 10 mm thick, were then positioned on the top of the concrete specimen to help generate uniform load distribution. To prevent bending of the top plate, a 25 mm diameter contact plate made of copper-coated mild steel was placed between the specimen and the plate.

The impact resistance of the concrete specimens was determined in terms of the number of blows required to either produce the first visible crack or cause complete failure of the specimens. In addition, the impact energy indicating the energy absorbed by the specimen up to failure has been computed as follows: $E_I = MhN$ where E_I is impact energy (kN-mm), M is mass of the drop hammer, h is height of drop (mm) and N is number of blows.

The microstructure of rubberized concrete were characterised using a Philips XL-30 field emission gun environmental SEM equipped with Oxford Instruments Inca model EDS, Abingdon, Oxfordshire, United Kingdom. Micrographs were recorded under high vacuum mode using an Everhart–Thornley type SE detector and a backscattered electron (BSE) detector supplied by K.E. Developments. Elemental mapping was carried out using an EDS spectral analysis at 113 eV resolution. Concrete samples were prepared as a small fragment prized away from the failed mixes. The imaged surface was an untouched fracture surface from one of the central cracks running along the specimen. The fragments were mounted on an Al stub with carbon cement, Pt sputter coated and imaged in the high vacuum SEM mode.

Table 1
Mix design (total volume: 1 m^3).

	Lytag (Ref)	20% Rubber	50% Rubber
	Mass (kg)	Mass (kg)	Mass (kg)
Cement	370	370	370
Water	200	200	200
Coarse Aggregate	570	572	572
Fine aggregate	Sand = 895	Sand = 716 Rubber = 77	Sand = 448 Rubber = 193

3. Results and discussion

3.1. Mechanical properties

The results of the compressive strength are shown in Fig. 1. The compressive strength that was attained in the reference concrete is relatively high, considering that the water/cement ratio (w/c = 0.54) was high and the cement content was 370 kg/m^3. Arguably, the improvement in compaction and bond strength that was ascertained from the respective spherical nature and rough surface texture of the Lytag particles may have help in optimizing the strength of the concrete. The compressive strength exhibited in the reference concrete is comparable to that in traditional concrete. However, it is shown that the rubberized concrete samples had lower strength than the pure Lytag concrete and the strength of the rubberized concrete was decreased when the replacement level for the rubber increased. Compared to the reference Lytag concrete, the respective compressive strength of the rubberized C20 and C50 samples was almost 22 and 30% lower. As with other concrete incorporating rubber, the geometrical and surface characteristics of the rubber particles have pronounced effects on the mechanical

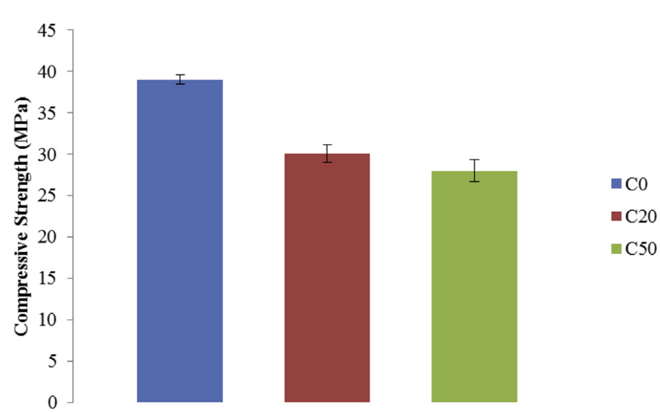

Fig. 1. Compressive strength of Lytag concrete samples.