Experimental investigation on the mechanical and chemical properties of lightweight aggregate concrete with CO_2 curing

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Experimental investigation on the mechanical and chemical properties of lightweight aggregate concrete with CO_2 curing

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Abstract. In the cement and concrete industry, enormous amounts of Carbon Dioxide (CO_2) are emitted during their production processes. Carbon dioxide emission significantly contributes to the global climate change, which has been one of the biggest challenges of our times. Some novel solutions have been proposed for CO_2 capture and storage, as well as reducing CO_2 emission in concrete production. Carbonation curing is an effective alternative for conventional water curing for concrete. It can store CO_2 in the hardened concrete and meanwhile improve early mechanical properties of concrete. Partial replacement of cement with fly ash shows environmental benefits, such as reducing greenhouse gas emissions and industrial waste destined for landfills. There has been some previous research studying on the effect of carbonation curing on normal Portland concrete in the past decade. Nevertheless, few studies have focused on the CO_2 curing for lightweight aggregate concrete (LWAC). In this paper, the influence of early carbonation curing on LWAC is studied. LWAC specimens with two different water-to-cement ratios are cast and cured for a series of experimental investigations. The mechanical and chemical properties including the 1-day compressive strength, 28-day compressive strength, flexural strength, CO_2 uptake, heat development, and pH level are investigated. Specimens with ordinary Portland cement are also tested as references in terms of compressive strength and CO_2 uptake.

1. Introduction

The World Energy Council estimated that worldwide CO_2 emissions would increase by 45% from 2010 to 2050 [1]. A global climate agreement entered into force in November 2016 after being adopted in Paris the previous December. As a signatory to the agreement, Norway targets a 40% cut of greenhouse gas emissions by 2030 compared to the 1990 level. Apart from the usage of coal and petroleum products, the cement industry has been another massive CO_2 emitter, which contributes to approximately 8% of the worldwide carbon dioxide emissions across all industries and sectors. Our society has a high demand for energy revolution in the coming decades.

Carbon capture and storage (CCS) methods have been widely developed to reduce CO_2 emissions. CCS mainly includes three major stages: CO_2 capture, CO_2 transport and CO_2 storage. In the first stage, CO_2 is captured from power plants or cement plants. Then, highly concentrated carbon dioxide is compressed and transported through pipelines or ships. Eventually, captured CO_2 is injected into the ocean bed, deep saline formations, aquifers, or depleted oil wells for storage. Despite the remarkable potential of CO_2 storage technologies, scientists [2] believe that trapped CO_2 would cause environmental damage due to leakage or other uncertainties.

Plaza et al. [3] provided an overview of CCS methods in the concrete industry. There are currently two primary laboratory technologies for the sequestration of carbon dioxide into concrete in airtight

chambers: CO_2 conditioning and CO_2 curing [4]. Early carbonation curing of concrete could be an efficient way to utilize carbon dioxide into concrete mixture. The effect of carbonation curing of concrete elements on their mechanical, chemical, and micro-structural changes has been investigated since the 1970s [5][6][7]. Carbonation curing at an early age has shown to be an effective alternative for water curing. In the reaction of calcium silicate with carbon dioxide, calcium carbonate is produced, which improves the concrete permeability and increases rapid strength [8]. A high amount of energy from steam curing of precast concrete blocks can be saved by deploying carbonation curing [9]. Shao et al. [10] reported that 1.8 million tonnes of carbon dioxide can be utilized annually into concrete products in the United States.

Lightweight aggregates, which are produced from natural raw materials or industry waste, can be introduced to substitute normal aggregates in concrete to reduce self-weight. Since the mid-1960s, LWAC has been exclusively or partially used to build skyscrapers, airport terminals, and bridges. The Stolma Bridge in Norway, which is known as the longest segmental concrete box-girder span bridge in the world, is an example of the application of lightweight aggregate concrete. LWAC has also shown to be a promising material to improve the seismic resistance of building structures as well as contributing to higher thermal insulation green buildings. The structural application of LWAC has, however, been reduced since its major material properties highly depend on the category of lightweight aggregates. Furthermore, LWAC is more brittle and thus can experience uncontrolled crack propagation in comparison with normal concrete. The tensile strength of LWAC is also lower than normal aggregate concrete. Nowadays, the application of LWAC is mainly limited to prefabricated products such as interior walls, beams, and roof blocks [11].

Partial replacement of cement with fly ash is promising in terms of environmental benefits, for example, reducing greenhouse gas emissions and industrial waste destined for landfills. The American Coal Ash Association stated that the replacement of cement by fly ash could reduce the water demand for a given slump [12]. When fly ash is used at approximately 20% of the total weight of cementitious paste, the water demand could be reduced by 10%, which barely has an adverse effect on drying shrinkage or cracking of concrete. Some researchers [13][14][15] have previously investigated the influence of carbonation reaction on the mechanical, chemical, and microstructural characteristics of cement mortar or normal concrete that partially contain fly ash. However, limited research has focused on the carbonation reaction and CO_2 curing on lightweight aggregate concrete.

The objective of this study is to investigate the effect of early carbonation curing on the lightweight aggregate concrete with fly ash. Cubic concrete specimens and mini beam specimens are cast and cured under both carbonation curing condition and normal water curing condition. Experimental work regarding the mechanical and chemical properties of carbonation cured concrete specimens is conducted. The mechanical characteristics of concrete including compressive strength, flexural strength and hardened density are measured. The chemical properties are also studied, in terms of pH level, heat development and CO_2 uptake. Normal concrete specimens are tested as reference samples regarding the compressive strength and CO_2 uptake.

2. Specimen preparations

2.1. Materials

Lightweight aggregate concrete consisting of 20% fly ash with two different water-to-cement (w/c) ratios (0.4 and 0.6) were subjected to early carbonation curing in this study. Cementitious material used in concrete mixture was the Norcem standard cement (CEM II/BM 42.5 R). Lightweight expanded clay aggregates (LECA), manufactured by heating clay up to around 1200 °C in a rotary kiln, were used as coarse aggregates. Sieve analysis was conducted to check whether the grading of LECA, as presented in Table 1, meets the standard specification for lightweight aggregates according to ASTM Standard [16]. The bulk density of LECA was measured as 665.7 kg/m^3 and the dry particle density was 1250 kg/m^3. The 1-day water adsorption rate was 5% with respect to its moisture content. Sand and gravels were supplied by NorStone, which were originally taken from Årdal, Norway. The aggregate size ranges are 0-8 mm and 8-16 mm for sand and gravels, respectively. The densities of them are 2680 kg/m^3 and 2690 kg/m^3. Tap water with a room temperature was used for concrete mixing. Silica xerogel was placed

inside airtight chamber during the carbonation curing to adsorb the residual water. Nippon Gases provided the high-pressurized CO_2 cylinder and the properties of the CO_2 gas are listed in Table 2.

Table 1. Grading of lightweight expanded clay aggregates.

Square mesh size (mm)	9.500	4.750	2.360	0.300	0.150	0.075
Mass percentage passing sieve (%)	100	65	38	11	5	0

Table 2. Physical and chemical properties of CO_2 gas.

Physical state at 20 °C/101.3 kPa	Gas
Melting/Freezing point	-78.5 °C
Boiling point	-56.6 °C
Vapor pressure (20 °C)	57.3 bar
Water solubility	2000 mg/l
Molar mass	44 g/mol

2.2. Mix design and preparation

The American Concrete Institute (ACI) provides guidelines and principles for LWAC mixing [16]. An optimum amount of moisture is needed to achieve an efficient carbonation curing. If excessive water exists, the diffusion of CO_2 inside specimens will be inhibited. As a result, the chemical reaction efficiency will decrease [17]. Therefore, considering the application of full-scale industrial production as well as investigation of the effect of water-to-cement ratio on early carbonation curing, two different w/c ratios of 0.4 and 0.6 were selected. A trial test was implemented before casting specimens regarding the efficiency of carbonation curing with respect to the presence of sand. One set of samples with a w/c ratio of 0.4 was cast without sand and the other set was cast following the mix design with cement-lightweight aggregate-sand-water ratio of 1:1.28:1.37:0.4. It turned out that the early carbonation was more efficient among the specimens without sand, which could be explained by the hindrance of sand in porous lightweight aggregates for carbon dioxide diffusion. Hence, sand was not mixed with other materials in all the LWAC specimens. The proportioning of both LWAC and normal concrete is presented in Table 3. Steel mini beam molds with the dimensions of 40 mm × 40 mm × 160 mm were used for three-point bending test. Standard steel cubic molds with the dimensions of 100 mm × 100 mm × 100 mm were used for compression test. Non-reactive oil was splashed on the inner surface of molds to avoid the adherence of any material to the molds.

Table 3. Normal concrete and LWAC proportioning.

	Binder (kg/m^3)	Sand (kg/m^3) [Moisture (%)]	Gravel (kg/m^3)	LWA (kg/m^3) [Moisture (%)]	Added water (kg/m^3)	Effective w/c
N-OPCFA-0.4 [a]	410.0	1020.8 [4]	811.1	-	134.6	0.4
N-OPCFA-0.6	322.0	1044.0 [4]	829.5	-	163.1	0.6
L-OPCFA-0.4 [b]	422.0	-	-	751.0 [5]	205.0	0.4
L-OPCFA-0.6	332.0	-	-	751.0 [5]	235.0	0.6

[a] N represents normal concrete, OPC represents the ordinary Portland cement and FA represents the fly ash.
[b] L represents lightweight aggregate concrete.

3. Experimental program

The curing procedure consisted of three phases: pre-carbonation curing, carbonation curing and after-carbonation curing. The first curing phase was identical to all the concrete specimens including reference samples. Then, reference samples were cured in normal condition while carbonation cured specimens were placed in the airtight chamber with CO_2 for 12 hours.

3.1. Curing

Stage I: pre-conditioning. Pre-conditioning was implemented before carbonation curing, allowing moisture in the specimens to evaporate in a dry environment. Therefore, more void channels would be present to efficiently transport CO_2 into concrete samples. The higher the CO_2 pressure, the more CO_2 transported into specimens through pores [18]. Shi et al. [17] suggested that the specimens shall be pre-conditioned in a dry environment with a relative humidity of 60~70% for several hours. In the test, specimens were placed in a climate chamber (CTS climate chamber C-40/600) for 6 hours and the relative humidity and temperature were set as 60% and 25 °C, respectively. After six hours of pre-conditioning, the samples were demolded and labelled. An impermeable plastic wrap was applied to the reference batch of specimens, which were maintained in laboratory environment with a relative humidity of 45% and a temperature of 20±2 °C until the end of carbonation curing.

Stage II: Carbonation curing. The carbonation curing set-up is shown in Figures 1 and 2. The equipment used for carbonation curing includes an airtight chamber, CO_2 gas cylinder and regulator, silica gel and vacuum pump. The airtight chamber is to keep a high level of CO_2 concentration and high pressure as they will contribute to accelerated carbon reaction as well as CO_2 diffusion [19]. In this study, a pressure of 6 bars was selected and the CO_2 gas was injected via a hose through an inlet valve. The regulator was used to control and stabilize the pressure (6 bars) inside the chamber during the entire curing period. A vacuum pump was used to remove the air in the chamber prior to CO_2 gas release. Silica gel was positioned in the bottom of the airtight chamber to absorb the residual water from the chemical reaction inside concrete specimens. Two metal net sheets were placed above the silica gel to ensure that the bottom of samples was exposed to carbon dioxide. After 12-hour carbonation curing, concrete specimens were weighed. The mass of water and moisture absorbed by silica gel and the residual water inside the climate chamber was weighed to determine the CO_2 uptake. The specimens were then sprayed with water for compensation of water loss during the carbonation curing.

Stage III: After carbonation curing. After 12 hours of carbonation curing, all the specimens, except those for the 1-day compression test, were placed in water at laboratory temperature for 28 days until the designated tests were carried out.

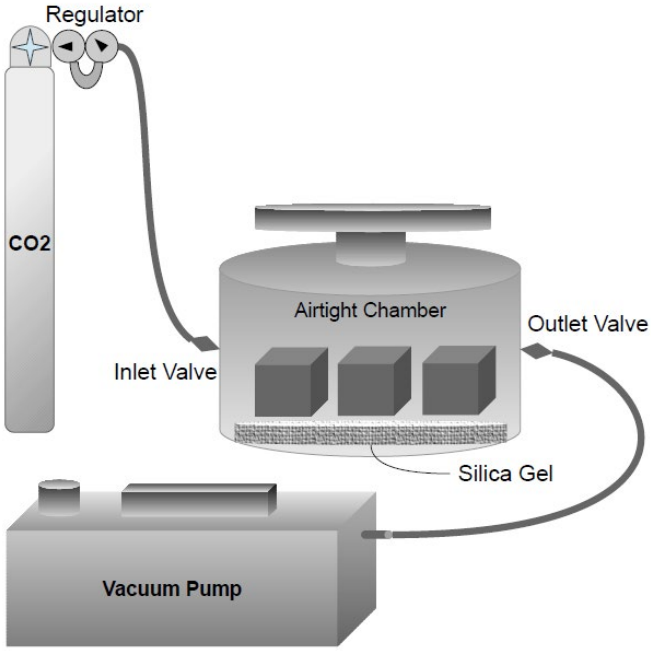

Figure 1. Schematic of carbonation curing set-up.

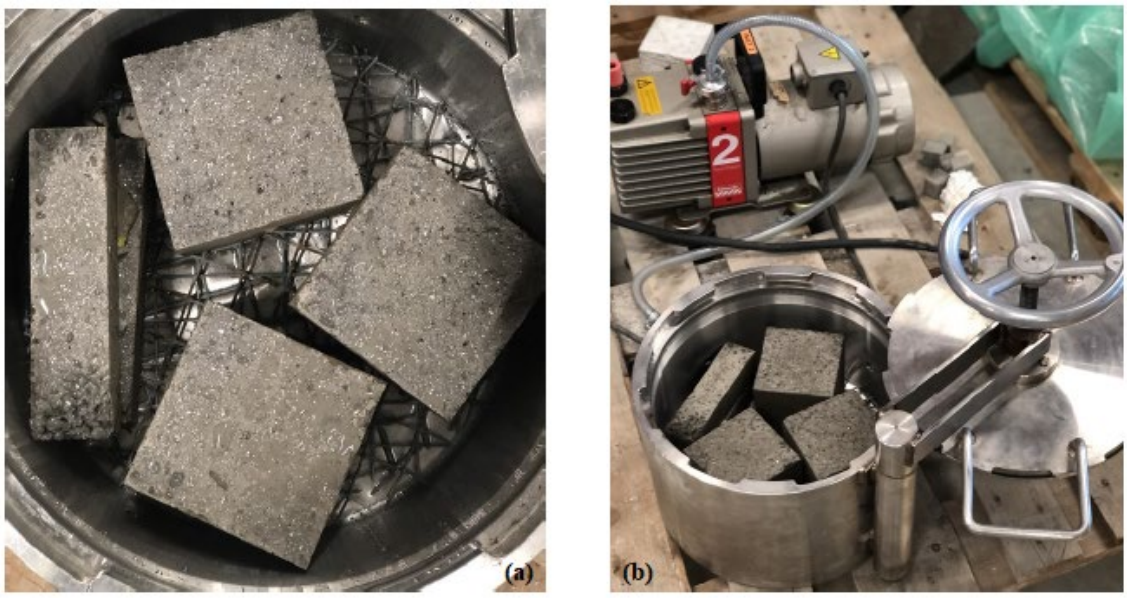

Figure 2. (a) Concrete specimens inside the carbonation curing chamber, and (b) overview of carbonation curing system.

3.2. Experimental scheme

The experiments conducted in this study are presented in Table 4. For the mechanical properties, the compressive strengths of cubic prism specimens at the age of 1 day and 28 days were measured with a loading rate of 500 N/s. Four specimens from references and three specimens from carbonated samples were tested for each batch and the average compressive strength was calculated. Three-point bending tests were implemented for three mini beam specimens in one batch to determine the flexural strength. To avoid a sudden failure during the initial test, a displacement-controlled rate of 0.1 mm/min was chosen for the loading scheme. The experimental equipment for compression test and bending test along with concrete specimens are shown in Figure 3. The hardened density of cubic samples was determined under water-saturation condition.

Table 4. Schematic of included experimental investigations.

Mechanical properties	1-day & 28-days compression
	Three-point bending
	Hardened density
Chemical properties	pH level
	Heat development
	CO_2 uptake

The pH level of concrete specimen was measure by a digital pH probe meter with an accuracy of one decimal. According to Bertos et al. [20], the temperature will rise immediately when the specimens are exposed to CO_2, since the reaction of CO_2 with cement phases (C_2S and C_3S) is exothermic and rapid. The temperature was recorded by Temperature Data Logger USB and the sensor locates in the core of cubic prism specimens.

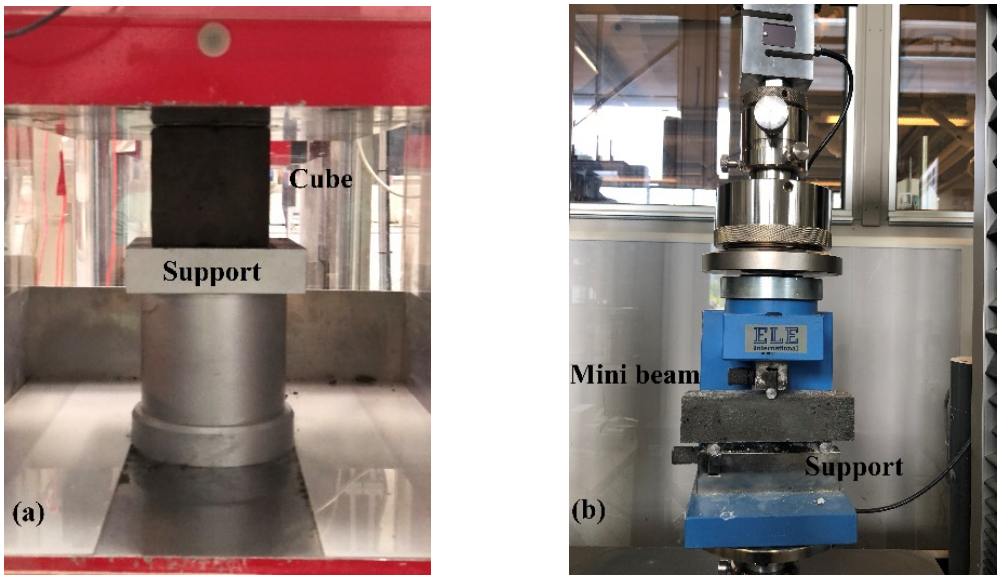

Figure 3. Experimental setup for (a) compression test of cubic prism specimens, and (b) three-point bending test of mini beams.

Carbon dioxide uptake refers to the amount of CO_2 that a material can capture and utilize. The mass gain method is introduced in this study to measure CO_2 uptake. In this method, the sample was first weighed prior to the application of carbonation curing (M_1). After the carbonation curing, the sample was weighed again (M_2). Silica gel was placed on the bottom of the airtight chamber to absorb the moisture as well as the water. The mass of water and moisture absorbed by the silica gel was added to the mass of residual water collected by the absorption paper (M_w). The CO_2 uptake can be calculated by using Equation (1), where M_b is the amount of cement binder used in the sample. The carbonation degree (α) of concrete samples can be calculated based on Equations (2) and (3). M_{max} represents the maximum theoretical CO_2 uptake of cement binder while M_{CO_2} represents the actual CO_2 uptake.

$$U(CO_2) = \frac{M_2 - M_1 + M_w}{M_b} \quad (1)$$

$$M_{max} = 0.785(CaO - 0.7SO_3) + 1.091MgO + 1.42Na_2O + 0.935K_2O \quad (2)$$

$$\alpha\% = \frac{M_{CO_2}}{M_{max}} \times 100\% \quad (3)$$

4. Experimental results and discussions

4.1. Mechanical properties

4.1.1. Compressive strength. Table 5 lists the 1-day and 28-days compression test results for both LWAC and normal concrete. All the presented values are the average from several specimens in the same batch. Figures 4 and 5 illustrate the compressive strength of LWAC cubic specimens and normal concrete cubic specimens, respectively. The percentages above the bars in these charts represent the differences in compressive strength between LWAC and references. For all batches of specimens, the specimens with a w/c ratio of 0.4 had much higher compressive strength than those with a w/c ratio of 0.6. The early carbonation curing caused an increase in the early compressive strength of lightweight aggregate

concrete containing fly ash, 14.6% and 107.3% for w/c ratios of 0.4 and 0.6, respectively. Such increase of early strength also occurred in normal concrete specimens, which were 49.0% and 44.1% for different w/c ratios.

Shi et al. [17] commented that higher water content in concrete samples would inhibit the diffusion of CO_2 through deep layers, so that lower efficiency of carbonation reaction would be expected. This is inline with the compression test results of normal concrete in this study, as shown in Figure 5. However, the increase of 1-day compressive strength in LWAC was higher for specimens with a larger w/c ratio, which suggested that the porous nature along with a higher water content would drive carbonation curing more efficiently. Carbonation cured concrete showed a lower 28-days compressive strength than their references at the same age. Usually, Belite (C_2S) in cement reacts much more slowly with carbon dioxide than Alite (C_3S) and thus mainly contributes to the long-term strength of concrete. More C_2S reacted intensively with carbon dioxide curing in this study, leaving less amount of Belite in carbonation cured specimens to develop long-term strength. Figure 6 summarizes the compressive strength for all batches of specimens.

Table 5. Average values of the measured compressive strength.

	Age (day)	Reference [a] (MPa)	CO_2 curing (MPa)	Difference
N-OPCFA-0.4	1	9.0	13.5	49.0
	28	49.2	47.6	-3.2
N-OPCFA-0.6	1	2.7	4.0	44.1
	28	33.3	31.5	-5.5
L-OPCFA-0.4	1	15.5	17.8	14.6
	28	44.8	33.0	-26.3
L-OPCFA-0.6	1	4.1	8.4	107.3
	28	23.8	11.3	-52.6

[a] Reference represents normal laboratory conditions of water curing.

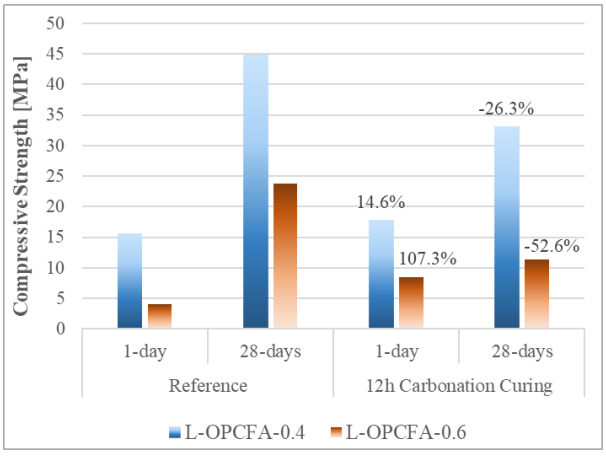

Figure 4. 1-day & 28-days compressive strength of lightweight aggregate concrete with fly ash.

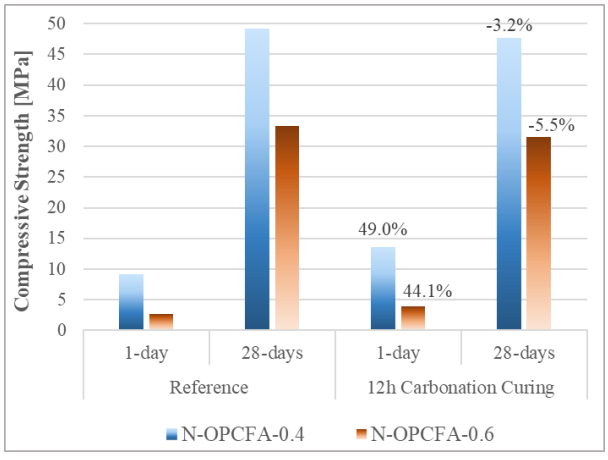

Figure 5. 1-day & 28-days compressive strength of normal concrete with fly ash.

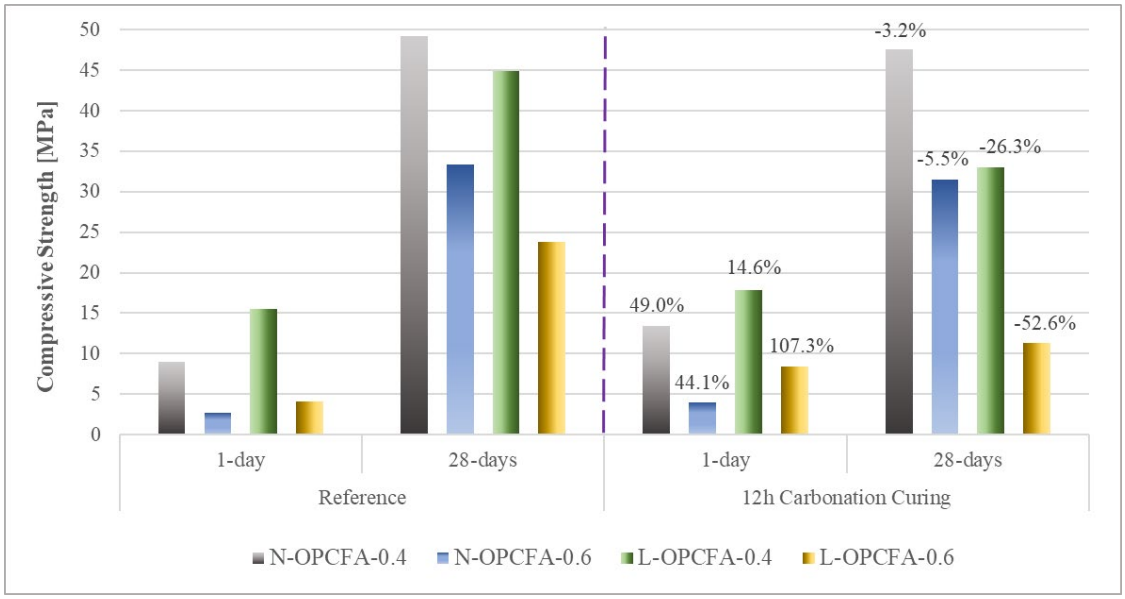

Figure 6. Measured compressive strength of both normal concrete and LWAC with fly ash.

4.1.2. Flexural strength. The 28-days flexural strength of lightweight aggregate concrete mini beams containing fly ash is presented in Figure 7. It can be observed that the LWAC showed lower flexural strength than water cured references. The flexural strength of carbonation cured LWAC specimens with a w/c ratio of 0.6 is 51.5% of the reference specimens. It was much more significant than 19.4% for specimens with a w/c ratio of 0.4. For concrete specimens without carbonation curing, more C_2S and C_3S were present after the pre-conditioning. The w/c ratio has little influence on the flexural strength for water-cured concrete.

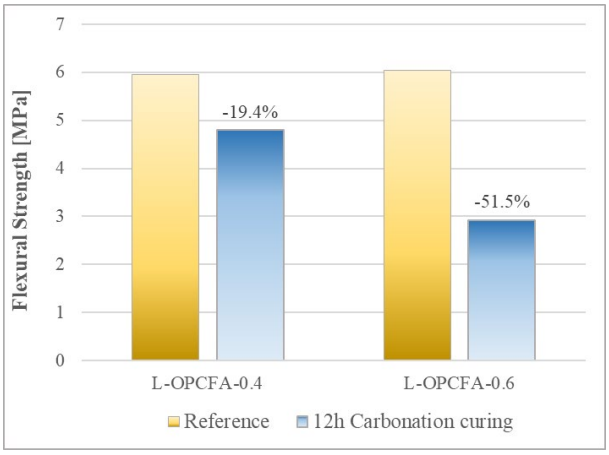

Figure 7. Flexural strength of LWAC with fly ash after 28-days.

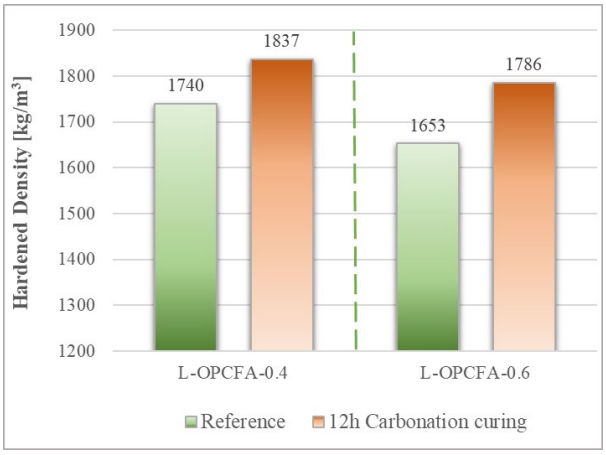

Figure 8. Hardened density of LWAC with fly ash after 28-days.

4.1.3. Hardened density. Figure 8 shows the average hardened density of lightweight aggregate concrete specimens with fly ash after 28 days from casting. It can be noticed that the batch with a lower w/c ratio of 0.4 had slightly higher hardened density, since a higher w/c ratio would result in more capillary pores in concrete samples. All carbonation cured specimens showed higher density compared to those under normal curing conditions. This is because the carbonation reaction of cement phase formed calcium carbonate inside concrete voids to occupy the free space adjacent to the solid phase.

4.2. Chemical properties

4.2.1. pH level. Calcium hydroxide plays a vital role in maintaining the pH level to avoid carbonation-induced corrosion since it provides OH^- in the cement phase. During early carbonation curing, the chemical reaction of carbon dioxide with water produces the acidic substance H_2CO_3, which is instantaneously ionized to H^+, HCO_3^- and CO_3^{2-}. OH^- and H^+ react with each other, decreasing the pH level in the concrete mixture. Figure 9 illustrates the pH values of lightweight aggregate concrete with fly ash at the age of 28-days. With 12h of carbonation curing, the pH of specimens dropped from 12.4 to around 11.7, which is still in the safe zone to be exempt from carbonation-induced corrosion [21]. It can also be observed that the w/c ratio is also not an influential parameter to the pH value.

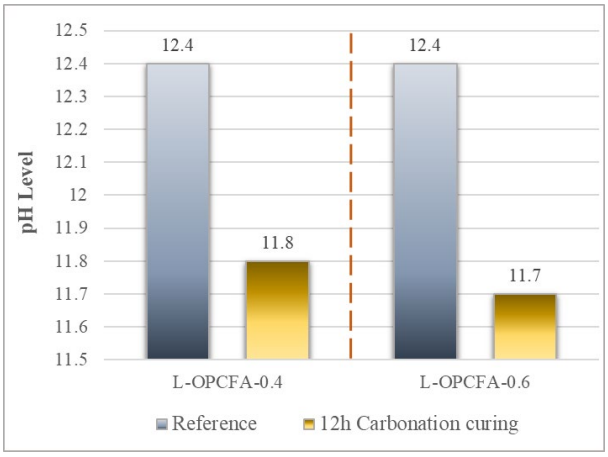

Figure 9. pH values of lightweight aggregate concrete with fly ash.

4.2.2. Heat development. Temperature data during the carbonation curing were recorded and collected by a temperature data logger in the core of 50 mm × 50 mm × 50 mm cubic specimens every five minutes. The temperature development during 12h CO_2 curing is presented in Figure 10, where the reference samples are cured with normal conditions. The temperature inside carbonation cured LWAC specimens with fly ash rose significantly to 84 °C and 75 °C for w/c ratios of 0.4 and 0.6, respectively. This occurred within the first hour of carbonation curing, which could be explained by the exothermic reaction between CO_2 and the cement paste consisting of tricalcium silicate and dicalcium silicate [20].

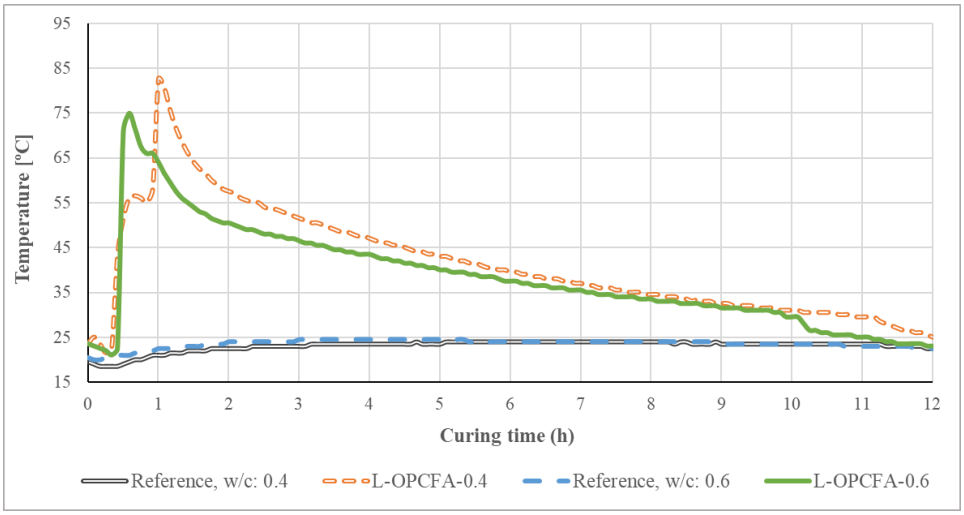

Figure 10. Temperature development for lightweight aggregate concrete with fly ash.

The porous nature of LWAC accelerated the reaction and thus the temperature in LWAC showed considerably higher values than the normal concrete. Several factors might influence the occurrence and duration of the most intensive carbonation reaction, for example, the concentration and the pressure of carbon dioxide, concrete proportioning, and water content. Shi et al. [22] have previously reported that the carbonation reaction mostly happens in the first two hours of CO_2 curing process. Higher pressure of carbon dioxide might cause shorter period of significant temperature rise. Lower water content can result in higher maximum temperature and a delay in the most significant exothermic reaction since water has a higher heat capacity.

4.2.3. CO_2 uptake. The CO_2 uptake of both the carbonation cured LWAC and normal concrete specimens with 1-day age was calculated by the mass gain method. One challenge is that it was difficult to identify the accurate amount of used cement binder in concrete specimens as the cement and water could be absorbed into porous lightweight aggregates during mixing. Therefore, the weight of binder was estimated based on the concrete mix design, fresh density, air content and the volume of tested specimens. As presented in Table 6, the amount of CO_2 uptake in LWAC with fly ash is 20% and 22% for the samples with water-to-cement ratios of 0.4 and 0.6, respectively. It was found that a higher water-to-cement ratio would cause a slightly higher amount of CO_2 uptake and the degree of carbonation. Compared with LWAC, the CO_2 uptake of normal concrete specimens was significantly lower. This could be explained by that fewer pores existed in the normal concrete, hindering the diffusion of CO_2 gas through the aggregates.

Table 6. CO_2 uptake and carbonation degree of LWAC and normal concrete.

	CO_2 uptake (%)		Carbonation degree (%)	
	w/c: 0.4	w/c: 0.6	w/c: 0.4	w/c: 0.6
LWAC	20	22	46.8	51.5
Normal concrete	4	5	9.4	11.7

5. Conclusions

In this paper, the effects of early carbonation curing on lightweight aggregate concrete and normal concrete were experimentally investigated. The following conclusions are drawn based on the findings in the study:

- Normal concrete with a w/c of 0.6 has a lower increase rate of 1-day compressive strength compared with LWAC. However, the normal concrete specimens with a w/c of 0.4 had a higher rate of increase in early compressive strength. Therefore, a higher amount of w/c in LWAC does not reduce the efficiency of early carbonation curing due to the porous nature of the concrete.
- All the carbonation cured samples of both LWAC and normal concrete, showed lower 28-days compressive strength compared to their references at the same age. This suggested that during the carbonation process, the more CO_2 uptake resulted in higher C_2S consumption. If C_2S is consumed in the early curing stage, it contributes less to the long-term compressive strength. It is also noticeable that there is a higher 28-days compressive strength reduction in LWAC in comparison to normal concrete due to higher CO_2 uptake.
- Carbonation curing also causes a reduction in the 28-day flexural strength for LWAC. The more intensive the carbonation reaction is, the higher reduction is in presence. Higher hardened density was observed in carbonation cured LWAC samples compared to their references as the formation of $CaCO_3$ crystals occupied the free space between the solid particles.
- Porous nature of LWAC can eliminate the inhibition effect of higher water content in concrete material. Carbonation curing was more intense in LWAC within the first hour of CO_2 curing based on the significant temperature rise inside the airtight climate chamber. Early carbonation curing contributes to a considerable increase of 1-day compressive strength for both LWAC and normal concrete, without triggering carbon-induced corrosion.

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References

[1] World Energy Council 2013 World Energy Scenarios: Composing energy futures to 2050 *Full Report* www.worldenergy.org/publications/2013/world-energy-scenarios-composing-energy-futures-to-2050
[2] De Silva G P D, Ranjith P G and Perera M S A 2015 Geochemical aspects of CO_2 sequestration in deep saline aquifers: A review, *Fuel* **155**, 128-43.
[3] Plaza M G, Martínez S and Rubiera F 2020 CO_2 capture, use, and storage in the cement Industry: State of the art and expectations, *Energies* 13(21)
[4] Tam V W Y, Butera A, Le K N and Li W 2020 Utilising CO_2 technologies for recycled aggregate concrete: A critical review, *Constr Build Mater* **250**, 118903,
[5] Berger R L and Klemm W A 1972 Accelerated curing of cementitious systems by carbon dioxide: Part II, *Cem Concr Res* **2**(6), 647-52
[6] Klemm W A and Berger R L 1972 Accelerated curing of cementitious systems by carbon dioxide: Part I, *Cem Concr Res* **2**(5), 567-76.
[7] Young J F, Berger R L and Breese J 1973 Accelerated Curing of Compacted Calcium Silicate Mortars on Exposure to CO_2, J *Am Ceram Soc* **57**(9), 394-7.
[8] Berger R L, Young J F and Leung K 1972 Acceleration of hydration of calcium silicates by carbon dioxide treatment, *Nat Phys Sci* **240**(97), 16-8
[9] Kashef-Haghighi S and Ghoshal S 2010 CO_2 Sequestration in concrete through accelerated carbonation curing in a flow-through reactor, *Ind Eng Chem Res* **49**(3), 1143-49.
[10] Shao Y, Monkman S and Boyd A J 2010 Recycling carbon dioxide into concrete: A feasibility study *Proc. of the 2010 Concrete Sustainability Conference.*
[11] Chung S-Y, Elrahman M A and Stephan D 2017 Effect of different gradings of lightweight aggregates on the properties of concrete, *Appl Sci* **7**(6).
[12] American Coal Ash Association 2003 Fly ash facts for highway engineers: Chapter 3 – Fly ash in Portland cement concrete, *Technical report.*
[13] Zhang D, Cai X and Shao Y 2016 Carbonation curing of precast fly ash concrete, *Mater Civil Eng* **28**(11).
[14] Van den Heede P, De Schepper M and De Belie N 2019 Accelerated and natural carbonation of concrete with high volumes of fly ash: Chemical, mineralogical and microstructural effects, *R Soc Open Sci* **6**(1), https://doi.org/10.1098/rsos.181665.
[15] Chen T, Bai M and Gao X 2021 Carbonation curing of cement mortars incorporating carbonated fly ash for performance improvement and CO_2 sequestration, J *CO_2, Util* **51**, 101633.
[16] ASTM C330 / C330M-09 2009 Standard Specification for Lightweight Aggregates for Structural Concrete *ASTM International* (West Conshohocken, PA).
[17] Shi C, Liu M, Zou Q and He F 2011 A study on factors influencing compressive strength of CO_2-cured concrete *Int. RILEM Conf. on Advances in Construction Materials through Science and Engineering* 703 – 711.
[18] Shi C and Wu Y 2008 Studies on some factors affecting CO_2 curing of lightweight concrete products *Resour Conserv Recycl* **52**(8-9), 1087-92.
[19] Shi C, Liu M, He P and Ou Z 2012 Factors affecting kinetics of CO_2 curing of concrete, J *Sustainable Cem-Based Mater* **1**(1-2), 24-33.
[20] Bertos M F, Simons S J R, Hills C D and Carey P J 2004 A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO_2 *Hazard Mater* **112**(3), 193 – 205
[21] Zhou Y, Gencturk B, Willam K and Attar A 2015 Carbonation-Induced and chloride-induced corrosion in reinforced concrete structures, *Mater Civil Eng* **27**(9).
[22] Shi C, He F and Wu Y 2012 Effect of pre-conditioning on CO_2 curing of lightweight concrete blocks mixtures, *Constr Build Mater* **26**(1), 257-67.