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Mechanical strength and drying shrinkage properties of concrete containing treated coarse recycled concrete aggregates

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HIGHLIGHTS

- We studied method for improving the properties of recycled concrete aggregate (RCA).
- A combination of two surface treatment methods were applied on coarse RCA.
- Effect of treatment methods significant to enhance the properties of coarse RCA.
- Treatment methods remarkably affect mechanical strength and drying shrinkage of concrete.

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ABSTRACT

In recycling concrete, the crushing process leaves weak mortar particles and surface cracks throughout the recycled concrete aggregates (RCA). Thus, the process is detrimental, resulting in inferior aggregate properties. This experimental study presents a method to improve the properties of coarse RCA by modifying their surface structure through the combination of two different surface treatment methods. In this study, coarse RCA are first treated by soaking in hydrochloric (HCl) acid at 0.5 mol (M) concentration. They are then impregnated with calcium metasilicate (CM) solution to coat their surface with CM particles. The effects of both surface treatments on the properties of RCA before and after treatment are determined. Moreover, the effect of the replacement of natural coarse aggregates with 60% treated coarse RCA on the mechanical strength of concrete is evaluated. The findings of this study show that the effect of the combination of these two surface treatment methods is beneficial, as the combined methods not only modify RCA surface but also enhance RCA properties. More specifically, after treatment, the particle density, water absorption, and mechanical strength of RCA are significantly improved. Consequently, the incorporation of treated RCA in concrete results in a mechanical strength that approximates concrete prepared with natural aggregates and surpasses the strength of concrete prepared with untreated RCA. In addition, the effect use of treated RCA tends to reduce the drying shrinkage of concrete.

1. Introduction

The recycling of concrete waste into recycled concrete aggregates (RCA) has been identified as a potential source of construction aggregates. Previous studies have highlighted the benefits of large-scale recycling of concrete waste: it reduces the quantity of concrete waste that otherwise would have been disposed in landfills, decreases the dependence of the construction industry on natural aggregates, thereby preserving natural resources, provides savings from the treatment of waste disposal, and yields alternative sources for urban areas facing shortage of natural aggregates [1–5]. Moreover, given the urgent need to preserve the environment and maintain ecological balance, the method ensures sustainable development.

The most common application of RCA is in the manufacture of roadbed gravel rather than concrete [6]. However, the acceleration of urbanization as a result of population growth has led to a greater demand for concrete. Concrete is one of the most important construction materials, with an estimated annual worldwide production of about five billion tonnes [7]. This situation requires considerable quantities of natural aggregate resources, the single largest component of concrete, making up 70–80% of its total volume [8]. However, the construction industry still has misgivings on the use of RCA in the commercial production of concrete, especially in structural applications.

This factor is attributable to certain unfavorable qualities of RCA compared with those of natural aggregates. RCA is produced by

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crushing concrete lumps into smaller particles, which are then separated using a sieve of specific size. This conventional crushing technique, such as the use of a jaw crusher, leaves particles of old mortar (cement paste) in the original aggregate particles of RCA. The amount of old mortar incorporated in RCA varies across different reports, but it can reach as high as 56% [9]. The presence of old mortar particles, which are characterized by relatively high porosity [10–14] results in the inferior quality of RCA compared with natural aggregates [15,16]. Moreover, the impact stress caused by the crushing process makes the surface layer of RCA weak, porous, and brittle [17]. The process also leaves numerous microcracks in RCA [12]. Thus, compared with natural aggregates, RCA are characterized by lower density, lower specific gravity, higher water absorption, and higher porosity [10,11,16,18,19]. These properties of RCA reportedly account for the decrease in the compressive, flexural, and tensile strength, as well as in the elastic modulus of concrete prepared with RCA [20–26]. Most researchers agree that the presence of weaker and porous old mortar in RCA particles is the main reason for the adverse characteristics of RCA and the overall deterioration of the mechanical strength of concrete.

In terms of the microstructure of concrete, the interface zone between the aggregate and the cement paste is important because this zone governs the mechanical strength of concrete [27]. Using scanning electron microscopy (SEM), Katz [28] found that the surface of RCA crushed by a jaw crusher are covered with loose particles, which may lower the bond between the RCA and new cement mortar, leading to a decrease in the mechanical strength of concrete. Tam et al. [12] similarly concluded that the adherence of old mortar composed of many minute pores and cracks on RCA results in the weakening of the links in the microstructure of concrete and ultimately affects the strength of concrete. Moreover, the high porosity and water absorption of RCA leads to a decrease in the effective water content for the hydration process and consequently results in a loose interfacial transition zone (ITZ) between the RCA and the new mortar in the hardened concrete [29].

Despite these disadvantages, the use of RCA in the production of concrete is still of particular interest because of the other economic and environmental benefits it offers. As such, various approaches and methods of treatment have been developed and studied to improve the material and minimize its disadvantages. Surface treatment is an innovative and beneficial method, which modifies and enhances the physical properties of RCA before its use in the concrete mix. The literature indicates various procedures of surface treatment in RCA. For instance, Tam et al. [30] proposed the use of a low concentration of acid to minimize weak or loose mortars attached on the surface of RCA particles, thereby improving the surface contact between the aggregate and the cement mortar. In this method, RCA is soaked in three different types of acid, namely, hydrochloric acid (HCl), sulfuric acid, and phosphoric acid, at a molarity of 0.1 M for 24 h. In general, the treatment significantly reduces the water absorption of RCA by 7.27–12.17%. As a result, the compressive strength, flexural strength, and elastic modulus of the treated RCA are improved compared with those of untreated RCA. Another procedure of RCA surface treatment is the modification or improvement of the surface of RCA by refilling the pores and cracks using suitable mineral admixtures like microfillers. Katz [28] introduced the surface treatment technique by impregnating RCA with a silica fume (SF) solution. In this method, the dried RCA is soaked in the silica fume solution to coat the surface of the RCA with the silica fume particles. This treatment strengthens the structure of the aggregate, particularly the ITZ between the RCA surface and the cement paste, thus improving the mechanical strength of the concrete. Other alternative methods reported include treatment by soaking in other types of admixtures or solutions, such as nanosilica solution [31], polymer solution [11] and silane-based water repellent [32].

Although each method implies a different and novel approach, they all improve the physical properties of RCA and minimize its adverse effects on concrete. However, the effects of combining the methods on the performance of the resulting concrete are not yet fully known. As such, this study aims to evaluate the feasibility of improving the poor physical properties of coarse RCA using a dual treatment method, in which coarse RCA are first pre-soaked in an acid solvent and then impregnated with a mineral admixture solution. The mineral admixture used is calcium metasilicate (CM), which eventually forms the coating layer of the impregnated RCA. This study investigates the effectiveness of this combined and dual treatment in enhancing the properties of coarse RCA and the mechanical strength of the resulting concrete.

2. Materials

2.1. Cement

Type I ordinary Portland cement (Cement Industries of Malaysia Berhad) with a specific gravity of 3.15 g/cm^3 was used as the main binder for the experiment. Its typical chemical compositions are presented in Table 1.

2.2. Aggregates

In this study, all the coarse aggregates used had a maximum size of 20 mm. The natural coarse aggregates used were crushed granite. The coarse RCA used were generated from waste concrete cubes collected from the debris area of the Laboratory School of Housing, Building, and Planning, USM Penang, Malaysia. The strength of the waste concrete cube was unknown. The concrete cubes were first crushed and then further pounded using a steel hammer to reduce their sizes. The concrete lump was placed in a jaw crusher, where it was broken down into smaller particles. After the crushing process, the RCA were graded according to particular sizes using a vibrator sieve to obtain the size required. The fine aggregates used were uncrushed quartzite natural river sand. The aggregates were washed with water to remove any unwanted substances such as clay, dirt and dust, after which they were air-dried. The gradation of the coarse and fine aggregates based on the sieve analysis is presented in Table 2.

2.3. Superplasticizer and mixing water

To enhance the workability of the concrete, a chloride-free super plasticizing admixture based on sulfonated naphthalene polymers was used. This superplasticizer complied with BS 5075-3 [33]. The mixing water used was tap water.

2.4. Acid

In the present study, the method involves the application of hydrochloric acid (HCl) as an acidic solvent in the degradation action for the removal of crumbs or loosely adhered mortars attached to the original RCA aggregate. Selection with HCl resulted in improved properties of the recycled aggregate concrete and marked improvement after pre-treatment, as reported by Tam et al. [30], which is due to its effectiveness in the treatment of RCA. In addition RCA subjected in acid solution was used to remove the adhered mortar and did not corrode or interfere with the original aggregate of RCA. Given that granite is a common natural coarse aggregate used for the production of concrete in Malaysia, the RCA produced in this study is predominantly composed of granite as the natural aggregate. Hence, selecting HCl is considered suitable for removing RCA mortar because of the highly corrosive-resistant nature of granite even at high acid concentrations [34]. Nevertheless, the prepared acid solution used for treating RCA has a low concentration with a molarity of 0.5 M. This optimal concentration is in accordance with the findings recommended by the works of Ismail and Ramli [35]. The HCl used in this research is supplied by the School of Chemistry, USM Penang, Malaysia.

2.5. Calcium metasilicate (CM)

CM or wollastonite, whose molecular formula is $CaSiO_3$, is widely used in the production of ceramics, insulation, roof tiles, and other construction materials. The CM used in this study was supplied by Berjaya Bintang Timur Sdn Bhd. It came in the form of white powder, with the range of its particle sizes similar to that of the cement particles. The specific gravity of CM is 2.87 g/cm^3 and its loss on ignition is 0.46%, values that are lower than those of ordinary Portland cement. The chemical composition of CM is presented in Table 1. The major compounds present in CM include 50.3% SiO_2 and 44.4% CaO. Fig. 1 shows the X-ray diffraction (XRD) pattern