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Effects of packing on compressive behaviour of recycled aggregate concrete

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HIGHLIGHTS

- Wet packing method was extended to measure packing density of recycled aggregate concrete (RAC).
- Workability and compressive behavior of RAC mixes were experimentally investigated.
- Strength, elastic modulus, toughness of RAC increase with increasing packing density.
- Packing density optimization is a promising way of improving the performance of RAC.

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ABSTRACT

It is well known that the packing of particles in concrete has great effects on the performance of concrete, but codified methods for measuring packing density are all carried out under dry condition, which tends to result in loose packing due to agglomeration of the fine particles. Nevertheless, a wet packing method has been developed recently to enable more accurate measurement of packing density. In this study, this wet packing method was extended to measure the packing density of the concrete mix of recycled aggregate concrete (RAC). Furthermore, three groups of concrete mixes with various aggregate proportions and W/C ratios were produced for compression tests. It was found that at given W/C ratio and age, the compressive strength, elastic modulus, toughness and specific toughness of RAC would increase with increasing packing density, indicating that the packing density is a key factor affecting the compressive behaviour of RAC. Hence, packing density optimization is a promising way of improving the performance of RAC.

1. Introduction

Every year, European Union generates more than 450 million tonnes of construction and demolition waste [1] and China produces about 200 million tonnes of waste concrete [2]. Such huge quantities of waste have major impact on the environment. Hence, the recycling of waste concrete, which can save landfill space, preserve natural resources and reduce carbon footprint, has received increasing attention from the academia and the construction industry. Recycled aggregate (RA), which is produced by processing waste concrete, has been regarded as a potential substitute of natural aggregate. However, relatively, RA has larger porosity, lower density, higher water absorption, lower abrasion resistance and higher content of impurities [3–6]. These inferior properties of RA have rendered the application of RA in concrete, especially structural concrete, a difficult task.

There are already numerous studies on the performance of recycled aggregate concrete (RAC). For instance, Mefteh et al. [7] found that the use of RA would lead to a substantial loss of workability due to the high water absorption of the RA. Poon et al. [8] reported that a high level of RA replacement (≥50%) would significantly reduce the compressive strength of concrete. Bravo and de Brito

Abbreviations: FRP, fibre reinforced polymer; GGBS, ground granulated blast-furnace slag; OPC, ordinary Portland cement; PFA, pulverized fuel ash; M, total mass of water-solid mixture; RA, recycled aggregate; RAC, recycled aggregate concrete; RS, river sand; RS/TA ratio, river sand to total aggregate ratio by volume; SP, superplasticizer; ST, specific toughness; W/C ratio, water to cement ratio by mass; W/S ratio, water to solid ratio by volume; R_α, R_β and R_γ, volumetric ratios of α, β and γ to the total solid materials; u_w, water to solid ratio by volume, same as W/S ratio; V, bulk volume of particles, i.e. volume of container; V_s, solid volume of particles; ρ_α, ρ_β and ρ_γ, densities of solid materials α, β and γ; ρ_{bulk}, bulk density of watersolid mixture; ρ_w, density of water; ϕ, solid concentration (ratio of solid volume to bulk volume.

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[9] pointed out that the strength and elastic modulus of RAC are generally lower than that of normal concrete made from virgin aggregate. Du et al. [10], and Kou and Poon [11] investigated the chloride permeability of RAC and revealed that the chloride permeability would increase as the coarse RA replacement increases. Xiao and his research group [12–14] carried out various studies on the seismic performance of RAC frame structures and the bond behaviour between RAC and steel rebar. Recently, Gholampour et al. [15] developed empirical models for predicting the mechanical properties of RAC using gene expression programming technique.

To mitigate the adverse impacts of RA on the performance of concrete materials or structures, some strategies have been developed. The use of mineral additives as cement replacement is one effective way. Ann et al. [16] showed that the addition of pulverized fuel ash (PFA) and ground granulated blast-furnace slag (GGBS) can improve the chloride resistance of RAC. Kou et al. [17] proved that mineral additives, such as PFA, GGBS, silica fume and metakaolin, can enhance the mechanical properties of RAC. Another strategy is to add fibres to RAC. Gao et al. [18] revealed that the compressive behaviour of steel fibre reinforced RAC is remarkably better than those of plain RAC and plain concrete. Liu et al. [19] investigated the bond behaviour between fibre reinforced polymer (FRP) bar and RAC reinforced with basalt fibres. Furthermore, Poon et al. [20] and Chen et al. [21,22] found that the addition of steel fibres can improve the fire resistance of RAC. FRP jacketing is also an emerging and effective strategy. The results of recent tests on FRP-confined RAC, such as those by Teng et al. [23], Zhao et al. [24], Chen et al. [25], Zhou et al. [26], and Xie and Ozbakkaloglu [27], showed that both the strength and ultimate strain of the RAC can be significantly enhanced.

On the other hand, the packing density of particles, which is defined as the ratio of the solid volume of particles to the bulk volume of particles, is an important parameter governing the properties of many materials, including ceramics, metals and soils [28–30]. Being a granular system, it is anticipated that cement-based materials, including RAC, also have their properties significantly affected by the packing density of the solid ingredients. In fact, the concept of particle packing has already been applied to aggregate proportioning for optimal concrete mix design. Early in 1960s, Powers [31] suggested that a concrete mix may be considered as a mixture of cement paste and aggregate particles, and the improvement of aggregate packing can increase the volume of excess paste (paste in excess of that needed to fill up the voids) to increase the workability, or reduce the paste volume needed for same required workability. In 1994, de Larrard and Sedran [32] applied a packing model to maximize the strength of ultra high-performance concrete and in 1996, Sedran et al. [33] used a packing theory to design self-consolidating concrete. Then, in the 21st century, more and more researchers tried to maximize the packing density of the solid ingredients in concrete for performance optimization [34–40]. It is believed that the same strategy of maximizing the packing density of the solid ingredients would also improve the performance of RAC.

However, the codified test methods for measuring the packing density under dry condition [41–44] have the following problems: (1) they do not include the effects of water and admixtures; (2) the test results are sensitive to the compaction applied [45]; and (3) the test results could be seriously affected by agglomeration of the fine particles [46–48]. Because of these problems, accurate measurement of the packing density of cement-based materials is not easy. To resolve these problems, the authors' research group has developed a wet packing method for measuring the packing density of cementitious materials under wet condition [49]. Later, it was extended to measure the packing density of fine aggregate, blended fine and coarse aggregate, mortar mix and normal concrete mix [50–53], and has been adopted by other researchers in similar research [54–56]. However, the wet packing density of RAC mix has not yet been measured and the effects of the wet packing density on the compressive behaviour of RAC have never been evaluated. The possibility that the wet packing of RAC may be significantly different from ordinary concrete due to the different characteristics of the RA necessitates separate research on the effects of packing on the performance of RAC.

In this study, the wet packing method was extended to measure the wet packing density of RAC mix and three groups of concrete mixes with various RA proportions and W/C ratios were produced for testing. Based on the test results, the effects of RA proportion and wet packing density on the compressive behaviour of RAC were evaluated. This is an important step for incorporating the packing theory into the mix design of RAC and for expanding the application of RA.

2. Experimental programme

2.1. Materials

For the cement, an ordinary Portland cement (OPC) of strength class 42.5N complying with the Chinese Standard GB175-2007 [57] was used. It had been measured to have a density of 3110 kg/m^3. For the fine aggregate, river sand (RS) was used. It has maximum size of 2.36 mm, density of 2580 kg/m^3, fineness modulus of 2.89, moisture content of 0.12% and water absorption of 0.21%, and had been tested to comply with the Chinese Standard GBT14684-2011 [58].

(a) Demolition site

(b) Waste concrete blocks

Fig. 1. Demolition site and waste concrete blocks.