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Strength prediction model and methods for improving recycled aggregate concrete

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HIGHLIGHTS

- Particle density, strength of aggregate, water absorption and RA content are used in a strength predictive model.
- Particle density is related to both LA value and WA and can be used as a quantity to classify RA.
- Treatment of RA with reactive microfillers (e.g. silica fume) can increase the strength of RAC by 17%.
- Short RTSF helped improve the strength of RAC by a further 13%.
- Appropriately sorted and treated RA can perform at the same level as NA.

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ABSTRACT

This paper examines the effect of various parameters on the performance of recycled aggregate concrete (RAC) and proposes a strength prediction model. Relations that link the properties of recycled aggregate (RA) to the strength of RAC are developed using multi-linear and non-linear regressing analysis. To enhance the compressive strength of RAC, the effect of surface treatment of RA using small quantities of reactive and non-reactive microfillers is examined. For the same purpose, two mixing methods and the addition of recycled tyres steel fibres (RTSFs) are also investigated. The results show that RTSF as well as reactive and non-reactive microfillers can enhance the strength of RAC by 30%. Furthermore, density separation can be used to produce high quality RA from construction and demolition waste (CDW).

1. Introduction

Large quantities of construction and demolition waste (CDW) materials arise annually worldwide. In the UK alone, this waste amounts to roughly 110 million tonnes per year which corresponds to 60% of total waste [1]. Only 40% of this amount is reused or recycled. At the same time, large quantities of natural aggregates are extracted for construction every year. The utilisation of recycled aggregates (RAs) in concrete production can potentially conserve the non-renewable natural resource of virgin aggregates, eliminate unnecessary consumption of limited landfill areas and reduce energy consumption. However, the variability in the characteristics of RA and recycled aggregate concrete RAC are the main engineering concern which hinders the use of RA. Low density and high water absorption and porosity, mainly caused by the heterogeneous nature of RA, can lead to low quality concrete (low compressive, tensile and flexural strength as well as high creep and shrinkage). For example, the use of recycled concrete aggregate (RCA) can lead to reduction of up to 40% in compressive strength [1–3]. As a result, current standards and specifications [4–7] impose limitations on the use of RA in new concrete and particularly in structural concrete. With limitations, such as only 20-30% of NA can be replaced by RA in new structural concrete being common. Therefore, more research in this field is necessary to understand the effect of the various key parameters and explore approaches to improve the properties of RA and RAC.

Different approaches have been adopted by researchers to improve the characteristics of RA and RAC. Some of these approaches deal with how to improve the RA itself while others focus on concrete production technology. Examples include, detaching the

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attached cement mortar from the aggregate through mechanical means (ball milling) [8], through immersing the RA in chemical solvents (acids) [9], through heating and rubbing [10,11], heating using microwaves [12], and through ultrasonic cleaning methods [13]. Although some of these approaches helped improve some of the properties of RA, they have shortcomings such as high costs, environmental pollution, energy consumption or compromising durability.

A possible better solution is surface treatment of RA with silica fume (SF) in liquid form. Katz [13] showed that this improved both the compressive strength (15% increase at 28 day) and the microstructure of the interfacial transition zone (ITZ). However, since the treatment was applied before mixing, it may not prove cost-effective in practice, due to the additional costs of this operation.

Cement treatment during mixing was also examined by others; for example, Tam et al. [14–17] developed a "two-stage mixing approach" (TSMA) aiming at coating the RCA with a layer of cement paste during the mixing procedure and reported strength and durability improvements. However, since cement particles are not small enough to penetrate and fill all microcracks, Tam and Tam [18] and Li et al. [19] tried to use the same technique, but with utilising reactive micro-fillers (pozzolans) such as SF, fly ash (FA) and ground granulated blast furnace slag (GGBS). Kong et al [20] used a triple mixing method to coat RCA (derived from crushing laboratory concrete samples with strength of 40 MPa) with first a layer of either FA or GGBS and then with a layer of cement paste. An improvement of 29% in compressive strength (at 28 day with 100% RCA) was obtained when RCA was coated with GGBS. This was attributed to the enhancement of the microstructure of the ITZ. The amount of cement replacement used (20% cement mass) was enough to provide a coating layer around the RA with a thickness ranging between 500–800 μm [19], which covered, not only the ITZ but also, the cement paste around the ITZ. However, improving the cement paste is known to improve the concrete properties irrespective of the aggregate used and if possible should be eliminated in comparative studies. For this reason, the current study attempts to exclude the effect of enhancing the cement paste by using small enough quantities of coating materials that only provide a thin coating layer to cover the ITZ. Since only few studies explored the effect of reactive micro-fillers on the properties of RAC and nothing was found in the literature on the use of nonreactive micro-fillers, the influence of reactive micro-fillers (SF, FA and GGBS) and non-reactive micro-fillers such as lime stone powder (LP) are studied in this paper. Two techniques are used to coat the RA, pre-mixing technique (PMT) and within mixing technique (WMT). The PMT is similar to the procedure used by Katz [13]and the WMT is proposed as an improvement to the TSMA and $TSMA_{sc}$ developed by Tam and Tam [18] as explained in Section 7.1. The effect of fine recycled tyres steel fibres (RTSFs) is also examined as they were shown in previous studies [21] to control microcracks propagation.

2. Materials

2.1. Cementitious materials

Portland Cement CEM I 52.5 N, meeting the requirements of BS EN 197 [22] was used in this research. The full chemical analysis of the cement is shown in Table 1. Table 2 presents the physical and mechanical properties of the cement, reactive micro-fillers (FA, GGBS, SF) and non-reactive micro-fillers (LP) used in this study.

Table 1
Chemical analysis of OPC.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O_{eq}
20.99	4.98	2.9	65.88	0.79	2.8	0.24	0.44	0.52

Table 2
Physical and mechanical properties of OPC, PFA, GGBS, SF and LP.

Property	OPC	FA	GGBS	SF	LP
Initial setting time (min)	110	–	–	–	–
Fineness (m^2/kg)	445	370	481	22300	640
Loss on ignition (%)	2.07	4.7	–	2.5	43.6
Compressive strength (MPa)	68.1	–	–	–	–
Density (Mg/m^3)	3.15	2.15	2.9	2.2	2.65
Activity index (28 day) %	–	86	96	107	–

2.2. Aggregates

The fine aggregate used throughout this study was natural sand with a maximum size of 5 mm, whilst two types of coarse aggregates were used, natural and recycled. The natural gravel was river aggregate with a maximum size of 20 mm. Two types of coarse RA were used; (a) construction and demolition waste CDW and (b) recycled concrete aggregate RCA produced by crushing old laboratory concrete specimens. The RCA from lab specimens can be considered as high quality RCA, since it is not contaminated and has no impurities and foreign matter.

The RA used originated from CDW and contained crushed concrete, masonry (brick) and asphalt. It was crushed by a jaw crusher (primary crusher) and a cone crusher (secondary crusher). The supplier could not provide information regarding the composition and properties of the RA. This is also true in general practice, as it is hard to track the properties or composition of rubble delivered to recycling plants from various demolition sites. Fig. 1a shows the RA used in this study, as received from the supplier.

Methodologies described and published in the current (BS and EN) standards were employed to conduct the characterisation of all aggregates used (see Table 3). The purpose of the characterisation was firstly to assess their suitability for use in concrete, in particular of that of RA, and secondly to determine the required mix design parameters.

Since one of the objectives of this study was to examine the effect of density of RA on concrete strength, the first step taken was to separate the mixed CDW into different types. This process started with the separation of RA by size (three fraction of sizes 14-20, 10-14 and 5-10 mm) and then by type using visual inspection and hand sorting. Based on the colours of the RA three distinct types of RA were identified:

- RA-Concrete (white or gray)
- RA-Brick (red)
- RA-Asphalt (black)

Since the quantity of the third type (black) was very low, it was excluded from the study. Therefore, the characterisation of the RA was conducted on the following types:

- NA (coarse and fine).
- RA-C (Coarse RA-Concrete from CDW).
- RA-B (Coarse RA-brick from CDW).
- RA-M (Coarse RA-Mixed from CDW).
- RA-C1 (Coarse RA-produced by crushing old laboratory concrete samples).

2.3. Recycled tyres steel fibre (RTSFs)

The RTSF used in this research is derived from the mechanical processing (e.g. shredding and granulation) of post-consumer tyres [31]. The RTSF used had an average diameter of 0.2 mm and tensile strength of around 2000 MPa [32]. The RTSF comes in variable lengths ranging from 3–30 mm (5% of the fibres had length shorter than 3 mm and 5% longer than 30 mm). The length distribution determined is shown in Fig. 1.

2.4. Superplasticizer and air entraining admixture

An aqueous solution containing polycarboxylate ether (PCE) polymers was used as superplasticizer. The air entraining admixture AEA used was Microair 103; both superplasticizer and AEA comply with EN 934-2 .

3. Aggregate characterisation

3.1. Composition

Fig. 2 illustrates the composition of all types of (5-20) mm coarse RA, while the quantities of the constituent materials of RA is shown in Table A1 in Appendix A. To identify the category for each type of