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Effects of CO_2 Carbonation Stabilization Parameters on the Performance of Lake Sediment

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Abstract

To investigate the effects of CO_2 carbonation parameters on lake sediment stabilization, a ternary binder of reactive MgO, slag, and silica fume was used in a full-factorial two-factor, three-level experiment. Carbonation times of 0.5, 1.0, and 1.5 h and CO_2 pressures of 0.2, 0.4, and 0.6 MPa were evaluated. Compressive strength, shear strength, and mass gain ratio were measured after 7, 14, and 28 d. All three responses generally increased with carbonation time and CO_2 pressure. Two-way ANOVA showed significant main effects of both factors at all curing ages ($p < 0.001$), whereas the interaction depended on the response and age. At 0.6 MPa, increasing carbonation time from 1.0 to 1.5 h increased the 28 d compressive strength only from 7.06 to 7.12 MPa. Therefore, 1.0 h–0.6 MPa provided a favorable balance between strength and treatment duration.

Keywords

Lake sediment; CO_2 carbonation; Stabilization; Carbonation time; CO_2 pres-sure; Interaction effect

1. Introduction

Lake sediment management is an important issue in lake restoration because dredging generates large volumes of high-water-content sediment that require dewatering, handling, and beneficial reuse [1–2]. Conventional disposal can be costly and may cause secondary environmental burdens. Reactive magnesium oxide (MgO) carbonation stabilization has therefore attracted attention as a low-carbon treatment approach. MgO can hydrate and react with CO_2 to form hydrated magnesium carbonates that fill pores, bind soil particles, and improve engineering properties while mineralizing CO_2 [3]. Carbonation time and CO_2 pressure are thus key process parameters affecting stabilization performance.

Previous studies have investigated reactive-MgO carbonation stabilization and its influencing factors. Wang et al. [4] used a reactive MgO–fly ash system to stabilize

sediment from East Lake, China, and examined strength gain and microstructural changes; a subsequent study further investigated durability and micromechanisms [5]. Wang et al. [6] applied bio-carbonation of reactive magnesia cement to high-water-content dredged sludge. Yi et al. [7] investigated forced carbonation of reactive-MgO-stabilized soil, while Liu et al. [8] examined the effect of compaction degree. Other studies evaluated the physical and strength characteristics, MgO reactivity, permeability, and stabilization mechanisms of carbonated soils [9–12]. Additional studies have addressed MgO-carbonated dredged sediment, pressure-enhanced carbonation, and MgO–slag solidified sludge [13–15]. However, the combined effects of carbonation time and CO_2 pressure on lake sediment remain insufficiently quantified, particularly for compressive strength, shear strength, and mass gain ratio.

Accordingly, this study used lake sediment collected from a lake in Hunan Province and a ternary binder of MgO, slag, and silica fume. A full-factorial two-factor, three-level experiment was conducted with carbonation times of 0.5, 1.0, and 1.5 h and CO_2 pressures of 0.2, 0.4, and 0.6 MPa. Compressive strength, shear strength, and mass gain ratio were measured after 7, 14, and 28 d, and two-way ANOVA was used to evaluate the main and interaction effects. The results provide a basis for selecting carbonation-stabilization parameters for lake sediment.

2. Materials and Experimental Program

2.1. Experimental materials and apparatus

Lake sediment collected from a lake in Hunan Province was used as the soil matrix. Its basic physical and physicochemical properties, determined in accordance with GB/T 50123-2019 [16], are summarized in **Table 1**. Reactive MgO, slag, and silica fume were used as a ternary blended binder (**Figure 1**). High-purity CO_2 (99.99%) conforming to GB/T 23938-2021 [17] was used for carbonation.

Table 1. Basic physical and physicochemical properties of lake sediment

Property	Water content (%)	pH	Organic matter ($g \cdot kg^{-1}$)	Dry density ($g \cdot cm^{-3}$)	Wet density ($g \cdot cm^{-3}$)	Liquid limit (%)	Plastic limit (%)	Plasticity index
Value	28.04	6.25	15.34	1.61	2.06	45.2	28.05	17.15



Figure 1. Three components of the ternary blended binder: (a) reactive MgO; (b) slag; (c) silica fume.

Carbonation was conducted using a self-developed pressurized CO_2 carbonation

apparatus consisting of a CO_2 supply system, control valve, pressure gauge, high-pressure tubing, and a sealed chamber (**Figure 2**). Before each test, residual air was discharged; CO_2 was then introduced and the chamber pressure was maintained at the prescribed value for the specified carbonation duration.

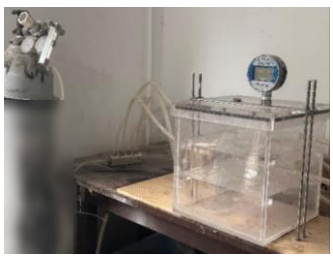


Figure 2. Photograph of the pressurized CO_2 carbonation apparatus.

2.2. Experimental design

For the carbonation-parameter tests, MgO, slag, and silica fume were fixed at 40%, 12%, and 2% of the dry sediment mass, respectively, with a water content of 20% and a sand content of 10%. Carbonation time (0.5, 1.0, and 1.5 h) and CO_2 pressure (0.2, 0.4, and 0.6 MPa) were varied in a full-factorial two-factor, three-level design, yielding nine groups (**Table 2**).

Table 2. Experimental design for carbonation parameters

Group	Carbonation time (h)	CO_2 pressure (MPa)
D-1	0.5	0.2
D-2	1.5	0.2
D-3	0.5	0.4
D-4	1.0	0.2
D-5	1.0	0.6
D-6	1.0	0.4
D-7	1.5	0.4
D-8	0.5	0.6
D-9	1.5	0.6

2.3. Specimen Preparation and Testing

The oven-dried, crushed, and screened sediment was mixed with water at 120 r/min for 15 min and then with MgO, slag, and silica fume at 180 r/min for 5 min. Cylindrical specimens (60 mm diameter × 125 mm height) for compression tests and disk specimens (61.8 mm diameter × 20 mm height) for direct shear tests were compacted, carbonated under the designated time–pressure combination, sealed, and cured at (20 ± 2) °C and RH ≥ 95% for 7, 14, or 28 d. Three replicate specimens were prepared for each time–pressure combination and curing age. Compressive strength was determined by axial loading of the cylindrical specimens to failure, while direct shear tests were conducted under normal stresses of 50, 100, 200, and 300 kPa in accordance with GB/T 50123-2019 [16]. The mass gain ratio was

calculated from the specimen mass before carbonation and the mass immediately before testing. Two-way ANOVA was used to evaluate the effects of carbonation time, CO_2 pressure, and their interaction, with $p < 0.05$ considered statistically significant.

3. Results and Analysis

Results for the nine parameter combinations are summarized in **Table 3** as mean values of three replicate specimens.

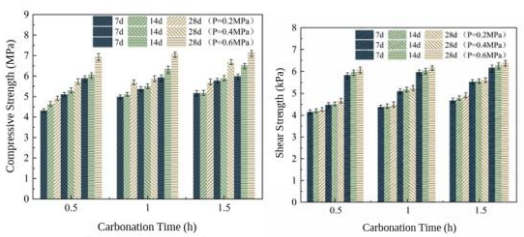
Table 3. Experimental results (mean values, n = 3)

Group	Compressive strength (MPa)			Shear strength (kPa)			Mass gain ratio (%)		
	7 d	14 d	28 d	7 d	14 d	28 d	7 d	14 d	28 d
D-1	4.31	4.64	4.92	4.15	4.21	4.27	4.05	4.30	4.55
D-2	5.16	5.18	5.71	4.68	4.79	4.92	5.36	5.50	5.87
D-3	5.10	5.30	5.73	4.47	4.52	4.67	5.08	5.18	5.69
D-4	4.98	5.11	5.69	4.38	4.42	4.49	5.02	5.17	5.71
D-5	5.92	6.33	7.06	5.98	6.05	6.19	5.77	5.92	6.86
D-6	5.36	5.50	5.87	5.10	5.19	5.25	5.41	5.89	6.68
D-7	5.77	5.89	6.68	5.53	5.57	5.62	5.88	6.33	6.92
D-8	5.88	6.04	6.92	5.84	5.97	6.09	5.16	5.30	5.73
D-9	5.98	6.51	7.12	6.17	6.29	6.38	5.98	6.42	7.12

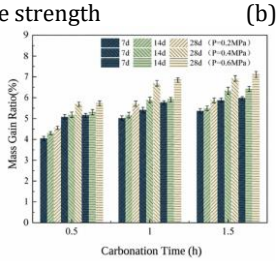
3.1. Effects of individual factors

3.1.1. Effect of carbonation time

Figure 3 summarizes the effects of carbonation time on compressive strength, shear strength, and mass gain ratio at 7, 14, and 28 d.



(a) compressive strength (b) shear strength



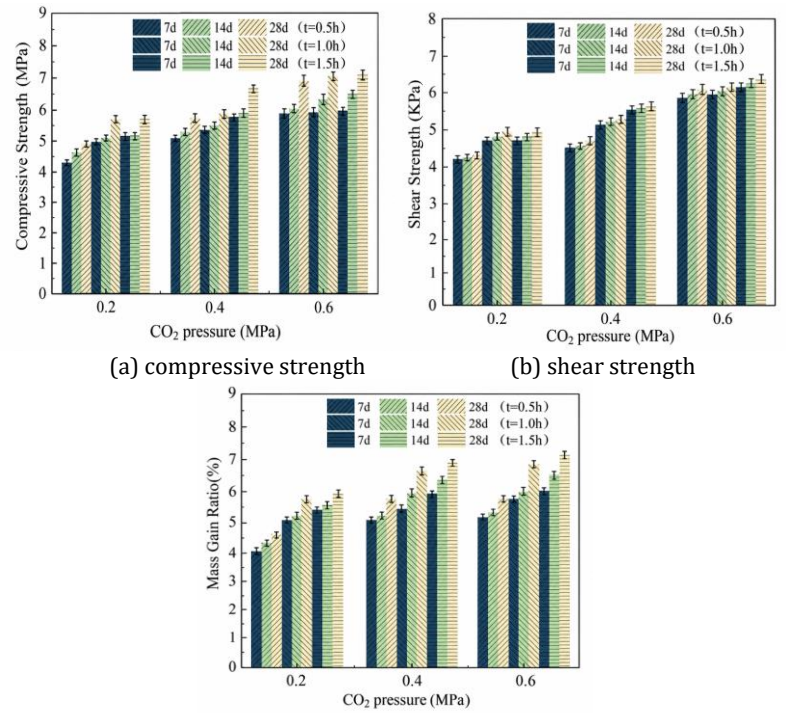
(c) mass gain ratio

Figure 3. Effect of carbonation time on stabilized lake sediment performance: (a) compressive strength; (b) shear strength; (c) mass gain ratio. Error bars represent standard deviations (n = 3).

Figure 3 shows that compressive strength, shear strength, and mass gain ratio generally increased as carbonation time increased from 0.5 to 1.5 h. This trend was observed at 7, 14, and 28 d, indicating that extending the treatment duration promoted the overall stabilization response. The increase in compressive and shear strength is consistent with more extensive carbonation during the longer treatment period. Mass gain ratio showed a similar upward trend, indicating a greater overall mass increase with longer carbonation. However, the magnitude of improvement was not uniform among the different CO_2 pressures and curing ages. Therefore, within the tested range, increasing carbonation time was beneficial, although the additional gain obtained from further extending the treatment depended on the specific carbonation condition.

3.1.2. Effect of CO_2 pressure

Figure 4 summarizes the corresponding effects of CO_2 pressure at 0.2, 0.4, and 0.6 MPa.



(a) compressive strength (b) shear strength

(c) mass gain ratio

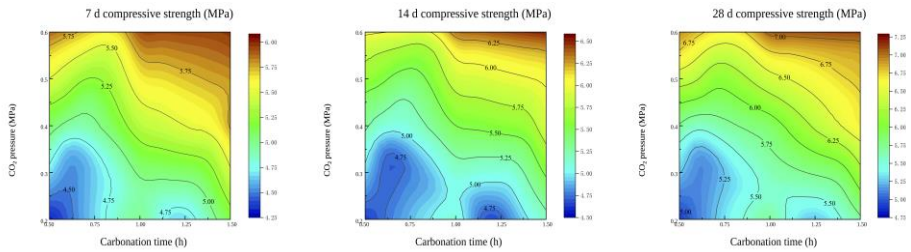
Figure 4. Effect of CO_2 pressure on stabilized lake sediment performance: (a) compressive strength; (b) shear strength; (c) mass gain ratio. Error bars represent standard deviations (n = 3).

Figure 4 shows that increasing CO_2 pressure from 0.2 to 0.6 MPa improved all three performance indicators at the investigated curing ages. Both compressive and shear strength increased with pressure, and the highest strength values at each curing age were obtained at 0.6 MPa. The mass gain ratio also generally increased as pressure

increased, showing a trend consistent with the mechanical properties. These results indicate that a higher CO_2 pressure promoted the carbonation response of the stabilized lake sediment and contributed to greater strength development during curing. The magnitude of the pressure effect varied among the three indicators and curing ages, but the overall trend remained consistent. Thus, within the tested pressure range, CO_2 pressure was an important factor controlling stabilization performance.

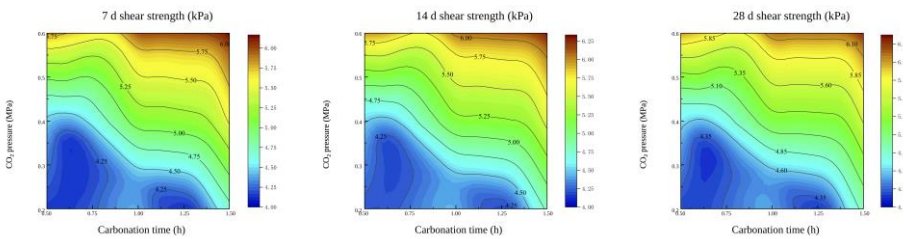
3.2. Combined response of carbonation time and CO_2 pressure

Figures 5–7 show the combined effects of carbonation time and CO_2 pressure on compressive strength, shear strength, and mass gain ratio at 7, 14, and 28 d.



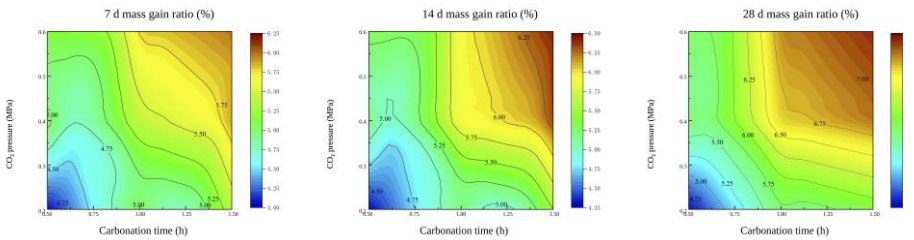
(a) 7 d (b) 14 d (c) 28 d

Figure 5. Compressive strength under different combinations of carbonation time and CO_2 pressure: (a) 7 d; (b) 14 d; (c) 28 d.



(a) 7 d (b) 14 d (c) 28 d

Figure 6. Shear strength under different combinations of carbonation time and CO_2 pressure: (a) 7 d; (b) 14 d; (c) 28 d.



(a) 7 d (b) 14 d (c) 28 d

Figure 7. Mass gain ratio under different combinations of carbonation time and CO_2 pressure: (a) 7 d; (b) 14 d; (c) 28 d.

A clear combined response was observed for compressive strength. Increasing carbonation time from 0.5 to 1.5 h increased the 7 d compressive strength by 19.7% at 0.2 MPa but only 1.7% at 0.6 MPa; the corresponding increases at 28 d were 16.1% and 2.9%. Shear strength showed the same tendency, with 7 d increases of 12.8% and 5.7% at 0.2 and 0.6 MPa, respectively. Mass gain ratio also generally increased with both factors. These results indicate that the marginal benefit of extending carbonation time decreased as CO_2 pressure increased. At 28 d, D-5 (1.0 h, 0.6 MPa) reached 7.06 MPa, only 0.8% below D-9 (1.5 h, 0.6 MPa; 7.12 MPa), while reducing carbonation time by 33.3%. Thus, 1.0 h–0.6 MPa provided a favorable time–pressure balance within the tested range.

3.3. Two-way analysis of variance

Two-way ANOVA was used to quantify the main and interaction effects of carbonation time and CO_2 pressure; the results are summarized in **Table 4**.

Table 4. Two-way ANOVA for carbonation time and CO_2 pressure

Performance indicator	Curing age (d)	Carbonation time F	p	CO_2 pressure F	p	Time × pressure F	p
Compressive strength	7	44.640	<0.001	186.490	<0.001	9.644	<0.001
	14	39.733	<0.001	239.920	<0.001	1.500	0.244
	28	52.456	<0.001	321.159	<0.001	13.527	<0.001
Shear strength	7	62.166	<0.001	390.703	<0.001	7.576	<0.001
	14	75.320	<0.001	482.649	<0.001	9.471	<0.001
	28	64.865	<0.001	459.610	<0.001	6.794	0.002
Mass gain ratio	7	192.554	<0.001	148.050	<0.001	8.846	<0.001
	14	204.577	<0.001	144.816	<0.001	0.833	0.522
	28	320.868	<0.001	275.962	<0.001	0.629	0.648

Note: The degrees of freedom for the carbonation time × CO_2 pressure interaction were 4, and the error degrees of freedom were 18. $p < 0.05$ indicates statistical significance.

Both carbonation time and CO_2 pressure significantly affected all three responses at every curing age ($p < 0.001$). For compressive and shear strength, the F values for CO_2 pressure were consistently higher than those for carbonation time, indicating a stronger pressure effect on mechanical performance within the tested range. The interaction was significant for compressive strength at 7 and 28 d, shear strength at all curing ages, and mass gain ratio at 7 d, but was not significant for the remaining cases. Thus, the interaction between carbonation time and CO_2 pressure was response- and age-dependent.

4. Conclusions

(1) Within the tested range, increasing carbonation time and CO_2 pressure generally increased the compressive strength, shear strength, and mass gain ratio of the stabilized lake sediment. Two-way ANOVA showed significant main effects of both factors at all curing ages ($p < 0.001$), with CO_2 pressure exerting a stronger effect than carbonation time on compressive and shear strength.

(2) For compressive strength, the effect of carbonation time depended on CO_2

pressure. Increasing carbonation time from 0.5 to 1.5 h at 0.2 MPa increased the 7 and 28 d compressive strengths by 19.7% and 16.1%, whereas the corresponding increases at 0.6 MPa were only 1.7% and 2.9%. Significant time × pressure interactions occurred for compressive strength at 7 and 28 d, shear strength at all curing ages, and mass gain ratio at 7 d.

(3) The highest 28 d compressive strength was 7.12 MPa at 1.5 h–0.6 MPa. At 1.0 h–0.6 MPa, the strength reached 7.06 MPa, or 99.2% of the maximum, while carbonation time was reduced by 33.3%. Thus, 1.0 h–0.6 MPa provided a favorable balance between strength and treatment duration within the tested range.

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