Cement and Concrete Composites 65 (2016) 67–74

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates

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ARTICLE INFO

Article history:
Received 18 June 2015
Received in revised form
8 October 2015
Accepted 9 October 2015
Available online 22 October 2015

Keywords:
Recycled concrete aggregates
Recycled aggregate concrete
Carbonation
Mechanical properties

ABSTRACT

An accelerated carbonation technique was employed to strengthen the quality of recycled concrete aggregates (RCAs) in this study. The properties of the carbonated RCAs and their influence on the mechanical properties of new concrete were then evaluated. Two types of RCAs, an old type of RCAs sourced from demolished old buildings and a new type of RCAs derived from a designed concrete mixture, were used. The chosen RCAs were firstly carbonated for 24 h in a carbonation chamber with a 100% CO_2 concentration at a pressure level of 0.1 Bar and 5.0 Bar, respectively. The experimental results showed that the properties of RCAs were improved after the carbonation treatment. This resulted in performance enhancement of the new concrete prepared with the carbonated RCAs, especially an obvious increase of the mechanical strengths for the concrete prepared with the 100% carbonated new RCAs. Moreover, the replacement percentage of natural aggregates by the carbonated RCAs can be increased to 60% with an insignificant reduction in the mechanical properties of the new concrete.

1. Introduction

Nowadays, with accelerated industrialization and urbanization, especially among developing countries and regions, huge amounts of construction and demolition waste are generated. These regions also suffer from depletion in natural mineral resources and shortages of waste disposal sites. Therefore, recycling and reuse of construction and demolition waste are certainly necessary from the viewpoint of environmental protection and effective utilization of resources. In many countries, reusing recycled concrete aggregates (RCAs) produced by crushing concrete debris as a renewable resource in lieu of virgin materials is to a large extent, already being promoted in new construction [1].

However, the reuse of RCAs still has shortcomings and their applications are often limited to low-level civil works like road subbases and non-structural concrete products. And, the reuse of RCAs in structural concrete is still limited. This is mainly because compared with natural aggregates (NAs), RCAs have lower density, higher water absorption, higher porosity and lower mechanical properties, which have an aversive impact on recycled concrete quality, resulting in lower strength, higher strain (elasticity, shrinkage, and creep) and poorer durability [2]. For example, using 100% coarse RCAs in concrete could result in over 30% reduction in compressive strength. It has thus been recommended that the limited usage of coarse RCAs to replace up to 30% of NAs would not result in an obvious strength reduction, but the addition of superplasticiser (SP) is required for achieving the required workability of new concrete [3].

In order to efficiently facilitate waste management through the reuse of RCAs, ways to improve the quality of RCAs and the performance of recycled aggregate concrete (RAC) have been paid much attention to in the past decades [4–14]. Table 1 summarizes techniques from previous researches which attempted to improve the properties of RCAs and the corresponding RAC. In particular, the three main technical methods are classified and highlighted: (i) Removal of residual cement mortars in RCAs; (ii) Coating of RCAs; and (iii) Modification of concrete mixing method. Note that the removal of the residual mortars in RCAs by mechanical or thermal-mechanical methods may significantly reduce the water absorption as well as increase the compressive strength of the new concrete, but the demerits of these techniques are the high energy input required and the corresponding increase in generation of recycled fines from 40% to 70% [4]. In practice, the fine RCAs with a particle size smaller than 5 mm have even poorer properties with little application and have to be discarded to landfills. Using cementitious or organic solutions to coat the RCAs may help enhance the

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http://dx.doi.org/10.1016/j.cemconcomp.2015.10.018
0958-9465/

Table 1
Techniques for improving the properties of RAC by previous researchers.

Technical treatments		24-h water absorption of RCAs	Compressive strength of concrete at 28 days	Practicality and environmental impacts
Removal of residual cement mortar in RCAs	Pre-soaking approach in acidic solutions: HCl, H_2SO_4, H_3PO_4 [8].	↓ up to12%	↑ up to 5% with 30% of RCA	• Inconvenient; • Need to dispose of fine aggregates; • Increased chloride and sulphate contents in RCAs.
	Ultrasonic cleaning method [9]	–	↑ up to 7% with 100% of RCA	• Time-consuming; • Need to dispose of more wastewater.
	Mechanical beneficiation: Eccentric rotor crusher, Screw abrading crusher, compression and impact process, et al. [4,10]	↓ up to 82%	↑ up to 39% with 100% of RCA	• Increased CO_2 emission; • Increased energy consumption; • An increase of fines production from 40% to 70%; • Need to dispose of fine aggregates.
	Thermal-mechanical beneficiation: High temperature and sorting, Heating and rubbing, Microwave-assisted and rubbing, et al. [2,4]	↓ up to 74%		
Coating of RCAs	**Organic surface improvement:** PVA solution, oil-type agent, silane-type agent, et al. [11,12]	↓ up to 82%	↑ up to 17% with 100% of RCA	• Inconvenient • Time-consuming; • Cost-intensive • Pollution of solution.
	Cementitious surface improvement: fly ash paste, silica fume paste, Kim powder paste, et al. [9,13,14]	↑ up to 50%	↑ up to 16% with 100% of RCA	• Inconvenient; • Time-consuming.
Mixing method	**Multi-step mixing methods with admixtures:** two-step mixing, triple mixing methods [5–7].	–	↑ up to 17% with 100% of RCA	• A practical efficient way.

properties of recycled aggregate concrete themselves, but these processes are time-consuming, cost-intensive and inconvenient in practice. So far, the most practical technique is to modify the mixing method of RAC, such as using a two-step mixing or a triple mixing with other cementitious materials together [5–7].

In recent years, adopting accelerated carbonation technique to improve the quality of RCAs has already been proposed by some researchers as well [15–18]. The idea is based on the reactions between CO_2 and hydration products of cement in concrete: $Ca(OH)_2$, C-S-H, Aft, et al. [19,20]. The theoretical calculation indicates that the full carbonation of concrete could uptake 50% of CO_2 by cement mass. The reaction product, $CaCO_3$, precipitates in the pore space of the system and densifies the whole microstructure. According to reactions (1) and (2) below, after carbonation, the solid volume may be increased by 11.8% based on reaction (1) and about 23% based on reaction (2) [17,21].

$$Ca\,(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

$$\text{C-S-H} + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O \tag{2}$$

The previous experimental results also indicated that the carbonated RCAs obtained an increase of density, a decrease of water absorption and an increase of crushing value [16]. For example, the 24-h water absorption of the carbonated RCAs were 1.3–2.6% lower than that of non-carbonated ones, affected by the size of RCAs, the cement content in RCAs, the strength grade of original concrete, etc. Applications of the carbonated fine RCAs in mortars and the carbonated recycled mortar aggregates in concrete showed the improvement of mechanical properties and durability [17,18].

In practice, under atmospheric conditions with 0.03–0.06% of CO_2 concentration, carbonation of concrete also occurs. But it could take more than 100 years for full carbonation [22]. Alternatively, accelerated carbonation techniques have been employed to try to quickly improve the properties of RCAs. Until now, however, there is limited information which could confirm the influence of carbonated coarse RCAs on the performance of RAC in the literatures. The aim of this study was to characterize the properties of old and new RCAs before and after accelerated carbonation treatment, and to further investigate the influence of the carbonated RCAs on the performance of new concrete.

2. Materials and experimental program

2.1. Materials

To investigate the effect of carbonation treatment on the properties of RCAs, two types of RCAs, a new type of RCAs (NRCAs) and an old type of RCAs (ORCAs), were used in this study. ORCAs derived mainly from demolished old concrete structures with less than 5% other types of impurities were collected from a local construction waste recycling company (TioStone Environmental Limited) and then stored under an indoor laboratory condition for over 1.5 years. The NRCAs were obtained from crushing a batch of concrete (14 m^3) produced by a ready-mixed concrete supplier. The mixture proportion of the original concrete for NRCAs is given in Table 2. After 6 months of external curing, the concrete was crushed at the same construction waste recycling plant. The crushed NRCAs and ORCAs were further sieved into three fractions: 10–20 mm, 5–10 mm and <5 mm. In this research, the first two coarse fractions, 5–10 mm and 10–20 mm RCAs, were used for the preparation of new concrete.

In addition to the recycled aggregates, coarse natural granite aggregates (NAs) (5–10 mm and 10–20 mm), river sand (<5 mm), cement and superplasticiser (SP) were used for the preparation of new concrete mixtures. The cement used was a type of ASTM Type I

Table 2
Mix proportion of original concrete for the preparation of NRCAs (kg/m^3).

Materials	Cement	Water	W/C	Natural aggregates (NAs)		Sand	SP
				5–10 mm	10–20 mm		
Content	460	205	0.45	430	530	700	3.47

Note: SP-superplasticiser.