



Characteristics of the carbonation resistance of recycled fine aggregate concrete



Jian Geng*, Jiaying Sun

Research Center of Green Building Materials and Waste Resources Reuse, Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, PR China

HIGHLIGHTS

- Effect of RFA on the carbonation resistance of RFAC.
- Fly ash addition favors the carbonation resistance of RFAC, especially at 20% cement replacement ratio.
- The microstructure of RAF and RFAC.
- The self-cementing ability of RFA was analyzed.

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ABSTRACT

This study investigates the effects of the minimum recycled fine aggregate (RFA) particle size, RFA amount, and fly ash addition on the carbonation resistance of RFA concrete (RFAC). The results reveal that the carbonation depth of RFAC increases with decreased minimum RFA particle size and increased RFA amount. At >40% RFA amount, water significantly affects RFAC carbonation. Fly ash addition favors the carbonation resistance of RFAC, especially at 20% cement replacement ratio. In this study, the self-cementing ability of RFA is proved by the microstructural analyses of RFA and RFAC but is found to have a negligible effect on RFAC carbonation for a few carbonizable hydrated products. The poor microstructure of RFAC and the interfacial zone between the new cement paste and RFA result in easier CO₂ ingress for RFAC.

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1. Introduction

The reuse of construction waste is important for saving resources, protecting the environment, and realizing sustainable development in the construction industry. The use of construction waste as recycled aggregate (RA) has become increasingly common worldwide. However, given the poor quality of RA, its application is severely limited in most countries and is confined to low-grade use, such as for unbound roads [1,2]. RA is mainly obtained from waste concrete by machine crushing, and leading to sharp corners and cracks and old cement paste adhering to the surface of RA, which lead to high water adsorption. Under this condition, fresh recycled aggregate concrete (RAC) requires more water than natural aggregate concrete (NAC) for mixing, which probably lead to high porosity in concrete. Otherwise, because of the old cement paste adhered, the interfacial zone between new cement mortar

and aggregate in RAC is usually weaker than that in NAC. As a result, hardened RAC has poor durability, low strength, and low elastic modulus [3–8].

Chloride penetration and carbonation are two major problems of RFAC durability. Many differences exist between them, although the basic mechanisms are the same and both of them are mainly controlled by the pore characteristics of concrete. Regarding the anti-chloride permeability chloride penetration, most researchers agree that it increase with increased RA amount and can be improved by the addition of fly ash [9–13]. Regarding the resistance to carbonation, no unanimous conclusion has been drawn from previous reports. Sagoe-Crentsil et al. [14] reported a 10% increase in the RAC carbonation depth when RA is used, as well as a parabolic rate law of the relationship between the carbonation depth and square root of the exposure time that applies to RAC and NAC. Limbachiya et al. [15] noted that the carbonation depth and rate increase with increased amount of recycled coarse aggregate (RCA). Lovato et al. [16] mentioned that using both RCA and recycled fine aggregate (RFA) can lead to increased carbonation depth in direct proportion to their amounts. Evangelista and de Brito [17] investigated the effect of 30% and 100% RFA amount on

* Corresponding author. Address: School of Civil Engineering and Architecture, Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, PR China. Tel.: +86 13780080829.

E-mail address: gengjian@whut.edu.cn (J. Geng).

the resistance to carbonation of RAC, and found 40% and 100% increases in the RAC carbonation depth compared with NAC. Zega and Di Maio [18] studied recycled fine aggregate concrete (RFAC) carbonation after a 310 and 620 day exposure test, and found that the carbonation depth of RFAC is similar to that of NAC because of the lower effective water/cement ratio of RFAC. Levy and Helene et al. [19] suggested that both RCA and RFA favor the resistance to carbonation of RAC and also proposed that the carbonation depth strongly depends on the chemical composition of concrete and not only on the physical aspects. The effect of fly ash on RAC carbonation is also unclear. Corinaldesi and Moriconi [20] investigated the effect of fly ash on the carbonation of RAC made with 100% RCA, and found that the addition of fly ash favors the resistance to carbonation of RAC. Abbas et al. [21] measured the carbonation depth of recycled coarse aggregate concrete (RCAC) with fly ash after a 140 day exposure test, and found that the resistance to carbonation of RAC declines with prolonged time because of the addition of fly ash. Limbachiya et al. [15] found that fly ash is not good for the resistance to carbonation of RAC, but also noted that fly ash favors its long-term anti-carbonation ability. Sim and Park [22] showed that the use of <30% fly ash leads to increased carbonation depth, but >60% fly ash does not affect carbonation. Kou and Poon [23] noted that the carbonation depth of RCAC increases with increased amount of fly ash regardless of the addition method, such as by weight cement replacement ratio and by weight cement addition.

These results indicate that many factors affect the resistance to carbonation of RAC and RFAC. RFA is a byproduct of RCA production, and its resource utilization degree is far lower than that of RCA because of the higher amount of old cement paste in RFA. However, an increase in the number of carbonizable particles that exist in old cement paste [19,24] probably benefits the resistance to carbonation of RFAC. Fly ash also has an effect on concrete carbonation, but there is still no unified conclusion about it, especially for its amount <30% [25]. Thus, the effect of fly ash addition on RAC carbonation, particularly on the improvement of concrete performance, warrants further study. In this paper, the effects of the minimum RFA particle size, RFA amount and effect of low fly ash addition on the resistance to carbonation of RFAC are studied. To explore the carbonation mechanism at the microscopic level, X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), scanning electron microscopy (SEM), and microhardness analyses are performed to analyze the microappearance and microcomposition characteristics of RFA and RFAC.

2. Experimental procedure

2.1. Materials

Ordinary Portland cement equivalent to GB 175-2007 type 42.5 grade and fly ash were obtained from the Guohua Power Plant in Ningbo, China. Natural coarse aggregate and river sand were used. The chemical composition and physical properties of these materials are shown in Tables 1 and 2, respectively. The grading curves of river sand and recycled fine aggregate are shown in Fig. 1.

RFA was obtained from a professional manufacturer of RA in Shanghai, China. Old cement paste adhered onto RFA is the major reason for the poor performance of RAC; a smaller RFA particle size indicates a higher content of old cement paste. Thus, RFA from the same parent concrete and with different minimum particle sizes (<0.16, 0.16, and 0.36 mm) were used to study their effect on the resistance to

Table 1
Chemical composition of cement and fly ash.

Materials	Chemical composition (%)						
	SiO ₂	CaO	MgO	Fe ₂ O ₃	Al ₂ O ₃	SO ₃	Loss
Cement	20.4	61.6	0.97	3.49	7.26	3.55	3.36
Fly ash	56.9	4.07	2.87	4.60	26.5	0.20	2.08

Table 2
Physical properties of river sand and recycled fine aggregate.

Fine aggregate	Fineness module	Water absorption (%)	Sediment percent (%)
River sand	2.8	1.6	1.0
RFA1	2.7	7.2	34.0
RFA2	2.9	6.8	31.8
RFA3	3.3	5.9	13.8

carbonation of RFAC, in which RFA1 was directly obtained from Shanghai, and RFA2 and RFA3 were sieved from RFA1 according to experiment requirements in laboratory. The corresponding samples were designated as RFA1, RFA2, and RFA3. The physical properties of the RFA samples are shown in Table 2. The amount of sediment percent of RFA is tested by thermal treatment [26].

2.2. Concrete mix design

The concrete mixtures were divided into two series. Series I was designed with a fixed water/blend ratio ($w/b = 0.40$). The replacement ratio of river sand by RFA1 was 0%, 20%, 40%, 60%, and 80% by weight. For RFA2 and RFA3, only 40% replacement ratio was considered. Series II was designed such that all concrete mixtures had similar workabilities with an 180 ± 10 mm slump. In all concrete mixtures, a poly-carboxylic acid water reducer (JS) was used. In series I, fly ash was also used with 10%, 20%, and 30% cement replacement ratios by weight. The proportions of the concrete mixtures are shown in Table 3. The properties of fresh and hardened concrete are shown in Table 4.

2.3. Test methods

All concrete mixtures used for the compressive strength test and accelerated carbonation test were $100 \times 100 \times 100$ mm cube models. After 26 days of curing in water at 20 ± 2 °C, the samples were dried for 48 h at 60 ± 2 °C to accelerate the carbonation test. All surfaces of the dried samples were sealed by paraffin, except for two opposing side surfaces. The accelerated carbonation test was conducted at 20 ± 5 °C and $70\% \pm 5\%$ RH with $20\% \pm 3\%$ carbon dioxide concentration in the testing chamber, whose reference was GB/T50082-2009 (standard for test methods of long-term performance and durability of ordinary concrete). After the test, the samples were split and 1% phenolphthalein solution was sprayed on the broken surfaces. The carbonation depth was measured after 7, 14, and 28 days of carbonation exposure. All results are the mean of three samples with the same proportion.

RFA1 used for X-ray powder diffraction (XRD), was prepared as a fine powder by grinding and passing through sieve 100#. XRD data were collected using a D8 Advance instrument of Bruker AXS with a Cu K α radiation generated with 40 kV and 30 mA. LC0 and LC14 were cured for 28 days. Next, fracture surface mortars were taken from concrete that previously had been subjected to the compressive strength test. The mortars used for examination under the SEM (HITACHI S-4800) by secondary electron imaging (SEI) were placed directly in an evaporator and maintained under high vacuum overnight. The accelerating voltage was 20 kV. At the same time, the EDX-detector equipped HITACHI S-4800 was used to obtain energy dispersive X-ray analysis data (EDXA) of RFA1 for identifying its composition. The microhardness of the interfacial zone (ITZ) of both LC0 and LC14 is measured by a Leitz microhardness tester (HVT-1000). In this test, the ITZ between new cement paste and fine aggregate is set as 0 distance point, and microhardness is tested every 20 μ m from fine aggregate to cement mortar. The microhardness of every sample was tested three times and represented by different color lines.

3. Results and discussion

3.1. Minimum RFA particle size

Fig. 2 shows the relationship between the minimum RFA particle size and concrete carbonation depth. The results indicate that the carbonation depth of RFAC is higher than that of control concrete (LC0) at the same exposure time, and also increases with prolonged exposure time. Thus, RFA is unfavorable to the concrete anti-carbonation ability.

The carbonation depth of RFAC is also related to the minimum RFA particle size. A smaller minimum RFA particle size results in higher carbonation depth at the same exposure time. In this case, the carbonation depth of LC14 (prepared from RFA1 with the smallest minimum particle size of <0.16 mm) is the highest and

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