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Effect of Carbonated Recycled Coarse Aggregate on the Durability of Recycled-Aggregate Thermal-Insulating Concrete under Salt Freeze-Thaw Conditions

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Abstract

This study investigated the effects of carbonation-treated recycled coarse aggregate on the compressive strength and splitting tensile strength of recycled-aggregate thermal-insulating concrete (RATIC-CO_2), as well as its durability under combined chloride exposure and freeze-thaw cycling. The water absorption and crushing index of the treated aggregate were 10.6% and 11.6% lower, respectively, than those of untreated aggregate. The mean compressive and splitting tensile strengths of RATIC-CO_2 were 21.2% and 7.1% higher, respectively, than those of RATIC. The tensile-strength difference is descriptive because its statistical uncertainty has not been quantified. RATIC-CO_2 retained a higher relative dynamic modulus after 100 cycles. The mean mass-loss rates were approximately 3.6% and 3.25% for RATIC and RATIC-CO_2, respectively, at 100 cycles.

Keywords

Carbonation, Recycled Coarse Aggregate, Recycled-Aggregate Thermal-Insulating Concrete, Chloride Attack, Freeze-Thaw Cycles

1. Introduction

Recycled-aggregate thermal-insulating concrete (RATIC) is a functional recycled concrete that provides both thermal insulation and structural performance [1] [2]. RATIC contains four aggregate types: glazed hollow beads (GHB) as thermal-insulating aggregate, natural coarse aggregate (NCA), natural fine aggregate (FA), and recycled coarse aggregate (RCA). RCA is produced by crush-

ing and screening ordinary concrete. The adhered old cement mortar and associated pores and microcracks give RCA poorer physical properties than NCA, particularly higher water absorption and a higher crushing index [3] [4]. These characteristics can limit the mechanical performance and durability of recycled concrete. Recent experiments also show that deterioration under combined chloride exposure and freeze-thaw cycling depends on aggregate replacement and exposure duration [5], emphasizing the need to evaluate durability under the relevant service conditions.

Several approaches have been investigated to improve recycled concrete durability, including nano-silica modification [6], CO_2 treatment of recycled aggregate [7] [8], prewetting and water-control strategies [9], improved mixing procedures [10], and silane-based aggregate pretreatment [11]. Bao *et al.* [6] reported that nano-silica refined the pore structure and improved salt-frost resistance under their tested conditions. Peng *et al.* [7] found that CO_2 curing of recycled aggregate mitigated deterioration during NaCl freeze-thaw exposure and produced a more compact aggregate-matrix interface. Sapata *et al.* [8] examined carbonated fine and coarse RCA and observed lower aggregate water absorption and improved mechanical and water transport properties in conventional concrete; those results did not assess salt freeze-thaw resistance. Prewetting benefits depend on initial saturation and the basis used to control water content [9], while silane surface treatment has improved water impermeability and freeze-thaw resistance in RAC [11]. The effects of these treatments therefore need to be distinguished by material and exposure conditions. Previous research on RATIC demonstrated substantial damage under combined chloride attack and freeze-thaw cycling [12]. Šeps *et al.* [13] also reported severe damage, particularly surface scaling, in fiber-reinforced recycled concrete exposed to freezing and deicing salts. These studies motivate a specific assessment of carbonated RCA in thermal-insulating concrete under salt freeze-thaw exposure.

In this study, recycled coarse aggregate was treated in an accelerated carbonation chamber to obtain carbonation-treated recycled coarse aggregate (RCA-C). Its basic properties and the mechanical performance and salt freeze-thaw response of concrete incorporating it were compared with those of untreated RCA and the corresponding concrete.

2. Materials and Methods

The cementitious materials used in the RATIC were grade 42.5 ordinary Portland cement and silica fume; their compositions and basic properties are listed in **Table 1**. The two mixtures contained RCA or RCA-C, natural fine aggregate (FA), and glazed hollow beads (GHB) as thermal-insulating aggregate. Neither mixture contained natural coarse aggregate (NCA), as shown in **Table 2**. The coarse aggregate particle size ranged from 5 to 20 mm. River sand with a fineness modulus of 2.37 was used as the fine aggregate. The RCA was sourced from Handan, Hebei Province, China.

Table 1. Properties and composition of cementitious materials.

Material	Loss on ignition (%)	Specific surface area (m^2/kg)	Chemical composition (%)				
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Cement	2.86	345	22.53	4.42	2.06	61.71	4.55
Silica fume	1.95	16,500	87.68	0.93	1.23	0.86	0.33

Glazed hollow bead thermal-insulating aggregate is an inorganic mineral material produced by expanding and calcining pretreated perlite ore sand. It has an irregular spherical cavity structure with a honeycomb-like interior. The thermal-insulating concrete used a high-performance polycarboxylate water-reducing admixture with a water-reduction rate of 35% - 40% at a dosage of 3%. The concrete mix proportions are given in Table 2. Before batching, the aggregates used in both mixtures, including RCA and RCA-C, were presoaked and brought to the saturated surface-dry (SSD) condition. No additional water was added to compensate for aggregate absorption. This SSD conditioning was used to limit differences in free mixing water caused by the different absorption capacities of RCA and RCA-C. Both mixtures were proportioned at a water-to-binder ratio of 0.50, with binder comprising 379 kg/m^3 of cement and 28 kg/m^3 of silica fume.

Table 2. Concrete Mix Proportions (kg/m^3).

Specimen designation	Water-to-binder ratio	NCA	RCA	RCA-C	FA	Cement	GHB	Silica fume
RATIC	0.5	0	911	0	407	379	132	28
RATIC-CO_2	0.5	0	0	911	407	379	132	28

Before carbonation, the RCA was held at room temperature and had an initial degree of saturation of 50%. The aggregate was then treated for 7 d in the accelerated carbonation chamber shown in Figure 1, at a CO_2 concentration of 20%, standard atmospheric pressure, 25˚C, and 70% relative humidity. At intervals during treatment, a random portion of the aggregate was removed, and the old cement mortar adhering to its surface was ground into powder and sprayed with phenolphthalein solution. The operational treatment endpoint was the absence of a visible color response in the sampled mortar powder (Figure 2). This endpoint indicates reduced alkalinity in the tested material; it does not establish complete carbonation of all adhered mortar or every aggregate particle. RCA-C denotes aggregate treated to this phenolphthalein-based endpoint.

(a) Sampled mortar with no visible phenolphthalein color response; (b) sampled mortar with a visible color response

Mechanical properties were measured in accordance with the Standard for Test Method of Mechanical Properties on Ordinary Concrete [14]. Compressive-strength and splitting-tensile-strength specimens were 100 mm × 100 mm × 100 mm cubes. The specimens were demoulded 24 h after casting and cured at 20˚C and 95% relative humidity until testing at an age of 28 d. Three specimens per mixture were tested for each mechanical property, and the arithmetic mean was reported.

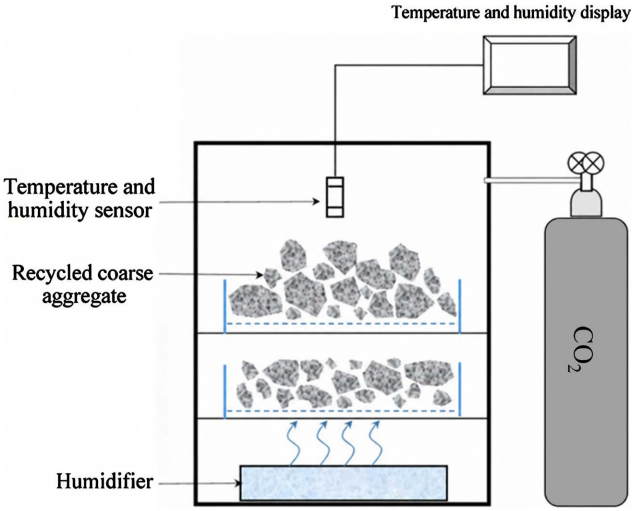


Figure 1. Schematic of the recycled-aggregate carbonation treatment.

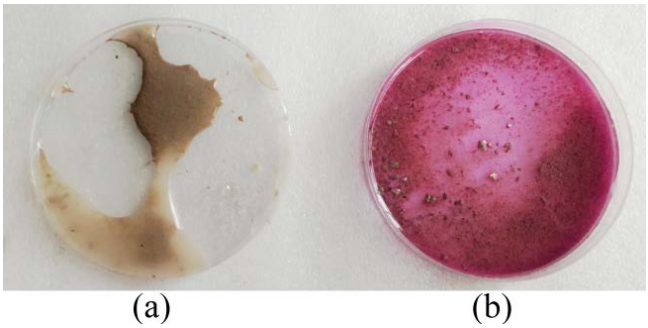


Figure 2. Old cement mortar after spraying with phenolphthalein solution.

Salt freeze-thaw specimens were 100 mm × 100 mm × 400 mm prisms. They were demoulded 24 h after casting and cured in a chamber at 20˚C ± 3˚C and 95% relative humidity until an age of 24 d after casting. The prisms were then immersed for 4 d in a 3.5% NaCl solution by mass, and freeze-thaw exposure began at an age of 28 d. Three prisms were tested for each mixture.

Salt freeze-thaw testing, including mass-loss and relative-dynamic-modulus measurements, followed the rapid freezing method specified in GB/T 50082-2009 [15]. A 3.5% NaCl solution by mass was used as the exposure medium. The solution was not renewed during testing; a salinometer was used to monitor and control its salinity. The time-temperature profile is shown in **Figure 3**. The displayed temperature profile spans approximately 160 min, with the curve labelled Center ranging from approximately −17˚C to +5˚C and the edge and diagonal curves ranging from approximately −24˚C to +22˚C.

Mass loss and relative dynamic modulus were measured at 0, 25, 50, 75, and 100 cycles for RATIC and at 0, 15, 30, 45, 60, 80, and 100 cycles for RATIC-CO_2. The reported durability results are arithmetic means of three specimens per mixture. The 60% relative-dynamic-modulus value is used as a comparison benchmark in

this study; measurements continued to 100 cycles, including after the reported modulus had fallen below this benchmark. Between-specimen variability is not quantified, so the statistical uncertainty of the reported means remains undetermined.

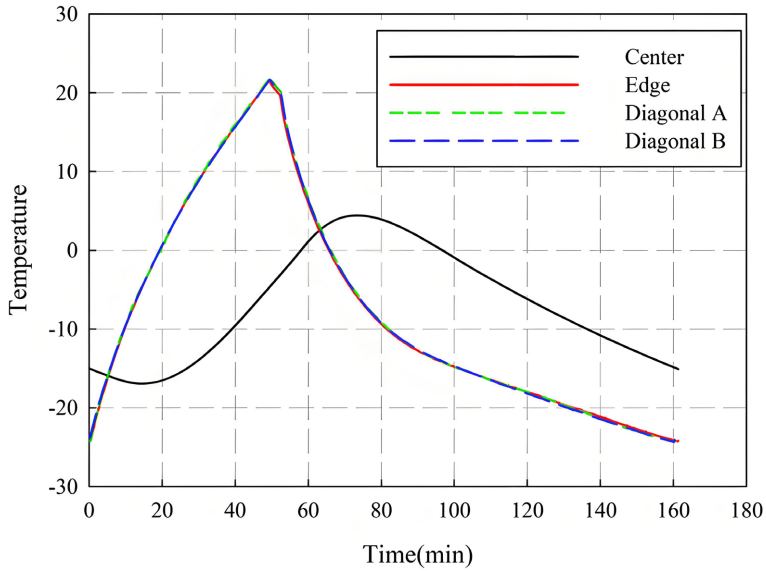


Figure 3. Temperature-control curve for freeze-thaw cycles.

3. Results and Discussion

3.1. Properties of Recycled Coarse Aggregate

According to GB/T 25177-2010, Recycled Coarse Aggregate for Concrete [16], the performance of recycled coarse aggregate is evaluated using apparent density, bulk density, water absorption, moisture content, crushing index, and fine-powder content. CO_2 treatment chiefly affects density, water absorption, and the crushing index. Accordingly, the apparent density, bulk density, water absorption, and crushing index of the recycled aggregate were measured before and after treatment; the results are listed in **Table 3**. All measured properties improved after carbonation. The crushing index decreased by 11.6%, water absorption decreased by 10.6%, and apparent density increased by 3.3%. These changes are consistent with reactions of CO_2 with $Ca(OH)_2$ and C-S-H in the old cement mortar adhering to the recycled coarse aggregate to form $CaCO_3$. The reactions are as follows:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \quad (1)$$

$$C\text{-}S\text{-}H + CO_2 = CaCO_3 + SiO_2 \cdot nH_2O \quad (2)$$

Recent microstructural evidence indicates that carbonation products can fill pores and reduce microcracking in the adhered mortar and old interfacial transition zone [3]. This densification provides a plausible explanation for the improved RCA properties measured here; the extent of improvement depends on the carbonation conditions and aggregate moisture state.

Table 3. Properties of RCA and RCA-C.

Property	RCA	RCA-C
Crushing index	14.7%	13.0%
Water absorption	4.7%	4.2%
Apparent density	2570 kg/m^3	2655 kg/m^3
Bulk density	1265 kg/m^3	1298 kg/m^3

3.2. Compressive and Splitting Tensile Strengths

Figure 4 shows the compressive and splitting tensile strengths of RATIC before and after aggregate carbonation. The mean values for RATIC-CO_2 were 21.2% and 7.1% higher, respectively, than those for RATIC (n = 3 per test and mixture). The 7.1% tensile-strength difference is a descriptive result; its statistical significance and reproducibility cannot be assessed without the replicate measurements and their variability. Recycled concrete contains porous old cement mortar, which can limit mechanical performance. Carbonation-related densification of this mortar provides a possible explanation for the observed strength differences. Both mixtures used SSD-conditioned aggregates without additional absorption-compensation water, limiting the influence of their different absorption capacities on the free mixing water.

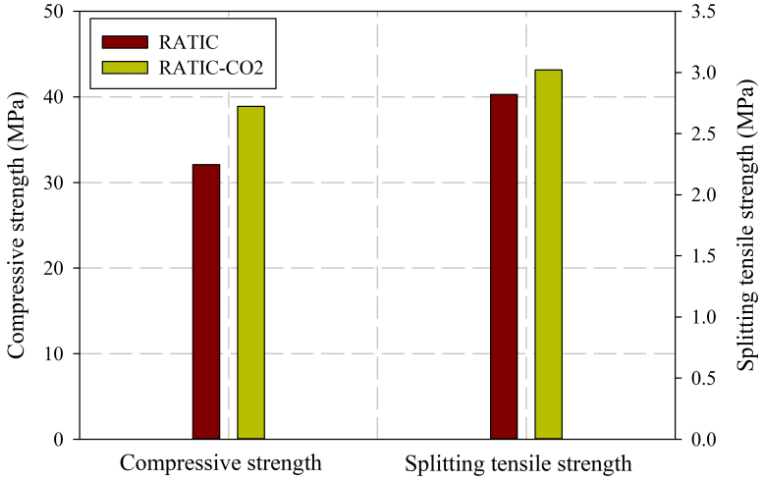


Figure 4. Compressive and splitting tensile strengths of RATIC with untreated and carbonated aggregate.

3.3. Resistance to Salt Freeze-Thaw Cycles

Figure 5 shows the surface condition of RATIC-CO_2 after different numbers of freeze-thaw cycles. The specimen surfaces progressively deteriorated as the number of cycles increased. After 30 cycles, corners were missing and fine cracks appeared near the top of the specimens. After 45 cycles, larger cracks formed near the top and gradually propagated with further cycling, causing extensive spalling of mortar and coarse aggregate. After 60 cycles, severe corner loss developed at

the bottom of the specimens and intensified with additional cycles. Previous research [12] has shown that recycled concrete can undergo splitting failure under the combined action of chloride attack and freeze-thaw cycles, as illustrated in Figure 6(a). After 100 cycles, numerous through-cracks formed on the surface of the RATIC specimens. The binarized local image in Figure 6(b) clearly shows the surface-crack distribution.

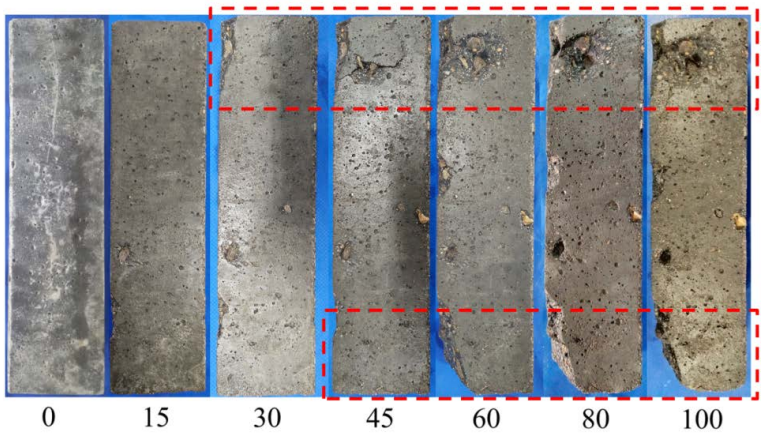


Figure 5. Surface condition of RATIC-CO_2 after salt freeze-thaw cycling.

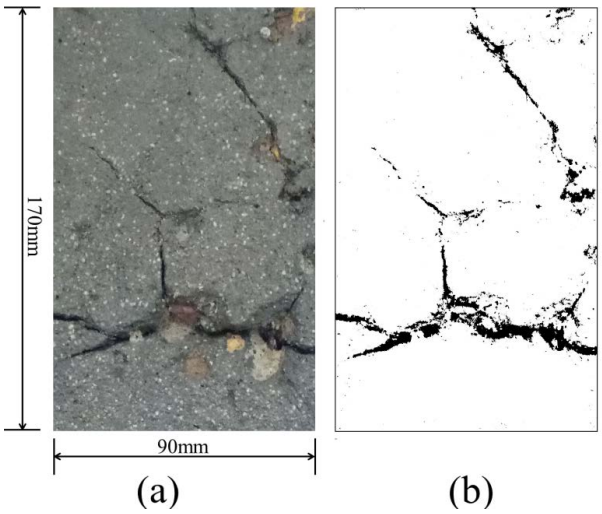


Figure 6. Local damage to a RATIC specimen after 100 salt freeze-thaw cycles.

Figure 7 shows the relative dynamic modulus of elasticity of RATIC and RATIC-CO_2 after different numbers of freeze-thaw cycles. At 50 cycles, the relative dynamic modulus of RATIC was already below 60%. By contrast, RATIC-CO_2 retained approximately 60% after 80 cycles and was below 60% at 100 cycles. As plotted in Figure 7, the 100-cycle relative dynamic moduli were approximately 23% for RATIC and 53% for RATIC-CO_2. These results indicate slower deterioration of the reported relative dynamic modulus for RATIC-CO_2 under the laboratory exposure used here.

Figure 8 shows the mass-loss rates of RATIC and RATIC-CO_2 after different numbers of salt freeze-thaw cycles. Before 50 cycles, the changes were small for both concretes and remained below 0.2%. The mass-loss rate of RATIC-CO_2 increased abruptly after 60 cycles, consistent with severe corner loss and extensive spalling of mortar and coarse aggregate (Figure 5). Figure 8 indicates 100-cycle mass-loss rates of approximately 3.6% for RATIC and 3.25% for RATIC-CO_2.

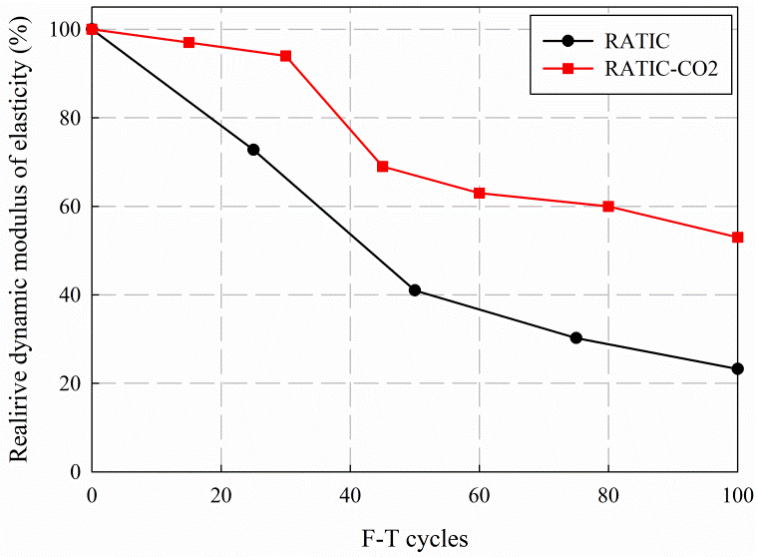


Figure 7. Relative dynamic modulus of elasticity of RATIC and RATIC-CO_2.

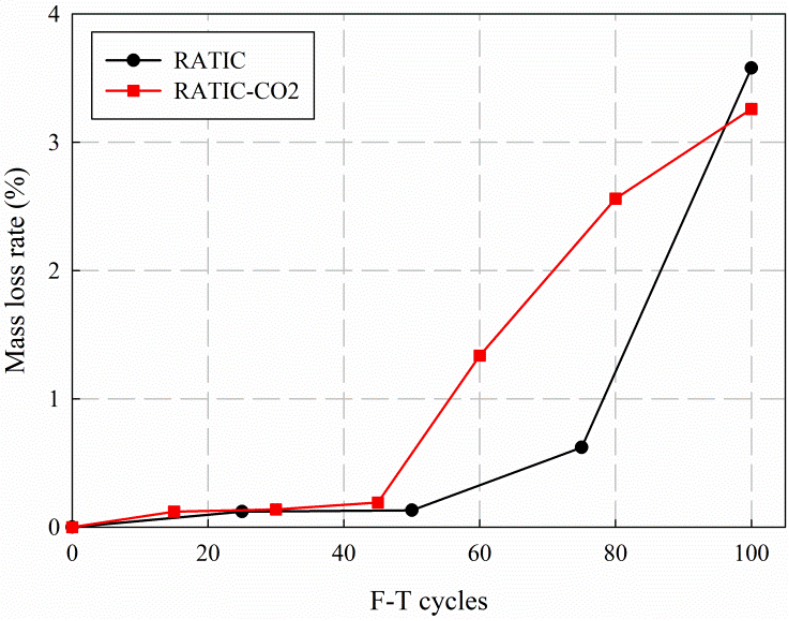


Figure 8. Mass-Loss rates of RATIC and RATIC-CO_2.

Osmotic and hydrostatic pressures generated under salt freeze-thaw conditions contribute to progressive deterioration in concrete specimens. Recycled concrete contains substantial amounts of porous old cement mortar, and the old interfacial

transition zone between this mortar and the natural aggregate can be a weak region. Recent studies have associated carbonation with pore filling, reduced microcracking in adhered mortar [3], and a more compact aggregate-matrix interface under NaCl freeze-thaw exposure [7]. These observations are consistent with the improved retention of dynamic modulus measured in RATIC-CO_2. The mass-loss results provide a separate measure of surface deterioration. Although both mixtures used SSD-conditioned aggregates and the same specified water-to-binder ratio, between-specimen variability must be considered before drawing a conclusion about the effect of carbonation on scaling.

4. Conclusions

1. Under the conditions tested, the mean compressive and splitting tensile strengths of concrete incorporating RCA-C were 21.2% and 7.1% higher, respectively, than those of RATIC. The tensile-strength contrast remains descriptive because between-specimen variability has not been quantified.
2. Concrete incorporating RCA-C retained a higher relative dynamic modulus during the laboratory salt freeze-thaw test. After 100 cycles, the plotted values were approximately 53% for RATIC-CO_2 and 23% for RATIC. These results characterize the tested exposure and do not quantify field service life.
3. After 100 salt freeze-thaw cycles, the mean mass-loss rates were approximately 3.6% for RATIC and 3.25% for RATIC-CO_2. Without the corresponding replicate variability, these results do not establish that carbonation had no appreciable effect on surface scaling.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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