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Mechanical strength and durability properties of concrete containing treated recycled concrete aggregates under different curing conditions

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HIGHLIGHTS

- The mechanical strength and durability of RAC with treated RCA was studied.
- Three different curing regimes were applied.
- Sea water remarkably deteriorates the compressive strength of RAC.
- Permeability and porosity of specimens are affected by curing regimes.
- Use of treated RCA significantly minimize the adverse effects in RAC.

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ABSTRACT

This paper examines the mechanical and durability properties of concrete incorporated with treated recycled concrete aggregate (RCA) under different curing conditions. Three different curing regimes were applied, namely, continuous normal water curing (NW), initial water curing for 28 days before exposure to an open air environment (OA), and initial water curing for 28 days before exposure to seawater (SW). Two concrete mixes were produced by replacing 60% of the coarse aggregate using treated and untreated RCA with one control specimen (100% natural coarse aggregate) to examine the mechanical strength (compressive and flexural strength) and durability (water absorption, oxygen permeability, and also porosity) properties of the concrete. Meanwhile, the microstructure of these mixes was studied via scanning electron microscopy (SEM). The inclusion of untreated RCA generally reduces the mechanical strength and durability of the concrete regardless of the curing conditions. The compressive strength of the concrete containing untreated RCA is more detrimental in SW than in the other two curing conditions. Moreover, the concrete with RCA have poor intrinsic air permeability and porosity because their intrinsic porosity and effect are more significant when the curing is performed in OA than in the other curing conditions. Incorporating the treated RCA helps limit the reduction in the mechanical strength and durability of the concrete particularly under a prolonged curing period.

1. Introduction

In conventional construction, external curing for concrete is applied after mixing, placing, and finishing. The main purpose of curing is to control the fast hydration process of concrete by keeping favourable moist conditions under a suitable temperature [1]. Proper curing of concrete structures is important to ensure that they meet their intended strength performance and to control the early volume change. These are related to durability enhancement. In other words, curing will enable the concrete to hydrate properly with good microstructure development, with less porosity, and with proper strength to maintain concrete dimensional stability without creeping or shrinkage [1]. On the other hand, carelessness in curing, particularly at an early stage, can cause irreparable loss as the concrete will not achieve the desired properties because of a lower degree of hydration [2]. This can also cause an early-age crack because of the damaging effects that drying and possibly autogenous shrinkage create, especially for concrete with lower water/cement (w/c) ratios [3].

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The problem of using recycled concrete aggregate (RCA) lies in the attached residual mortar, which makes RCA characteristically lower strength, porous and highly absorbent. When RCA is incorporated in new concrete to produce recycled aggregate concrete (RAC), the higher water absorption capacity of RCA causes difficulties in controlling the effective water/cement (w/c) ratio, which decreases the workability of fresh concrete [4] and consequently influences the strength [5,6] and durability [7,8] of the hardened concrete. Moreover effect from high water absorption of RCA and the use of high total w/c ratio of RAC induce water transfer during and after hydration. Therefore, the curing conditions have a considerable effect on the final performance of concrete [9]. However the effect of curing process on RAC depends on the types of curing regime or condition. Otsuki et al. [10] observed that curing conditions under high relative humidity of up to 90% lead to better mechanical properties at the ITZ, which can be attributed to the reduction in the porosity of the ITZ. Buyle-Bodin and Hadjieva-Zaharieva [9] founded that initial absorption, air permeability and carbonation depth of RA concrete cured in water is lower than that was achieved under air storage curing condition. Qi et al. [11] investigated the effect RAC when exposed to sodium sulfate solution under wetting-drying cycles for about 9 months and they observed that the damage of RAC against sulphate attack are significantly affected by increasing the quantity of RCA replacement. Research conducted by Chakradhara Rao et al. [12] revealed that partial curing (combination of wet and dry) condition of RAC effectively and significantly improves the strength compared with curing in continuous wet condition due to improvements in the old ITZ. Specifically, in this experimental study, the concrete cured in air after 7 days of wet curing was observed to show better strength than concrete cured completely under water for 28 days for all coarse aggregate replacement ratios. Poon et al. [13] observed that the compressive strength and modulus elasticity of RAC seem to exhibit increase in early stage of steam curing period which is not the case with standard water curing. The steam curing method was also observed to improve the drying shrinkage and the resistance to chloride-ion penetration. However, the effect of this curing method is significantly influenced and affected by the increase of RCA content. In another study, Gonzalez-Corominas et al. [14] found that the effect steam curing is beneficial to compensate the reduction in long term compressive strength of RAC made from medium-low quality RCA in comparison with normal aggregate concrete mixtures. Moreover steam-cured RACs up to 90 days had greater reductions of capillary pores volume thus results RAC low porosity than natural aggregate concrete. Fernando et al. [15] found that the 28-day compressive strengths of RAC were found similar to the natural aggregate concrete when exposed under the standard curing condition while the compressive strength of RAC decrease up to the 20% when they were exposure in open-air conditions. Meanwhile research study conducted by Fonseca, et al. [16] found that compressive strength results of RAC seem negligible to be affected by curing conditions or in another words insensitive to curing condition.

However the effect of higher porosity and water absorption capacity of RCA has potential to become internal curing agent. Kim and Bentz [17] reported that blending of RCA and saturated lightweight fine aggregates provides an internal source of water to offset the chemical shrinkage that occurs during hydration of the paste, thus effectively resisting autogenous shrinkage while maintaining compressive strength reduction. The high absorption characteristic of RCA which absorbs more water during mixing results in acting as a natural moisture reservoir to assist in the later hydration [18]. This reservoir promotes in the formation of calcium silicate hydrate in the later age and refines the interfacial transition zone [19], thus would improving the RAC performance. Using saturated or semi-saturated RCA in the concrete positively affected the durability via internal curing. The duration of the curing period also influences the performance of RAC. The durability of RAC has been benefited from extended periods of curing [8,9,20]. In addition, long-term curing period shows that after 5 years, concrete made with 100% crushed concrete aggregate has the lowest porosity and slightly significant effect in increasing the compressive and splitting tensile strengths [21].

This research was performed in consideration of our previous studies [22] on the effectiveness of multi-phase surface treatment methods in enhancing the properties of coarse RCA. The main aim of this research is to assess the influence of different types of curing conditions on the short- and long-term mechanical strength (compressive and flexural strength) and durability (water absorption, intrinsic air permeability, total porosity, chloride resistance and SEM examination) of modified RAC with treated RCA. All test specimens were subjected to initial water curing for 28 days and were then exposed to three curing conditions, namely, normal water (NW), outer/open air environment (OA), and seawater (SW). The mechanical strength and durability of the modified RAC were analyzed and compared with those of normal aggregate concrete and unmodified RAC specimens to determine their effectiveness.

2. Experimental program

ASTM Type 1 Ordinary Portland cement with a specific gravity of 3.15 g/cm^3 was used as the main binder for the experiment (see Table 1 for detail chemical composition). In this study, all of the coarse aggregates used had a maximum size of 20 mm. The natural coarse aggregate used was crushed granite. The coarse RCA used were generated from waste concrete cubes collected from the debris area and crushed by jaw crushers and then sieve to get the specified size. Two types of coarse RCA were produced in this study, treated and untreated. The treated RCA is prepared by modifying the RCA surface structure through the combination of two different surface treatment methods. In this process, the RCA is initially treated by soaking in hydrochloric (HCl) acid at 0.5 M (M) concentration for 24 h. They are then impregnated with wollastonite (calcium metasilicate) solution. The chemical composition of wollastonite is presented in Table 1. The details on the procedures involved in this treatment process and beneficial effect of this surface treatment were described in previous research [22]. Table 2 provides a comparison of the properties of coarse natural aggregate (granite) and coarse treated and untreated RCA in terms of physical and mechanical strength characteristics. Natural river sand which consisted of particles that passed through a sieve size of 5.00 mm was used as fine aggregate. Table 3 shows the sieve analysis of the fine and coarse aggregates that were used in this study, which were graded according to BS 812-Part 103.1. Other properties of the natural fine aggregates are presented in Table 4. To enhance the workability of the concrete in this study, chloride-free super plasticising admixture based on sulphonated naphthalene polymers was used during the mixing of concrete. The physical and chemical properties of the superplasticiser was formulated in accordance with ASTM C494.

The designated concrete mix proportions were based on a constant effective water/cement ratio of 0.41 for all concrete mixtures in accordance with the British method published by the Department of Environment [23] to achieve a target slump range of 30–60 mm and a compressive strength of 50 MPa on 28 day. Three series of mixtures were prepared depending on the type of coarse aggregate content, as follows: (i) specimen type CO (control concrete) was prepared using only natural coarse aggregates; (ii) specimen types RO refer to RAC composed of untreated coarse RCA: (iii) specimen types TR refer to RAC composed of treated coarse RCA. The dosage compositions of the coarse aggregates in this experiment were kept constant by replacing the natural coarse aggregate with untreated or treated RCA at 60% of the weight of the total coarse aggregate content in all RAC mixtures. The detailed mix design and proportions in the constituent materials for the overall concrete specimens are presented in Table 5.

All concrete mixes in this study were mixed in accordance to the sequence prescribed in BS1881-125 [24]. The specimens were demolded at 24 h after casting, and then were initially cured under water curing at an atmospheric temperature of 25 ± 2 °C for 28 days before further exposure to different curing regimes; NW-series, OA-series and SW-series environments. The NW series are using standard moist or the specimens were continuously cured in normal water. For the OA series were placed the specimens in the open area of a laboratory corridor to be exposed to a tropical climate, which included solar radiation and rain. The ambient temperature ranged from 26 + 2 °C (rainy day) to 35 + 2 °C (sunny day) and the relative humidity ranged from 60% to 90%. The rationale for this curing was the need to examine the characteristics of the specimens when subjected to uncontrolled conditions of humidity and temperature, which involved different weathering cycles such as wetting and drying conditions. Meanwhile the SW series the specimens