Carbonation Curing of a Dry-Cast Mixture Using Fine Recycled Concrete Aggregate (up to 7 mm)

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Carbonation curing can store CO_2 within concrete while accelerating early-age strength development. This study examined carbonation curing of a freshly cast, dry-cast concrete mixture containing recycled concrete aggregate (RCA) as the sole aggregate, with a maximum size of 7 mm. Twenty-four specimens were cast in two batches of 12, one day apart. In each batch, six were primed by fan-assisted air drying and then carbonated in a sealed chamber (test-batch A: 2 h drying + 2 h carbonation; test-batch B: 4 h drying + 4 h carbonation), and six were sealed after demoulding as sealed controls. Three of each group were tested at 3 and 7 days. The primed and carbonated specimens were compared against the sealed controls from the same batch for compressive strength, and CO_2 uptake was found from the weight change as a percentage of cement mass. CO_2 uptake was 1.63% for test-batch A and 3.02% for test-batch B. At 7 days, the primed and carbonated specimens showed higher mean strengths than their sealed controls (12.2% for test-batch A and 14.3% for test-batch B), but none of the four treatment-versus-control comparisons was statistically significant after Holm correction. Each treatment schedule was based on a single casting and chamber run. Drying duration, carbonation duration and casting day varied together, preventing their individual effects from being determined. Because the sealed controls underwent neither drying nor CO_2 exposure, carbonation's contribution cannot be separated from that of priming. These exploratory results warrant further investigation under controlled, replicated conditions.

Keywords: Recycled concrete aggregate (RCA), carbonation curing, CO_2 uptake, compressive strength, concrete recycling.

Introduction

The construction industry is the backbone of any country's economy, and due to improving living standards and an increase in population, it is expanding rapidly. But this expansion places a burden on the environment, since every step of construction produces large amounts of waste and has become one of the main causes of environmental pollution worldwide[1]. According to global data on construction and demolition waste (CDW), in 2018, the United States generated 600 million tons of CDW, while the European Union generated 862 million tons in 2022 and China generated 3,000 million tons in 2023, much of which was concrete[2]. Similarly, in the UAE, the construction industry accounts for a large amount of solid waste, and 75% of this waste comes from construction[3]. To reduce the environmental impact of this waste and divert from passive landfilling, recycling is necessary[1].

One way to make use of concrete waste is to process it into aggregates. Since aggregates make up most of concrete, their reuse as recycled concrete aggregates (RCA) offers a practical solution. In this paper, recycled concrete aggregate (RCA) refers specifically to aggregate derived predominantly from crushed waste concrete, such as the aggregate used in this study. However, this approach presents several material-specific challenges. RCA granules are usually covered with previous-life hardened mortar paste, making them more porous, absorptive, friable, and less dense than natural stone. Moreover, the residual paste is characteristically high in micro-cracks, making it a weak interfacial substrate that could affect RCA's cohesion with new paste[2,4–6]. The water to cement ratio (w/c) has a significant effect on strength, but with RCA it becomes more complicated as the porous old mortar absorbs part of the mixing water[6,7]. Even so, recycled aggregates are already recognised in construction standards: in Europe, EN 12620 classifies aggregates as natural, recycled or manufactured[8], while EN 206 provides recommendations for the use of recycled coarse aggregate[9].

Several pre-treatments aim to improve RCA by removing or strengthening the adhered mortar. One method is surface abrasion through mechanical grinding, which removes the mortar layer and improves bonding with new paste but is energy- and cost-intensive and can generate excessive fines[10,11]. Another

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is slurry wrapping, which covers the particles with a new cementitious paste that fills pores and microcracks, improving durability, though gains in mechanical properties are less evident[6,12]. Carbonation reactions between CO_2 and calcium hydroxide and other hydration products in the old mortar generate stable calcium carbonate crystals that fill surface pores and microcracks, densifying the residual mortar layer and thereby effectively modifying the RCA[6]. These approaches treat the aggregate before mixing; the present study instead examines carbonation curing of freshly cast concrete containing RCA.

Carbonation curing of concrete has become an increasingly active area of research in recent years, with demonstrated environmental and performance benefits. Unlike the pre-treatments described above, which modify the aggregate before mixing, carbonation curing is applied to the freshly cast concrete itself. Zhang and coworkers reviewed how early-age carbonation engages the calcium silicates in the cement binder, converting them into calcium carbonate and calcium silicate hydrate and thereby accelerating strength development[13]. Because much of the reaction can take place within the first few hours of CO_2 exposure, it could make carbonation curing a possible alternative to energy-intensive steam curing for precast, unreinforced products such as blocks and pavers[14].

The extent of the reaction depends on CO_2 concentration, pressure, exposure duration and moisture conditions, and because carbonation does not consume all of the cement, the remaining unreacted cement can continue to hydrate during later moist exposure to form a denser combined matrix[13]. However, the duration of exposure has to be controlled. Liu and coworkers found that excessive carbonation decomposed the calcium silicate hydrate gel and coarsened the pore structure, and after 72 hours of carbonation, subsequent cement hydration was almost completely prevented[15]. Zhang and coworkers also reported improved durability in carbonated concrete, including greater resistance to low temperature sulphate attack after a year-long submersion in a sulphate solution[16]. As a practical example, Bergmans and coworkers made zero-cement hollow blocks from recycled concrete fines and stainless steel slag, where carbonation itself cured and bound the material, reaching a compressive strength of 15.4 MPa at laboratory scale and meeting the minimum strength required for non-load-bearing blocks[7].

Among the curing conditions, CO_2 pressure has a non-linear effect on carbonation. Liu and coworker noted that higher pressure generally promotes CO_2 diffusion, but the gain in carbonation degree slows as pressure increases further[17]. Controlled drying before CO_2 exposure can improve gas penetration, but sufficient pore water must remain for the carbonation reaction to proceed, since excess water obstructs CO_2 diffusion while excessive drying halts the reaction[13]. This balance makes the moisture state established during priming an important consideration when examining CO_2 uptake and early-age strength. Compressive strength is perhaps one of the most critical and widely used performance metrics for concrete products (e.g. ASTM C39, C90, C140)[18–20]. However, it is rarely evaluated on its own and is usually considered alongside measures such as water absorption, elastic modulus, drying shrinkage, and durability tests, which together give a fuller assessment of suitability[6,16].



Figure. 1 The three DRCM size fractions used in the concrete mix-design.

This study examined the early-age compressive strength and CO_2 uptake of a dry-cast concrete mixture containing RCA as the sole aggregate, with a maximum aggregate size of 7 mm. Specimens receiving combined priming and carbonation were compared with sealed controls for compressive strength at 3 and 7 days. It was hypothesised that the combined treatment would produce higher early-age compressive strength than sealed curing. The results from two priming-and-carbonation schedules were examined as exploratory observations, since each schedule was performed in a single run.

Table 1 Mix proportions of the recycled-aggregate concrete specimens

Constituent	Mass (g)	Proportion (% by mass)
Recycled aggregate, DRCM 0.6–2 mm	300.0	23.2
Recycled aggregate, DRCM 2–5 mm	300.0	23.2
Recycled aggregate, DRCM 0–7 mm	300.0	23.2
OPC	300.0	23.2
Water	86.0	6.7
Admixture (Pantahit 444)	4.72	0.4
Total	1,290.7	100.0

Note: Water/cement ratio (w/c) = 0.29

Materials and Methods

Materials and Mix Proportions

Ordinary Portland cement (OPC) was used as the sole binder. The aggregate was Ducon Recycled Concrete Material (DRCM), produced by crushing and screening concrete

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demolition waste. It had a water absorption of 8.7%, an oven-dry relative density of 1.96 (ASTM C128)[21], and was in an air-dry condition at the time of batching. It was used in three size fractions of 0.6–2 mm, 2–5 mm and 0–7 mm, each added in an equal amount of 300 g per lab batch (Figure 1), giving an aggregate-to-cement ratio of 3.0:1 by mass. A chemical admixture (Pantahit 444) was added at 1.57% by mass of cement. The same mix was used in both test-batches at a water-to-cement ratio of 0.29. Since porous DRCM could absorb part of the mixing water, the nominal water-to-cement ratio does not establish the effective water-to-cement ratio available for cement hydration. The proportions are given in Table 1.

Specimen Preparation

The dry constituents (the three DRCM fractions and OPC) were first weighed cumulatively into the tared mixer bowl (Figure 2) and placed in the mixer (Figure 3a), after which the mixing water and admixture were added, and the materials were mixed for 2 minutes until a uniform, damp consistency was obtained. For each specimen, 600.0 g of the fresh mix was weighed and placed in a 100 mm steel cube mould fitted with a spacer insert to form a slab-shaped cavity (Figure 3b–f). The mix was compacted in the steel mould by vibration for 30 seconds, and the specimen was then demoulded. The resulting slabs measured approximately 100 mm × 100 mm × 33 mm, with an average weight of 587.3 g after demoulding (Figure 4). A total of 24 specimens were prepared in an identical fashion and divided into four groups of six specimens each. Figure 5 shows two sets of six slabs prepared for curing. The specimens were cast in two batches of 12, one day apart: test-batch A on the first day and test-batch B on the following day. In each batch, six specimens were primed and carbonated (test-batch A: 2 h drying followed by 2 h carbonation; test-batch B: 4 h drying followed by 4 h carbonation), and the other six were sealed in plastic bags straight after demoulding, with no drying or CO_2 exposure, as controls. Because the two batches were cast on different days, each carbonated group was compared with the controls cast alongside it. Three specimens of each group were tested at 3 days and three at 7 days (Table 2). Each treatment schedule was carried out in a single casting batch and a single carbonation run. Each therefore represents one run rather than a replicated condition.

Curing

Two curing conditions were compared: combined priming and carbonation and sealed curing (conventional hydration curing). The 12 control specimens (six per test-batch) were not dried: immediately after demoulding they were sealed in labelled plastic bags (Figure 6) and stored until the target test age, receiving hydration curing only, with no CO_2 exposure.

Table 2 Breakdown of the 24 specimens by batch, curing condition and test age

Batch	Treatment	No. of specimens	Tested at 3 days	Tested at 7 days
Test-batch A (cast on day 1)	Dried 2 h + carbonated 2 h	6	3	3
	Sealed control (no drying, no CO_2)	6	3	3
Test-batch B (cast on day 2)	Dried 4 h + carbonated 4 h	6	3	3
	Sealed control (no drying, no CO_2)	6	3	3
Total		**24**	**12**	**12**



Figure. 2 Batching sequence for the dry constituents, weighed cumulatively: (a) empty bowl, (b–d) the three DRCM fractions added in turn, (e) OPC added, (f) the mixed dry constituents, and (g) the water and admixture.

For the carbonated groups, the specimens underwent a priming step before CO_2 curing, with a duration equal to that of the carbonation step. Priming consisted of weight-monitored, fan-assisted air-drying, with the slabs standing upright on their edges (Figure 7a), to partially remove free (evaporable) water from the surface pores of the specimens. The purpose of drying was to partially open pore structure to make CO_2 diffusion easier, while leaving enough water for carbonation. Each specimen was weighed before and after priming, and the water removed was expressed as a percentage of the mixing water in the specimen. Test-batches A and B were primed and carbonated in two separate runs under the same recorded conditions, summarized in Table 3. In each run, the six primed specimens

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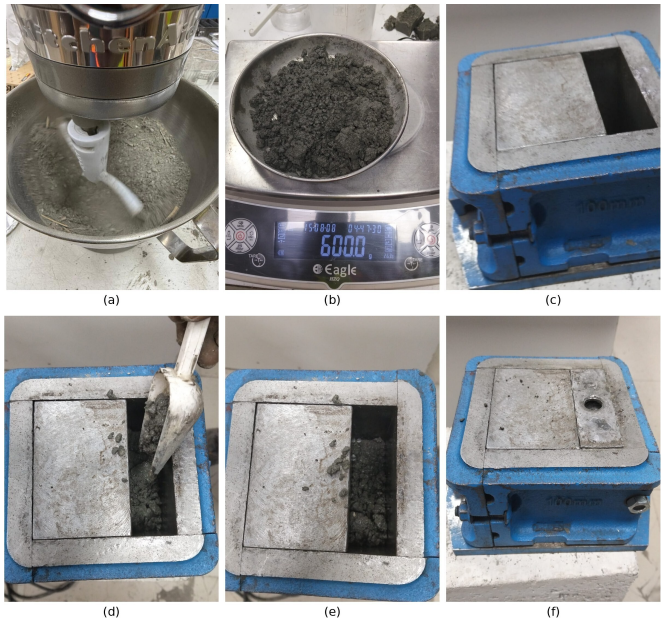

Figure. 3 Mixing and moulding: (a) mixing of the constituents, (b) a 600 g portion of fresh mix weighed out, (c) the steel cube mould fitted with the spacer insert, (d) filling the mould, (e) the filled mould, and (f) the assembled mould.



Figure. 4 Demoulded specimens: (a, b) demoulded slabs being weighed, and (c–f) slab dimensions measured with calipers.

were placed on a mesh rack inside a sealed CO_2 curing chamber (Ducon Carboclave; Figure 7b, c) and exposed to CO_2 supplied from a cylinder through a dual-gauge regulator (Figure 7d, e). The chamber air was not purged or evacuated before



Figure. 5 Sets of six demoulded specimens: (a) and (b) the two sets, each of six slabs, prepared for curing.

CO_2 was introduced. At the end of each run, the chamber was vented through a water jar (Figure 8a). Specimen mass was recorded before and after CO_2 exposure, with average gains of 2.07 g per specimen in test-batch A and 3.75 g per specimen in test-batch B. Owing to the exothermic nature of the carbonation reaction, some water evaporated from the specimens and condensed on the interior walls of the chamber; this water was collected on pre-tared tissue and weighed after each run (1.0 g for test-batch A and 2.3 g for test-batch B; Figure 8b–c). The slabs were weighed after that (Figure 8d). The collected water was apportioned to the specimens of that run in proportion to their pre-carbonation weight and added to the measured weight gain (Eq. 1), giving an average CO_2 uptake of 2.23 g per specimen for test-batch A and 4.13 g per specimen for test-batch B. As with the controls, the carbonated specimens were then sealed in plastic bags and stored until testing, three at 3 days and three at 7 days.

Table 3 Priming and carbonation conditions (same recorded settings for both runs; only the durations differed)

Parameter	Value
CO_2 purity	99.98% (industrial grade).
CO_2 delivery pressure	∼1.5 kgf/cm^2 (∼1.5 bar gauge, regulator delivery pressure, not independently measured in chamber).
Gas supply	Regulator open for the whole run; CO_2 supplied continuously at a constant regulator setting.
Drying method	Fan-assisted air-drying; slabs upright, ∼25 cm from a pedestal fan on high.
Drying air temperature	24 °C (air-conditioned lab).
Drying start	Immediately after demoulding and weighing.
Sealed-slab storage temperature	24 °C

Note: Chamber volume, chamber internal temperature and relative humidity, drying relative humidity, and fan air speed were not recorded.

CO_2 Uptake Determination

CO_2 uptake was determined by the mass-gain method and expressed as a percentage of the cement mass of the specimen. The mass gained during carbonation was corrected for the water collected from the chamber after carbonation:

$$\text{CO}_2\text{ uptake }(\%) = \frac{(M_{ac} - M_{bc}) + M_w}{M_c} \times 100 \qquad (1)$$

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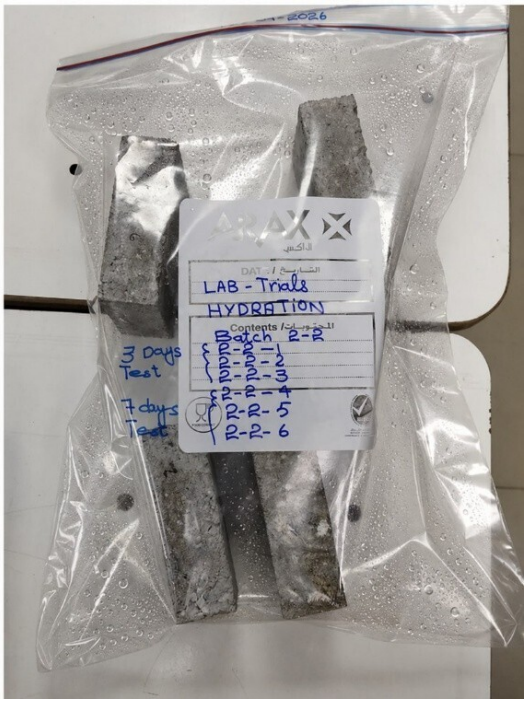

Figure. 6 Sealed control specimens.



Figure. 7 Priming and carbonation set-up: (a) fan-assisted drying of the slabs, (b) slabs on the mesh rack inside the chamber, (c) the sealed carbonation chamber, (d) the CO_2 cylinder, chamber and water jar, (e) the dual-gauge regulator, and (f) the ambient CO_2 monitor.

Where M_{ac} is the slab mass after carbonation, M_{bc} is the mass before carbonation (after drying), M_w is the share of the water collected from the chamber after carbonation that is apportioned to the specimen (in proportion to its pre-carbonation mass), and M_c is the cement mass of the specimen (23.24% of its mass after demoulding, i.e. the cement share of the mix). Uptake was computed for each of the six carbonated specimens in a test-batch and averaged. Because water vapour remaining in the chamber air or lost during venting was not captured, the reported uptake is a lower-bound estimate.



Figure. 8 After carbonation: (a) the chamber vented through a water jar, (b) the pre-tared tissue before use, (c) the tissue after collecting the condensed reaction water, (d) a carbonated slab being weighed, and (e) the carbonated specimens.

Compressive Strength

Compressive strength was the primary performance indicator. It was measured at 3 and 7 days on both the carbonated slabs and the sealed control slabs, and is reported in MPa. The compressive strength of hardened concrete is commonly evaluated on standard cube specimens according to EN 12390-3[22]. However, in this study, the specimens were non-standard slab sections rather than standard cubes, so the test did not follow EN 12390-3 and was instead carried out as an internal comparative assessment based on the general principles of ASTM C140/C140M[19]. The strength was calculated over the slab's nominal loaded face of 3,300 mm^2 (100 $\times$ 33 mm). Testing was carried out on a Matest compression machine (Model C055PN258, Matest S.p.A., Treviolo, Italy), equipped with a 250 kN load cell. The machine first brought the loading plates into firm contact with the specimen, and once the load reached the transition point of 10 kN it applied load at a controlled rate of 0.3 kN per second until failure. This corresponds to about 0.09 MPa per second over the loaded face, which is below the rate specified in ASTM C39[18]; because the same rate was applied to every specimen, it did not bias the comparison between groups. Testing stopped automatically once the load

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fell 10% past its peak, confirming the break point (Figures 9 and 10). Three specimens were tested for each combination of curing condition and age, and the mean and standard deviation of the three results are reported. The difference between the combined-treatment specimens and their sealed controls of the same test-batch and age was expressed as a percentage of the control strength.



Figure. 9 Compressive strength testing equipment: (a) the compression testing machine, (b) the control unit, (c) a specimen positioned between the platens, (d) a specimen under load, (e) the test-control display, and (f–h) the machine identification and capacity labels.



Figure. 10 Compression-testing setup: (a) and (b) a slab positioned upright between the platens, loaded on its 100 × 33 mm face.

Results

The results are presented in three parts. The first part covers the drying degree achieved during the priming step, the second part covers the CO_2 taken up by the specimens during carbonation, and the third reports the compressive strength of the carbonated slabs and their sealed controls. Test-batch A refers to the shorter processing time of 4 hours (2 hours of priming + 2 hours of carbonation) and test-batch B refers to the longer processing time of 8 hours (4 hours of priming + 4 hours of carbonation).

Priming – Monitored Moisture Loss

In preparation for carbonation, the specimens were intentionally dried by fan-assisted air-drying so that their surface pores would not be fully saturated with water during the subsequent carbonation, leaving room for CO_2 gas to permeate through the microstructure. The degree of drying was determined by weighing the specimens before and after this priming step. In test-batch A, the six specimens lost a cumulative mass of 50.9 g (8.48 g per specimen on average) over the 2-hour drying period, equivalent to 21.7% of the mixing water they contained. Test-batch B lost 66.9 g (11.15 g per specimen) over the 4-hour drying period, equivalent to 28.4% of the mixing water. This approach is consistent with previous research showing that an intermediate moisture condition is required for effective carbonation, because excessive moisture restricts CO_2 diffusion while insufficient moisture limits the carbonation reaction[23]. Table 4 gives the drying figures for both test-batches.

Table 4 Drying and associated weight loss experienced by the specimens (totals for the six carbonated specimens in each test-batch).

Measured variables	Test-batch A (2 h drying)	Test-batch B (4 h drying)
Weight, fresh (g)	3,525.1	3,529.8
Weight, post-drying (g)	3,474.2	3,462.9
Weight loss (g)	50.9	66.9
Mixing water in specimens (g)	234.9	235.2
Moisture loss (% of mixing water)	21.7%	28.4%

CO_2 Uptake

The CO_2 uptake during carbonation was calculated from the specimens' weight gain and the water collected from the chamber after carbonation (Eq. 1), and expressed as a percentage of the cement mass. Test-batch A specimens cumulatively gained 12.4 g during 2 hours of carbonation; adding the 1.0 g of collected water gives a total CO_2 uptake of 13.4 g, or 1.63% of the cement mass. Test-batch B specimens gained 22.5 g during 4 hours of carbonation; with the 2.3 g of collected water, the total CO_2 uptake was 24.8 g, or 3.02% of the cement mass (Figure 11). The total cement mass of the six carbonated specimens amounted to 819.3 g in test-batch A and 820.4 g in test-batch B. The individual uptakes were 1.29, 1.30, 1.38, 1.81, 2.01 and 2.02% of cement mass for test-batch A, and 2.43, 2.76, 2.92, 2.96, 3.12 and 3.94% for test-batch B. Expressed per unit volume, this corresponds to about 6.8 kg CO_2/m^3 for test-batch A and 12.5 kg CO_2/m^3 for test-batch B (about 3.8 and 7.0 kg per tonne of concrete).

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Test-batch B took up more CO_2 than test-batch A. However, because the drying and carbonation durations were both doubled between the two test-batches, it is not possible to determine from the present study whether the observed increase in CO_2 uptake was primarily due to the longer drying period, the longer carbonation period, or a combination of both. The two batches were also cast on different days, and each schedule was run only once, so the uptake difference reflects a single observation per schedule rather than a replicated effect. Previous studies suggest that the degree of drying may play an important role in promoting CO_2 diffusion through the pore structure. Intermediate moisture conditions can facilitate CO_2 diffusion while retaining sufficient water for the carbonation reaction[24]. In the present study, the longer drying period used for test-batch B may have contributed to the increased CO_2 uptake by removing more pore water and increasing pore accessibility for CO_2 penetration, while retaining sufficient residual moisture for carbonation to occur. Table 5 summarizes the cumulative CO_2 uptake of the test-batches.

Table 5 Cumulative CO_2 uptake per test-batch (six carbonated specimens each)

Measured variables	Test-batch A (2 h carbonation)	Test-batch B (4 h carbonation)
Weight, pre-carbonation (g)	3,474.2	3,462.9
Weight, post-carbonation (g)	3,486.6	3,485.4
Weight gained (g)	12.4	22.5
Water collected from chamber (g)	1.0	2.3
Total CO_2 uptake (g)	13.4	24.8
Total cement mass (g)	819.3	820.4
CO_2 uptake (% of cement mass)	1.63%	3.02%

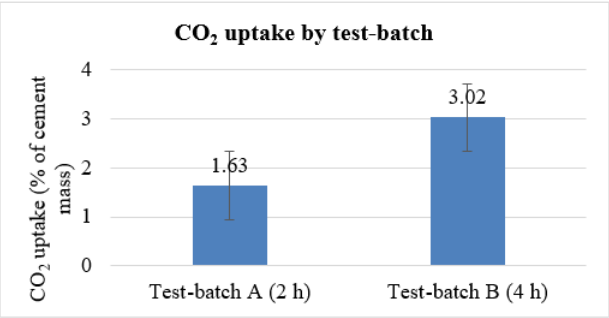

Figure. 11 CO_2 uptake measured for the two test-batches, expressed as a percentage of cement mass; error bars show ± 1 SD (n = 6)

Compressive Strength

Compressive strength was measured at the age of 3 and 7 days for all batches. Each value is the mean of three specimens. The carbonated test-batches had higher mean strengths than their controls at both ages, with test-batch B yielding the highest strengths overall. The results are summarized in Table 6 below.

Table 6 Compressive strength of prime and carbonated and sealed control specimens (mean $\pm$ standard deviation, n = 3)

Strength result (MPa)	Test-batch A (2 h/2 h)	Control A (sealed)	Test-batch B (4 h/4 h)	Control B (sealed)
3 days	25.97 $\pm$ 1.96	24.47 $\pm$ 3.49	30.27 $\pm$ 0.86	26.50 $\pm$ 1.57
7 days	35.67 $\pm$ 2.35	31.80 $\pm$ 1.25	38.70 $\pm$ 0.44	33.87 $\pm$ 1.65
Gain over own control, 3 days	+6.1%	–	+14.2%	–
Gain over own control, 7 days	+12.2%	–	+14.3%	–

Each test-batch had its own group of six sealed control specimens, prepared alongside the carbonated specimens from the same mix. After demoulding, the controls were sealed directly in plastic bags, without drying or CO_2 exposure, and three were tested at 3 days and three at 7 days. Because the two test-batches were cast one day apart, each test-batch was compared with its own controls to account for batch-to-batch variation in mixing, casting, compaction and curing. The specimens had similar densities across all four groups, from about 1,770 to 1,790 kg/m^3 based on the demoulded mass and nominal slab volume, suggesting similar compaction across the four groups.

This variation was evident in the control strengths, which were about 2 MPa higher for test-batch B than for test-batch A at both ages (26.50 vs 24.47 MPa at 3 days and 33.87 vs 31.80 MPa at 7 days), although the controls of the two batches received identical treatment. This difference is not statistically significant and may reflect day-to-day variation in casting. The differences in mean strength between 3 and 7 days were 7.33 MPa and 7.37 MPa for controls A and B, respectively. By comparison, the corresponding differences in mean strength for the carbonated groups were 9.70 MPa (test-batch A) and 8.43 MPa (test-batch B) over the same period. The carbonated results were therefore expressed as a percentage gain over the control of the same test-batch and age. At 3 days, test-batches A and B showed gains of 6.1% and 14.2%, respectively, over their controls; at 7 days, the gains were 12.2% and 14.3%.

Test-batch B therefore showed a larger difference from its controls, and its carbonated specimens showed the least scatter (standard deviation below 1 MPa at both ages). In test-batch A, the 3-day difference of 1.5 MPa was smaller than the scatter among its control specimens (20.7–27.6 MPa), so it should be interpreted with caution. Figure 12 shows the 3-day and 7-day strengths side by side for all four groups of specimens.

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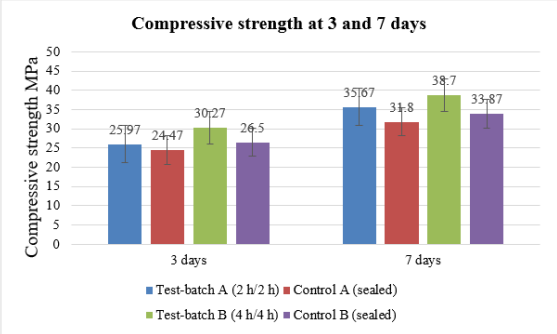

Figure. 12 Compressive strength at 3 and 7 days for carbonated and control specimens for both test-batches; error bars show ±1 SD (n = 3)

Statistical Comparison of Control Groups

The two control groups received identical treatment: both were demoulded and sealed directly in plastic bags, with no drying and no CO_2 exposure. The only difference between them was that test-batch B was cast one day after test-batch A. Their strengths are compared in Table 7.

Table 7 Comparison of the sealed control specimens of the two test-batches (mean of three specimens, range in brackets)

Control specimens	Test-batch A	Test-batch B	Difference	Significance
Strength at 3 days (MPa)	24.47 (20.7–27.6)	26.50 (25.1–28.2)	+2.03	No ($p \approx 0.43$)
Strength at 7 days (MPa)	31.80 (30.6–33.1)	33.87 (32.2–35.5)	+2.07	No ($p \approx 0.16$)
Strength difference, 3 to 7 days (MPa)	7.33	7.37	+0.04	Not tested

The controls of test-batch B were about 2 MPa stronger at both ages, but the difference was not statistically significant (two-sample Welch t-test: $p \approx 0.43$ at 3 days and $p \approx 0.16$ at 7 days). The difference in mean strength between 3 and 7 days was 7.33 MPa for test-batch A and 7.37 MPa for test-batch B.

Statistical Comparison of Carbonated and Control Specimens

The carbonated specimens were compared with their controls of the same batch and age. Individual compressive strengths of all 24 specimens are presented in Table 8. The differences were +1.5 MPa (95% CI −5.7 to 8.7) and +3.9 MPa (95% CI −1.0 to 8.7) for test-batch A at 3 and 7 days, and +3.8 MPa (95% CI 0.5 to 7.0) and +4.8 MPa (95% CI 1.1 to 8.6) for test-batch B. After correcting for the four comparisons using the Holm method, the adjusted p-values were 0.561 and 0.171 for test-batch A and 0.120 for both ages of test-batch B. None was significant at $\alpha = 0.05$, so the strength differences

Table 8 Individual compressive strengths of all 24 specimens (MPa)

Batch	Treatment	Age	Specimen 1	Specimen 2	Specimen 3
A	Priming + carbonation	3 days	26.2	27.8	23.9
A	Priming + carbonation	7 days	38.1	35.5	33.4
A	Sealed control	3 days	20.7	25.1	27.6
A	Sealed control	7 days	30.6	31.7	33.1
B	Priming + carbonation	3 days	30.1	31.2	29.5
B	Priming + carbonation	7 days	39.2	38.4	38.5
B	Sealed control	3 days	26.2	28.2	25.1
B	Sealed control	7 days	33.9	35.5	32.2

are treated as exploratory. A two-way ANOVA (treatment × age), pooling test-batches A and B, was performed as an exploratory analysis and did not test treatment duration (age $p < 0.001$, treatment $p \approx 0.002$, interaction $p \approx 0.39$). However, because specimens shared chamber runs rather than representing independent treatment repetitions, its p-values are not used to establish a statistically significant treatment effect. Both control groups received the same casting, sealing and storage procedure. The observed differences between the combined-treatment and sealed-control groups are therefore reported as associated with the priming and carbonation treatment rather than carbonation alone.

Discussion

The two test-batches showed that the primed and carbonated specimens had higher mean compressive strength than the sealed controls, and that the longer drying and CO_2 exposure condition was associated with greater CO_2 uptake and a higher relative strength difference. Test-batch A had a CO_2 uptake of 1.63% and test-batch B had 3.02%, with corresponding 7-day strength differences of 12.2% and 14.3% relative to their sealed controls. These results are consistent with literature suggesting that increased air-drying can reduce pore-water saturation, improve pore accessibility, and facilitate the diffusion of CO_2 through the concrete pore structure[24]. The diffused CO_2 then reacts with the calcium-bearing phases in the cement paste to form calcium carbonate ($CaCO_3$), which fills pores and densifies the matrix[13]. Although this study did not measure the combined effect of drying and carbonation on the microstructure of the specimens, the treatment was associated with a difference in compressive strength. The difference between the two test-batches was most pronounced at 3 days (6.1% and 14.2%) and smaller at 7 days (12.2% and 14.3%). Because each condition was run only once, strength development cannot be inferred from these results.

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This study does not directly treat RCA with carbonation; rather, carbonation occurs in situ while the RCA is incorporated as a component of the concrete composite. The strength differences observed in the primed and carbonated test-batches are consistent with the CO_2-modification effects associated with carbonation curing, which has been reported to accelerate cementitious reactions and densify the paste microstructure [13]. Aside from its strength effects, carbonation stores CO_2 by mineralizing it as carbonate minerals within the concrete [17]. In the present study, the adopted experimental conditions limited carbonation curing to 4 hours, which resulted in a CO_2 uptake equivalent to 3.02% of the mass of cement, or about 4.1 g of CO_2 per specimen (about 12.5 kg per cubic metre). Taking a cement content of about 400 kg per cubic metre and an emission factor of about 0.84 kg CO_2 per kg of CEM I cement [25], cement production releases roughly 336 kg CO_2 per cubic metre, so the measured uptake corresponds to about 3.7% of the CO_2 released in producing the cement. Any net CO_2 benefit would also need to account for emissions from drying the specimens and capturing and transporting the CO_2; these were not quantified. Because the depth and degree of carbonation achieved under these conditions were not directly quantified, future replicated experiments should test whether longer exposure durations increase CO_2 uptake.

Limitations and Future Prospects

The study was preliminary and had several limitations. One limitation was the small sample size which constrained the statistical power and representativeness of results. A single batch was cast for each test scenario, and within each batch only three specimens were tested per curing condition and age. Future work should include larger sample sizes and more specimens per condition to give more representative results.

Another limitation was variability between specimens and between batches. Although the three specimens per group and the batch-specific controls allowed specimen-to-specimen scatter to be quantified, this scatter was uneven between the control groups. It was largest among the 3-day controls of test-batch A (20.7–27.6 MPa) and more moderate in the other control groups (ranges of about 2.5 to 3.3 MPa). In addition, the controls of test-batch B were about 2 MPa stronger than those of test-batch A at both 3 and 7 days despite identical treatment, which reflects variation between batches cast one day apart. Because the two test-batches were also cast on different days, part of the difference between them may reflect the casting day rather than the drying and carbonation durations. Therefore, the results are best regarded as exploratory observations under the two combined schedules rather than a confident attribution of the strength differences to the processing conditions. Future studies should replicate batches for each test condition and a broader range of processing conditions.

A further limitation was that the carbonated specimens were dried before CO_2 exposure while the controls were sealed without drying, so the two groups differed in both drying and carbonation. Drying may have lowered the effective water-to-cement ratio of the carbonated specimens, which can raise strength on its own, so the measured difference reflects the combined priming-and-carbonation treatment rather than carbonation alone. A further control that received the same priming and chamber duration without CO_2, under the same conditions, would be needed to distinguish the two effects.

In addition, the simultaneous variation of both priming and CO_2-curing duration made it difficult to determine which variable contributed to the observed difference in compressive strength. Therefore, the results can only be described as exploratory observations of the combined effect of the two processing conditions rather than of either variable individually. Future studies should separate priming duration from CO_2 exposure duration by keeping one factor fixed while varying the other, allowing the individual effects of each variable to be determined.

Moreover, compressive strength was measured only up to 7 days, leaving the long-term strength development and behaviour of the specimens largely unknown. CO_2 uptake was estimated using a simple mass-gain method, which may be less precise than established analytical techniques. Because this method does not capture water vapour remaining in the chamber air or lost during venting, the reported uptake should be regarded as a lower-bound estimate. Future studies should include later-age strength measurements to determine whether the observed strength differences persist with time. The mass-gain method could also be complemented by a more precise analytical technique, such as thermogravimetric analysis (TGA), to improve the accuracy of CO_2 uptake measurements. In addition, phenolphthalein staining of fractured specimens could also be used to reveal the depth and extent of carbonation.

Finally, the specimens were non-standard rectangular slabs rather than standard cubes, which limits direct comparison with cube-based studies. Strength was calculated using a nominal loaded area of 100×33 mm for all specimens, although the slab thickness varied slightly between specimens. Using a nominal rather than an individually measured area adds some uncertainty to the reported values.

Conclusion

This study compared two combined priming-and-carbonation schedules applied to recycled-aggregate concrete slabs, based on CO_2 uptake and compressive strength, with sealed specimens serving as controls. Based on the results obtained, CO_2 uptake was 1.63% of cement mass for the shorter sched-

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ule and 3.02% for the longer one. Compared with the controls, the carbonated specimens had higher mean strength in both test scenarios. At 7 days, test-batches A and B reached compressive strengths of 35.67 MPa and 38.70 MPa, respectively, compared with 31.80 MPa and 33.87 MPa for their corresponding controls. These results indicate that priming and carbonation treatment may have improved the compressive strength of recycled-aggregate concrete, although none of the four treatment-versus-control comparisons was statistically significant. The carbonated specimens were both primed and carbonated, while the controls were neither, so the effect of carbonation cannot be separated from that of priming. Because the two schedules differed in duration and were cast on different days, any duration effect cannot be separated from casting-day differences. These findings are promising but preliminary, as the study used a single batch with three specimens per curing condition and age for each test scenario. These findings are most relevant to unreinforced products such as blocks and pavers. Future studies should include replicate batches, more specimens, additional processing durations, and longer curing ages before drawing firm conclusions.

Artificial Intelligence Use Statement

Artificial-intelligence tool Claude was used to support data analysis and statistical calculations, and to identify spelling errors. The tools were not used to draft, paraphrase, or reword any text. All sentences in this manuscript were written by the author.

References

1 A. K. Badraddin, R. A. Rahman, Z. Zakaria, M. Hasan. Factors affecting concrete recycling adoption in the construction projects. IOP Conference Series: Earth and Environmental Science. Vol. 641, pg. 012018, 2021, https://doi.org/10.1088/1755-1315/641/1/012018.

2 J. Xiao, C. Yu, B. Wang, H. Liu, C. S. Poon, J. de Brito, X. Xiao, J. Liu, S. P. Shah. Recycled aggregate concrete design, application and challenges. Nature Reviews Clean Technology. Vol. 2, pg. 67–83, 2026, https://doi.org/10.1038/s44359-025-00125-2.

3 M. Mawed. Construction and demolition waste management in the UAE: application and obstacles. International Journal of GEOMATE. Vol. 18, pg. 235–245, 2020, https://doi.org/10.21660/2020.70.45101.

4 Q. Liu, J. Xiao, Z. Sun. Experimental study on the failure mechanism of recycled concrete. Cement and Concrete Research. Vol. 41, pg. 1050–1057, 2011, https://doi.org/10.1016/j.cemconres.2011.06.007.

5 K. McNeil, T. H.-K. Kang. Recycled concrete aggregates: a review. International Journal of Concrete Structures and Materials. Vol. 7, pg. 61–69, 2013, https://doi.org/10.1007/s40069-013-0032-5.

6 J. Wang, J. Zhang, D. Cao, H. Dang, B. Ding. Comparison of recycled aggregate treatment methods on the performance for recycled concrete. Construction and Building Materials. Vol. 234, pg. 117366, 2020, https://doi.org/10.1016/j.conbuildmat.2019.117366.

7 J. Bergmans, H. Kazemi Kamyab, D. Ghosh, P. Van Mierloo, H. Carens, P. Nielsen. Carbonation of recycled concrete aggregates for new concrete and concrete fines to make cement-free hollow blocks. Sustainability. Vol. 16, pg. 3494, 2024, https://doi.org/10.3390/su16083494.

8 D. J. Collery, K. A. Paine, T. O'Flaherty. Building on a performance related approach to use normal weight aggregates in concrete: Recycled aggregate. UKIERI Concrete Congress, 2019.

9 CEN. EN 206:2013+A2:2021 Concrete — specification, performance, production and conformity. European Committee for Standardization, Brussels, 2021.

10 J. V. M. Raman, V. Ramasamy. Various treatment techniques involved to enhance the recycled coarse aggregate in concrete: a review. Materials Today: Proceedings. Vol. 45, pg. 6356–6363, 2021, https://doi.org/10.1016/j.matpr.2020.10.935.

11 Y. Ding, J. Wu, P. Xu, X. Zhang, Y. Fan. Treatment methods for the quality improvement of recycled concrete aggregate (RCA) — A review. Journal of Wuhan University of Technology-Mater. Sci. Ed. Vol. 36, pg. 77–92, 2021, https://doi.org/10.1007/s11595-021-2380-3.

12 J. Ying, Z. Han, L. Shen, W. Li. Influence of parent concrete properties on compressive strength and chloride diffusion coefficient of concrete with strengthened recycled aggregates. Materials. Vol. 13, pg. 4631, 2020, https://doi.org/10.3390/ma13204631.

13 D. Zhang, Z. Ghouleh, Y. Shao. Review on carbonation curing of cement-based materials. Journal of CO_2 Utilization. Vol. 21, pg. 119–131, 2017, https://doi.org/10.1016/j.jcou.2017.07.003.

14 S. Monkman, Y. Shao. Integration of carbon sequestration into curing process of precast concrete. Canadian Journal of Civil Engineering. Vol. 37, pg. 302–310, 2010, https://doi.org/10.1139/L09-140.

15 M. Liu, S. Hong, Y. Wang, J. Zhang, D. Hou, B. Dong. Compositions and microstructures of hardened cement paste with carbonation curing and further water curing. Construction and Building Materials. Vol. 267, pg. 121724, 2021, https://doi.org/10.1016/j.conbuildmat.2020.121724.

16 S. Zhang, Z. Ghouleh, A. Azar, Y. Shao. Improving concrete resistance to low temperature sulphate attack through carbonation curing. Materials and Structures. Vol. 54, pg. 37, 2021, https://doi.org/10.1617/s11527-021-01626-9.

17 Z. Liu, W. Meng. Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites: a review. Journal of CO_2 Utilization. Vol. 44, pg. 101428, 2021, https://doi.org/10.1016/j.jcou.2020.101428.

18 ASTM International. Standard test method for compressive strength of cylindrical concrete specimens (ASTM C39/C39M-21). ASTM International, 2021.

19 ASTM International. Standard test methods for sampling and testing concrete masonry units and related units (ASTM C140/C140M-23). ASTM International, 2023.

20 ASTM International. Standard specification for loadbearing concrete masonry units (ASTM C90-22). ASTM International, 2022.

21 ASTM International. Standard test method for relative density (specific gravity) and absorption of fine aggregate (ASTM C128-22). ASTM International, 2022.

22 CEN. EN 12390-3 Testing hardened concrete — part 3: Compressive strength of test specimens. European Committee for Standardization, Brussels, 2019.

23 L. Wu, W. Zhang, H. Jiang, X. Ju, L. Guan, H. Liu, S. Chen. Synergistic effects of environmental relative humidity and initial water content of recycled concrete aggregate on the improvement in properties via carbonation reactions. Materials. Vol. 16, pg. 5251, 2023, https://doi.org/10.3390/ma16155251.

24 H. S. Farahani, A. Hosseini Zadeh, J. Hu, C. Hawkins, S. Kim. Carbonation reaction of recycled concrete aggregates (RCA): CO_2 mass consumption under various treatment conditions. Cleaner Materials. Vol. 15, pg. 100296, 2025, https://doi.org/10.1016/j.clema.2025.100296.

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25 D. Casey. Embodied CO_2e of UK cements. Fact Sheet 18 (ST/FS/18, Revision 4). Mineral Products Association, 2025.

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