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CO_2 curing of hydrated lime modified pervious concretes

H. Rahmani*, M. Montazer Gheib
University of Zanjan, Zanjan, Iran
** E–mail: hrahmani@znu.ac.ir*

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Abstract. This paper presents the effect of carbonation curing on the properties of hydrated lime modified pervious concretes. Also, CO_2 absorption capacity (COAC) of the mixtures was investigated to more explanation of the results. Three mix designs containing of 0, 15 and 30 % of hydrated lime were considered. Water to cement ratio, cementitious material content, inner pressure of the chamber and workability of the mixtures were kept constant. Concrete samples were cured in the CO_2 chamber and then the conducted experiments were performed and the results compared with the results of moist cured concretes. The results showed a significant increase in the mechanical properties of the concretes at the initial time of CO_2 curing. Carbonation reactions were approximately stopped after 12 hours of CO_2 curing in which the concrete properties after 12 hours of CO_2 curing were closed together. Also, COAC of the mixtures increased by increasing hydrated lime substitution.

1. Introduction

Carbon dioxide (CO_2) as one of the major greenhouse gases causes world climate changes. It has been estimated that the CO_2 emission will be increased during the next decades, nevertheless the CO_2 concentration in the atmosphere is higher than the maximum allowable concentration. Therefore, sequestration of CO_2 is essential to reduce its concentration in the atmosphere [1]. Geological sequestration of CO_2 in oceans and other fluid storages such as aquifers and oil wells are in progress [2]. However, some minerals can react chemically with CO_2 and produce carbonates. Calcium and Calcium-silicate minerals can properly convert CO_2 to calcium carbonates, but they are rarely found in the nature. However, popular synthetic materials such as Portland cement as a calcium-silicate material and hydrated lime as a calcium material can be efficiently used to mineralize CO_2 to calcium carbonate. This process of direct sequestration of CO_2 is called carbonation curing or CO_2 curing of cement-based materials, where appropriate curing provides a proper mineralization of CO_2 [1, 3–5]. Since the pervious concretes are more porous, it is estimated that the mineralization of CO_2 is simply completed. Therefore, CO_2 curing of the hydrated lime modified pervious concretes is the main object of this study.

1 kg cement can absorb 0.5 kg CO_2 to form 1.5 kg silica gel and calcium carbonates [1]. Reactivity of calcium silicates and mineral admixtures with CO_2 were systematically studied by the researchers [6–9]. Carbonation curing or CO_2 curing improves compressive strength, surface hardness and durability of non-reinforced cement-based products [10–12]. However, the carbonation process reduces the pH of concrete and initiate the corrosion of reinforcing bars in concrete [13–16]. Therefore, non-reinforced concretes have a great potential to friendly absorb CO_2. This would be appreciated by the manufacturers of cement-based materials when CO_2 curing is accelerated by increasing of curing temperature, pressure, CO_2 concentration, porosity of concrete and water to cement ratio and also by adjusting the proper relative humidity (RH) of the chamber [17–19]. In addition, cement replacement materials and novel concretes have been investigated to absorb CO_2 in the last decades [9, 12, 17, 19–22]. For instance, Monkman and Shao have used slag-cement concrete to bind CO_2 [12] and Kou et al. and Zhan et al. have investigated CO_2 curing of concretes prepared with recycled aggregates [19–21]. Also, CO_2 curing of self-compacting and lightweight concretes have been systematically investigated by Shamsad et al. and Shi and Wu, respectively [17, 22]. Nevertheless several researchers have investigated carbonation curing of concretes including novel ones, but there is a limit research on CO_2 curing of pervious concretes [23, 24]. For instance, Hasegawa has investigated static and dynamic carbonation curing of pervious concrete using ordinary Portland cement and Portland limestone cement and concluded that the early carbonation curing (2 hours for static and 30 minutes for dynamic carbonation curing) significantly improves the

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physical and mechanical properties of the concretes [23]. Sidhu indicated that the pervious concretes with 12 hours of CO_2 curing showed the highest compressive strength and the lowest porosity when they were compared with other curing regimes [24].

The major chemical reactions of CO_2 curing of cement-based materials such as concrete are given by Equations (1) and (2) [1, 5, 9, 17]. Also, CO_2 reacts with $Ca(OH)_2$ and forms $CaCO_3$, where the rate of reactions depends on the rate of CO_2 diffusion [5].

$$3CaO \cdot SiO_2 + 3CO_2 + \mu H_2O \rightarrow SiO_2 \cdot \mu H_2O + 3CaCO_3; \quad (1)$$

$$2CaO \cdot SiO_2 + 2CO_2 + \mu H_2O \rightarrow SiO_2 \cdot \mu H_2O + 2CaCO_3. \quad (2)$$

Nevertheless a lot of researches have been conducted on the properties and the durability of pervious concretes including modified ones [25–30], but carbonation curing of pervious concretes has not been completely investigated. Therefore CO_2 curing of pervious concretes is investigated in this study. Also, since hydrated lime can react with CO_2 and accelerate the CO_2 curing process of the concretes, substitution of hydrated lime is considered in the mixtures up to 30 % of cement to absorb more CO_2. It is predicted that the properties of pervious concretes will diminish in case of more substitution of hydrated lime because of low content of cement in the mixtures. Consequently, main objects of this study are the increasing of CO_2 absorption capacity and the improvement of mechanical and physical properties of pervious concretes simultaneously by means of carbonation curing.

2. Methods

2.1. Materials

Locally sourced ordinary Portland cement type I-425 and hydrated lime respectively produced by Kordestan and Espandar Company were used as cementitious materials. Chemical composition and L.O.I of the binders are shown in Table 1. Hydrated lime or calcium hydroxide is decomposed into calcium oxide and water when it is heated up to 500° and therefore its L.O.I is significant.

Table 1. Chemical composition and physical properties of the cement and hydrated lime (%).

	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	$Ca(OH)_2$	L.O.I
Cement	64.2	22.2	3.6	4.9	1.41	1.76	–	0.7
Hydrated lime	72.26	–	–	–	3.02	–	91.14	23.74

Locally sourced crushed coarse silica aggregate was used to make the pervious concretes without using fine aggregates. Physical properties of the aggregate were measured according to ASTM C127 and ASTM C566 and the results are shown in Table 2. Also grading curve of the aggregate, which was measured according to ASTM C136, and lower and upper limit of ASTM C33, size number of 67 (4.75–19.0 mm) for pervious concretes, are shown in Figure 1. It is clear that the grading curve of the aggregate that is close to the lower limit of the ASTM standard is appropriate to produce pervious concretes.

Renewable silica gel with capacity of 40 % of water absorption was used to absorb the evaporated water in the CO_2 chamber during the carbonation curing of the pervious concretes.

Table 2. Physical properties of the aggregates.

Physical property	Maximum nominal size (mm)	Water absorption (%)	Moisture content (%)	Specific gravity (t/m^3)
Coarse aggregate	19	1.8	0.9	2.57

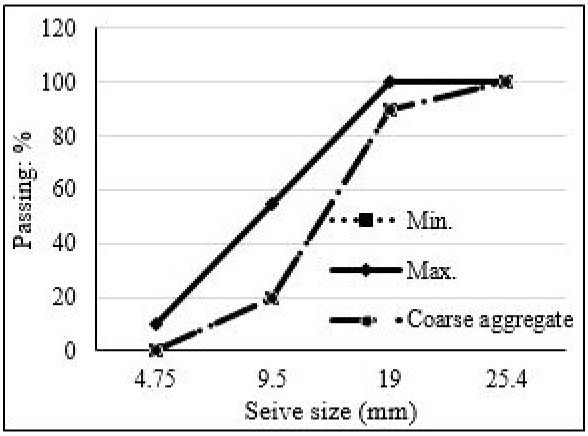

Figure 1. Grading curve of the coarse aggregate and lower and upper limits of ASTM C33.

2.2. Mix designs

Three mixtures containing 0, 15 and 30 % substitution of the hydrated lime were considered, where the mixture without substitution of hydrated lime was considered as the control one. The control mixture was designed using ACI 211.3R-02 [31] by assuming the compressive strength of 15 MPa and void content of 20 %, where water to cement ratio and the cement content were obtained equal to 0.35 and 350 kg/m^3, respectively to obtain a desired pervious concrete. Slump of all mixtures were obtained lower than 20 mm and therefore there was no need to use superplasticizer. Water to binder ratio was kept constant in the mixtures. Details of the mixtures are summarized in Table 3.

Table 3. Details of mix designs.

	Cement (kg/m^3)	Hydrated lime (kg/m^3)	Hydrated lime (%)	Coarse aggregate (kg/m^3)
C1	350	0	0	1539
C2	297.5	52.5	15	1539
C3	245	105	30	1539

All mixtures were mixed for at least 3 minutes and the fresh concretes were then placed in the moulds ready to be compacted. Dimensions of the moulds which depend on the experiment type are mentioned in the next section. All mixtures were poured in three layers and each layer was gently compacted with 16 mm diameter of a bar in a same manner. Specimens were demoulded after 24 hours of moist curing and were then placed in a water bath (moist curing) or in the CO_2 chamber (CO_2 curing, see Figure 2). Considered specimens for CO_2 curing had been dried for 2 hours at a laboratory room before applying carbonation process to reduce their moisture content as the same as control room.

2.3. Experiments

Compressive and tensile strength, void content, permeability and CO_2 absorption capacity of the pervious concretes were investigated in this study, where the experiments were conducted at the age of 3, 7 and 28 days of moist curing and 1, 2, 4, 6, 12 and 24 hours of CO_2 curing. Two specimens were considered for each experiment and their average was reported. Compressive strength and void content testing were performed on 100×100×100 mm cubic specimens according to the BS 1881-116 test method. Void content of the specimens can be calculated using Equation (3), where W_1 is the oven dry weight of the specimen, W_2 is the weight of the immersed specimen in water, Vol is the volume of the specimen and ρ_w is the water density [32].

$$Vc(\%)=1-\left[\frac{W_1-W_2}{\rho_w \times \mathrm{Vol}}\right]\times 100. \quad (3)$$

Tensile strength testing was carried out on 100×200 mm cylindrical specimens according to ASTM C496. Water permeability of the 100×100 mm cylindrical specimens was measured according to Darcy's law. Permeability coefficient (k (cm/s)) of the specimens is calculated using Equation (4), where α and A (cm^2) are the cross section area of the tube and the specimen, respectively, L (cm) is the specimen length, h_1 and h_2 (cm) are the water head in the tube before and after the measurements, respectively and t (s) is the time of head loss from h_1 and h_2 [33].

$$k=\frac{\alpha \cdot L}{A \cdot t}\times \mathrm{Ln}\left(\frac{h_1}{h_2}\right). \quad (4)$$

CO_2 absorption capacity (COAC) test was conducted to explanation of the physical and mechanical properties of the CO_2 cured previous concretes containing hydrated lime powders. No additional specimens were considered to COAC determination. First, the CO_2 cured cubic specimens were tested for the considered purpose and then were completely dried for 24 hours at the temperature of 105 °C. Then, some binder powder about 40 g were prepared by separation of the coarse aggregates from the specimens. Finally, COAC of the powders was determined by measuring the mass loss of the powder between 500 °C and 850 °C [14] and using Equation (5), where M_{850} and M_{500} are the powder mass at the correlated temperatures. Binder powders were placed into the oven and retained for 1 hour at the relevant temperature to achieve the constant mass.

$$\mathrm{COAC}(\%)=\frac{M_{500}-M_{850}}{M_{500}}\times 100. \quad (5)$$

2.4. Carbonation curing of the specimens

The setup similar to the research of Kou et al [21] was used to apply CO_2 curing on the hydrated lime modified pervious concretes and schematic process of CO_2 curing is shown in Figure 2. To process the CO_2 curing, first the specimens were placed in the chamber and a vacuum was then applied to the chamber before the CO_2 injection. Then, CO_2 gas having a purity of 97 % was used to simulate a point source. The pressure inside the chamber was kept constant equal to 1 MPa using a regulator to ensure a continuous supply of CO_2 gas. Temperature and humidity of the chamber were continuously controlled during the curing time using a group sensor. CO_2 curing time of the mixtures was considered equal to 1, 2, 4, 6, 12 and 24 hours. Then the CO_2 cured specimens were tested corresponding to the test program. Temperature of the chamber varied between 16–25 °C and the humidity of the chamber was controlled using silica gel. It should be noted that further silica gels were needed to absorb the evaporated water because of high porosity of the specimens.

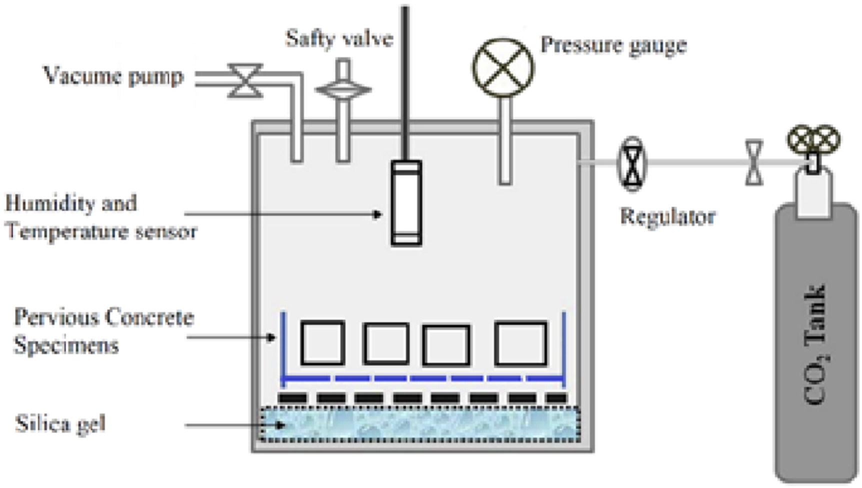

Figure 2. Schematic process of CO_2 curing similar to [21].

3. Results and discussion

3.1. Compressive strength

The results of the compressive strength tests are shown in Table 4 and Figures 3, 4. Table 4 shows the measured results and Figure 3 shows the compressive strength development over curing time in both cases of curing. Figure 4 shows the variations of relative compressive strength of CO_2 cured samples to the relevant 28 days compressive strength of moist cured samples.

Figure 3-a shows the control mixture was obtained the desired compressive strength after 28 days of moist curing. Also, mixtures covered about 50 % and 75 % of 28 days compressive strength after 3 and 7 days of moist curing, respectively. Figures 3-b and 4 show that the compressive strength increases with the increasing CO_2 curing time, where the increasing rate decreases with time in which the control mixture was obtained 45 % of 28 days moist cured compressive strength after 2 hours of CO_2 curing. This result is consistent with those found with the CO_2 curing of slag cement concrete [12]. These improvements are about 66 and 82 %, respectively after 6 and 12 hours of CO_2 curing. Also, the strength of C1 increased by 43 % and 74 % when CO_2 curing time was increased from 1 to 2 and 4 hours, respectively. These values have been reported about 16 % and 25 %, respectively for lightweight concretes [17]. Baojian et al. have reported 28 % and 42 % increasing in the strength when CO_2 curing time was increased from 6 to 12 and 24 hour [34], respectively for recycled aggregate concretes while these values are obtained about 24 % and 28 %, respectively in this study. Porous media of pervious concretes facilitates the penetration of CO_2 gas and therefore improvements are significant at the early ages of CO_2 curing in comparison with other concretes and consequently these improvements are declined for the later ages. Improvement of the compressive strength after 12 hours of CO_2 curing is negligible. Similar results were obtained for the concretes containing hydrated lime powder. Since the specimens are porous, CO_2 gas can simply be directed inside the specimens and the chemical reactions are completed. Therefore, first hours of initial CO_2 curing is more effective and can be simply used in the curing process of concretes.

Table 4. The results of the compressive strengths (MPa).

Mixture code	Moist curing (days)			CO_2 Curing (hours)					
	3	7	28	1	2	4	6	12	24
C1	7.01	10.40	14.94	4.70	6.73	8.20	9.82	12.19	12.53
C2	8.04	11.52	15.58	5.03	7.25	9.18	10.05	12.68	12.94
C3	6.03	7.95	10.07	2.58	4.80	6.45	6.86	8.55	8.80

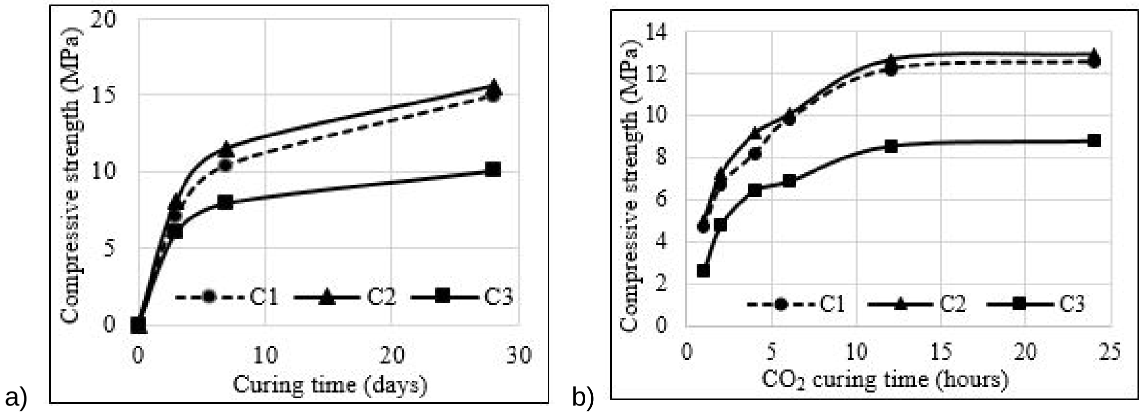

Figure 3. Compressive strength of the mixtures, a) moist cured and b) CO_2 cured.

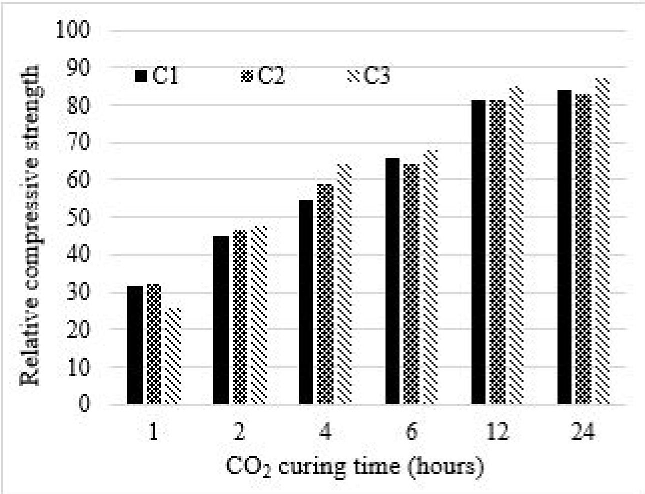

Figure 4. Relative compressive strength of CO_2 cured concretes to the relevant 28 days moist cured concretes.

Mixtures containing 15 % of hydrated lime showed higher compressive strength in both curing cases, but the mixture with substitution of 30 % hydrated lime showed lower compressive strength. This is due to in fact that the cementitious behavior of the hydrated lime is less than the cement and the 15 % substitution of the cement by hydrated lime make a dense structure of the binder. It is nevertheless predicted that the concretes containing 30 % hydrated lime absorb more CO_2 gas (see the COAC results), but their compressive strength are still lower than the control concretes.

3.2 Tensile strength

The results of tensile strengths tests are shown in Table 5. Results are similar to the compressive strength test results and the tensile strengths increase with increasing the curing time in both case of curing regimes. Table 6 present the tensile/compressive ratios and it is clear that the ratio decreased by increasing the curing time. The ratio was reached to 0.12–0.14 at the end of curing time. When the curing is continued, the compressive strength is increased more than tensile strength since the micro-cracks control the tensile strength [35] and therefore the tensile/compressive ratio is decreased.

Table 5. The results of the tensile strengths (MPa).

Mixture code	Moist curing (days)			CO_2 Curing (hours)					
	3	7	28	1	2	4	6	12	24
C1	1.04	1.51	2.01	0.55	0.98	1.11	1.17	1.24	1.56
C2	1.05	1.43	2.00	0.72	0.90	0.99	1.22	1.30	1.55
C3	0.98	1.10	1.26	0.58	0.70	0.95	1.02	1.15	1.23

Table 6. Tensile/compressive ratio of the pervious concretes.

Mixture code	Moist curing (days)			CO_2 Curing (hours)					
	3	7	28	1	2	4	6	12	24
C1	0.15	0.15	0.13	0.12	0.15	0.14	0.12	0.10	0.12
C2	0.13	0.12	0.13	0.14	0.12	0.11	0.12	0.10	0.12
C3	0.16	0.14	0.12	0.22	0.15	0.15	0.15	0.13	0.14

3.3. Void content

Void content of the specimens at the relevant curing times are shown in Table 7. It is clear that the void content of the concretes decreases with the increase of curing time in both cases of curing regimes and the reduction in Void content after 12 hours of CO_2 curing can be neglected similar to the compressive strength test results. Also, void contents of pervious concretes are controlled by aggregate composition rather than the porosity of the binder and therefore the variations of the void contents are ranged between 16.46–18.92 % according to Table 6.

Table 7. Void content of the pervious concretes (%).

Mixture code	Moist curing (days)			CO_2 Curing (hours)					
	3	7	28	1	2	4	6	12	24
C1	18.64	17.80	17.09	17.65	17.50	17.40	16.81	16.63	16.57
C2	18.13	17.35	16.55	17.25	17.25	17.10	16.82	16.63	16.46
C3	18.92	18.31	17.43	18.80	18.34	17.68	17.47	17.12	17.10

Void contents of the mixtures are obtained in the predicted range of the mix designs, but the void content of the concretes containing hydrated lime after 12 hours of CO_2 curing is lower than that of the relevant mixtures after 28 days of moist curing. It is clarify that the mixtures containing hydrated lime have high ability to absorb further CO_2 gas. Figure 5 shows the relation between the compressive strength and void content in case of CO_2 curing, where the compressive strength is directly depended to the void content and it is increased by decreasing the void content.

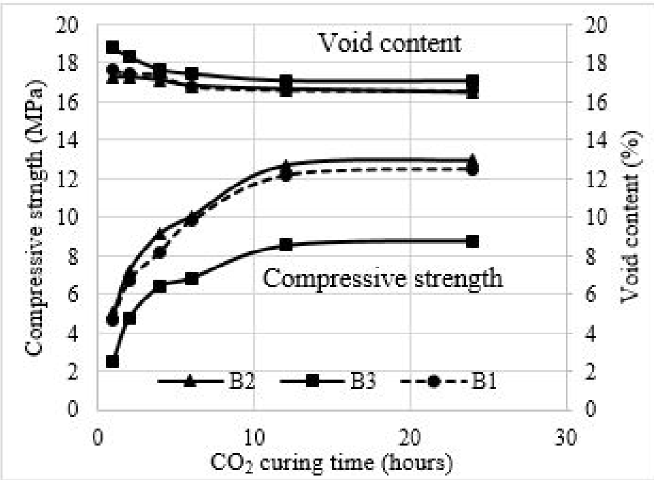

Figure 5. Validation of compressive strength and void content.

3.4. Water Permeability

Permeability coefficient of the specimens were calculated using Equation (5) and the results are summarized in Table 8. Water permeability of the concrete specimens depends on the connectivity of the pores and it is estimated that the permeability and void content are correlated and the results (see Figure 6) confirm such correlation and the permeability increases by increasing the void content. Also, permeability of the concretes decreases by increasing the curing time in both cases of curing.

Table 8. Permeability coefficients of the hydrated lime modified pervious concretes (sm/s).

Mixture code	Moist curing (days)			CO_2 Curing (hours)					
	3	7	28	1	2	4	6	12	24
C1	6.63	5.37	5.30	7.00	6.84	6.48	5.60	5.06	5.08
C2	6.21	4.85	4.45	6.31	5.99	5.61	5.26	5.01	4.75
C3	7.21	6.82	6.48	8.37	7.30	6.77	6.72	6.50	6.50

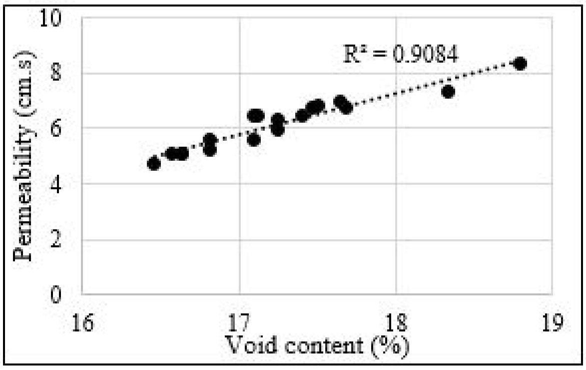

Figure 6. Correlation between permeability coefficient and void content.

3.5. CO_2 absorption capacity (COAC)

COAC of the concrete samples are shown in Figure 7, where the COAC of all mixtures was increased by increasing the curing time, but COAC at the first 2 hours of CO_2 curing covered about 70 % of COAC after 24 hours of CO_2 curing. Also, COAC was increased with the increasing of hydrated lime content. Moreover, concretes containing hydrated lime powders showed more potential to absorb CO_2 and the COAC of the hydrated lime modified concretes relatively is more than that of the control one, where the C2 and C3 were obtained 142 % and 192 % of COAC in comparison to the control one during the first hour of CO_2 curing. Figure 8, which shows the relative COAC of hydrated lime modified concretes to the relevant control one, clarify that the hydrated lime modified concretes have more potential than the control one despite of their low cement content. High volume of pores and high permeability coefficient of the concretes results in high permeation of CO_2 gas and high absorption of CO_2 during the initial time of curing. Also, high content of $Ca(OH)_2$ in the mixtures containing hydrated lime substitution increases the chemical reactions and lead to high carbonation content in the hydrated lime modified concretes. Moreover, increasing in the COAC after 12 hours of curing can be neglected.

Furthermore, COAC of the control mixture increased by 123 % and 167 % when CO_2 curing time was increased from 1 to 2 and 4 hours, respectively. These values have been reported about 5 % and 13 %, respectively for lightweight concretes [17]. Baojian et al. have reported 11 % and 33 % increasing in the COAC when CO_2 curing time was increased from 6 to 12 and 24 hour [34], respectively for recycled aggregate concretes while these values are about 5.9 % and 6.2 %, respectively in this study. Porous structure of pervious concretes simplifies the penetration of CO_2 gas into the concretes and therefore COACs are significant at the early ages of CO_2 curing in comparison with other concretes and consequently COACs are significantly reduced for the later ages.

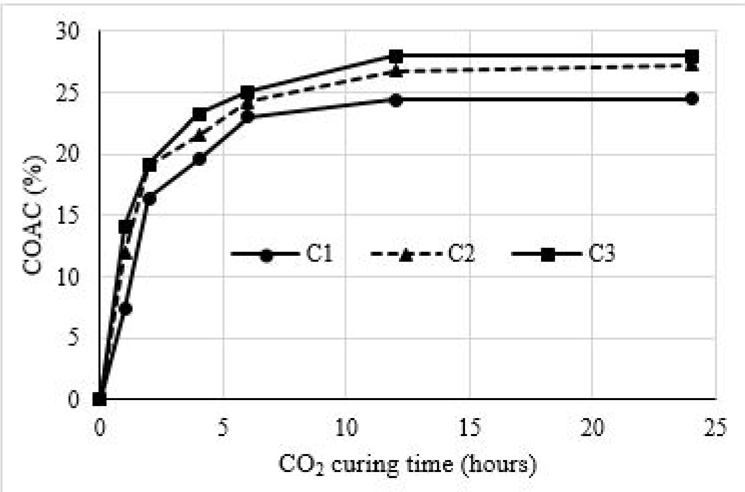

Figure 7. COAC of the pervious concrete over CO_2 curing time.

It is recommended to consider time of CO_2 curing of pervious concretes lower than 6 hours by respect of COAC result, while it is recommended about 12 hours of CO_2 curing by respect of obtaining mechanical properties.

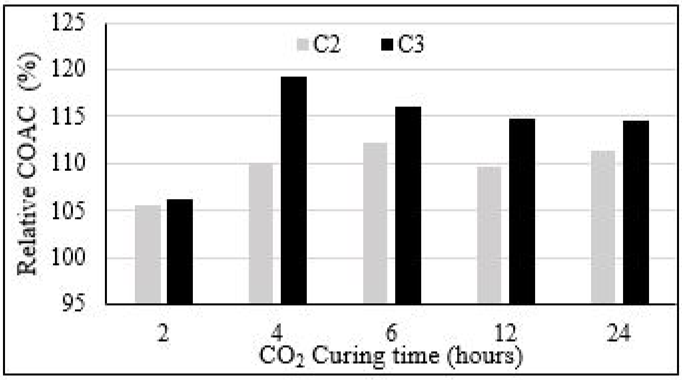

Figure 8. Relative COAC of the mixtures to the COAC of the control mixture.

4. Conclusion

An experimental program was conducted to investigate the effect of CO_2 curing on the physical and mechanical properties of pervious concretes with substitution of hydrated lime powders up to 30 % of cement. Moist curing and CO_2 curing were applied by up to 28 days and 24 hours, respectively. Also, CO_2 absorption capacity of the mixtures was investigated. The results of the conducted experiments are summarized as follows.

1- The major carbonation reactions of the pervious concretes were occurred in the first two hours of curing and then reactions were slowly continued up to 12 hours and then were approximately stopped.

2- Compressive strength of the CO_2 cured pervious concretes were obtained by up to 87 % of relevant compressive strength after 28 days of moist curing.

3- Hydrated lime substitution increases the CO_2 absorption capacity, where the 15–30 % replacement of hydrated lime increased the COAC up to 15 %.

4- Void content of the CO_2 cured hydrated lime modified concretes was less than the relevant void content of 28 days moist cured mixtures which confirms high CO_2 absorption capacity of the hydrated lime modified concretes.

5. Acknowledgments

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Contacts:

Hamid Rahmani, +982433054057; hrahmani@znu.ac.ir

Mohammad Montazer Gheib, +989369635763; mohammmadmontazer.ci@gmail.com