

Axial Compression Effect on Carbonation Resistance of Fly Ash Concrete: An Experimental and Modeling Study

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Abstract: To investigate the durability of fly ash concrete under service conditions, this study systematically examined the effect of axial compressive load on its carbonation resistance. Prismatic specimens of ordinary Portland cement concrete (OPC) and concrete with 30% fly ash (FAC30) were prepared. Axial compressive loads at three levels (0%, 30%, and 60% of the ultimate strength) were applied using a self-designed long-term loading device. The specimens were then subjected to accelerated carbonation for 28 days in an environment with a CO₂ concentration of 20±1%, a temperature of 20±2°C, and a relative humidity of 70±3%. Carbonation depths were measured at 7, 14, and 28 days, and the distributions of internal pH value and calcium carbonate content were analyzed. The results showed that the axial load had a dual effect on the carbonation resistance of concrete. Under a low load level (30%), the carbonation depth of FAC30 decreased by approximately 6.5% compared to that of the unloaded specimens, indicating a certain inhibitory effect. However, under a high load level (60%), the carbonation depths of OPC and FAC30 increased significantly by 44.4% and 43.2%, respectively. The incorporation of fly ash substantially reduced the alkali reserve of concrete, resulting in a carbonation depth much greater than that of OPC, which was the dominant factor affecting carbonation resistance. Based on Fick's law and the experimental data, a prediction model for carbonation depth considering the axial load ratio was established as $X_c = X_0(1 + kS^m)$. Validation showed that the predicted values agreed well with the experimental results ($R^2 > 0.96$). This study provides an important theoretical and experimental basis for accurately predicting the service life of fly ash concrete structures under load.

Keywords: Fly Ash Concrete; Axial Compressive Load; Anti-Carbonation Performance; Carbonation Depth; Durability

Published: Mar 19, 2026

DOI: <https://doi.org/10.62177/apemr.v3i2.1136>

1. Introduction

Carbonation of concrete is one of the key factors leading to durability deterioration, steel reinforcement corrosion, and even structural failure^[1]. Against the background of the carbon peaking and carbon neutrality goals, the use of fly ash, an industrial by-product, to partially replace cement has become an important technical approach for producing green high-performance concrete^[2]. The morphological effect, micro-aggregate effect, and pozzolanic effect of fly ash can effectively improve the workability of concrete, reduce hydration heat, and optimize the pore structure in the later stage^[3]. However, the pozzolanic reaction consumes Ca(OH)₂ produced by cement hydration, which reduces the alkali reserve inside the concrete and weakens its ability to resist CO₂ erosion, thereby accelerating the carbonation process^[4].

In practical engineering, concrete structural members such as columns and walls are subjected to long-term stress. Loading can

alter the internal microcracks and pore structure of concrete, thereby affecting the transport rate of CO_2 [5]. Currently, research findings on the coupling effect of loading and carbonation remain inconsistent. Most studies [6-7] indicate that tensile stress accelerates carbonation, while the effect of compressive stress is more complex. Long-term experiments conducted by Castel et al. [8] showed that moderate compressive load within the serviceability range slightly inhibits carbonation. Zhao et al. [9] reported that under long-term loading, the carbonation rate of fly ash concrete increases with the development of damage. Therefore, this study aims to simulate the real stress state of concrete structures by conducting accelerated carbonation tests on concrete with different fly ash contents under long-term axial compressive load. By systematically analyzing the evolution of carbonation depth, internal pH value, and calcium carbonate content, the coupling mechanism between loading and fly ash content is revealed. Finally, a prediction model for carbonation depth that can quantify the effect of axial compressive load is established, providing theoretical support for the durability design and service life prediction of fly ash concrete structures.

2. Methods

2.1 Materials and Experimental Design

The materials used in this study included cement, fly ash, aggregates, and a superplasticizer. The cement was P-I 42.5 grade Portland cement (Shandong Shanshui, China), and its physical properties are presented in Table 1. The fly ash was Class I fly ash (Borun, Gongyi, China), with silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) as its main chemical components, accounting for 45.1% and 24.2%, respectively. Natural river sand with a fineness modulus of 2.3 was used as the fine aggregate, and crushed stone with a continuous grading of 5–20 mm was used as the coarse aggregate. A polycarboxylate-based superplasticizer with a water-reducing rate of 40% was employed to adjust the workability of the mixtures. Concrete mixtures with a target strength grade of C30 were designed. The water-to-binder ratio was fixed at 0.6 for all mixtures. The detailed mix proportions are provided in Table 2.

Table 1. Physical properties of P-I 42.5 grade Portland cement

Specific surface area (m^2/kg)	Setting time (min)	Compressive strength (MPa)	Flexural strength (MPa)
335	Initial:170; Final:215	3d: 28.1, 28d: 53.0	3d: 6.4, 28d: 9.0

Table 2. Concrete mix ratio (kg/m^3)

Type	Concrete	Coal gangue powder	Water	Coarse aggregate	Fine aggregate	Water reducer
OPC	330	0	198	1162	719	0.74
FAC30	231	99	198	1160	719	0.74

2.2 Sample preparation and preservation

Prismatic samples with dimensions of 100 mm × 100 mm × 300 mm were cast for carbonation and axial compressive strength tests. Cubic samples with dimensions of 100 mm × 100 mm × 100 mm were also prepared to determine the standard compressive strength. All samples were compacted by vibration during molding and demolded after being covered with plastic film for 24 hours. They were then cured in a standard curing room at a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of over 95% for 28 days.

2.3 Experimental Procedures

Mechanical Property Tests: The cubic compressive strength was determined using a YAW-3000D microcomputer-controlled compression testing machine. The axial compressive strength of prismatic samples was measured using a YE-200A hydraulic material testing machine to provide reference values for subsequent loading.

Long-term Axial Compressive Load Application: A self-designed spring-bolt loading system (Figure 1) was used to apply long-term loads corresponding to 30% and 60% of the axial compressive strength to the cured prismatic samples. Load variations were monitored in real time using strain gauges attached to the bolts and a data acquisition instrument. When the load loss exceeded 10%, manual compensation was performed to ensure the stability of the load level.

Accelerated Carbonation Test: The samples, together with the loading devices, were placed vertically into a TH-B type carbonation chamber. The chamber environment was controlled as follows: CO_2 concentration of $20 \pm 1\%$, temperature of 20

$\pm 2^{\circ}\text{C}$, and relative humidity of $70 \pm 3\%$. The carbonation ages were 7, 14, and 28 days.

Carbonation Depth Measurement: At each specified age, samples were removed and split using a compression testing machine. A 1% phenolphthalein ethanol solution was immediately sprayed onto the split surface. After the color stabilized (the non-carbonated area appeared purple-red, while the carbonated area remained unchanged), carbonation depths were measured using a vernier caliper at six selected points on each surface. The average value was taken as the carbonation depth of the sample.

Microscopic Performance Analysis: For samples after 14 days of carbonation, powder was collected layer by layer from the surface inward. The calcium carbonate content in each layer was measured using a GMH3151 digital pressure measuring instrument. Meanwhile, the pH value of the pore solution was determined using precision pH test paper.

Figure 1: Diagram and physical image of the self-made long-term load device.



3. Results and Discussion

3.1 Mechanical Property Analysis

The mechanical property test results (Table 3) showed that the 28d cubic compressive strength (21.3 MPa) and prismatic axial compressive strength (10.94 MPa) of FAC30 were significantly lower than those of OPC (25.9 MPa and 28.79 MPa, respectively). This was mainly attributed to the low pozzolanic activity of fly ash at an early age, resulting in slow early strength development. These results provided an accurate load ratio basis for subsequent long-term load application.

Table 3 Mechanical properties of concrete

Type	Cubic compressive strength (MPa)	Prismatic axial compressive strength (MPa)	30% Load Value (kN)	60% Load Value (kN)
OPC	25.9	28.79	288	576
FAC30	21.3	10.94	109.4	218.8

3.2 Carbonation Depth Analysis

3.2.1 Effects of Load and Fly Ash Content

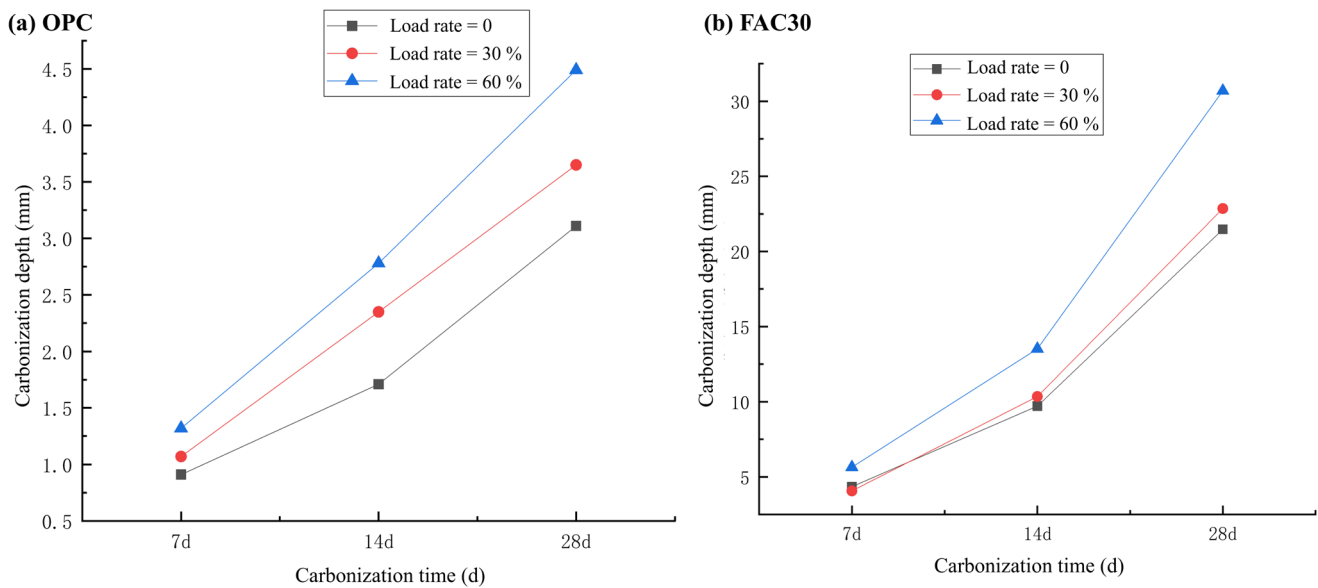
The carbonation depth test results under different conditions are presented in Table 4 and Figure 2. Under all load levels, the carbonation depth of FAC30 was substantially greater than that of OPC. For example, at 28 days, the carbonation depth of unloaded FAC30 (21.23 mm) was 6.8 times that of OPC (3.11 mm), confirming that the reduction in alkali reserve caused by fly ash consuming $\text{Ca}(\text{OH})_2$ is the primary factor responsible for the deterioration of carbonation resistance. Regarding the effect of load, a dual phenomenon was observed. Under a low load level of 30%, the carbonation depth of FAC30 at 7 days (4.06 mm) was slightly lower than that of the unloaded specimens (4.34 mm), suggesting that moderate compressive stress can compress initial microcracks and defects, temporarily densify the structure and hinder CO_2 diffusion. In contrast, when the load increased to 60%, the carbonation depth of both concrete types increased significantly. At 28 days, the carbonation depths of OPC and FAC30 increased by 44.4% and 43.2%, respectively, compared to their unloaded counterparts. This acceleration is attributed to the formation of new microcracks and the propagation and interconnection of existing cracks under high sustained load, which provide convenient pathways for rapid CO_2 intrusion.

Table 4 Carbonation depth (mm) of concrete under different load levels and time

Type	Load level	7d	14d	28d
OPC	0%	0.91	1.71	3.11
	30%	1.07 (+17.6%)	2.35 (+37.4%)	3.65 (+17.4%)
	60%	1.32 (+45.1%)	2.78 (+62.6%)	4.49 (+44.4%)
FAC30	0%	4.34	9.71	21.23
	30%	4.06 (-6.5%)	10.34 (+6.5%)	22.57 (+6.3%)
	60%	5.64 (+29.9%)	13.52 (+39.2%)	30.41 (+43.2%)

Note: Values in parentheses represent the change rate compared to the 0% load specimens in the same group.

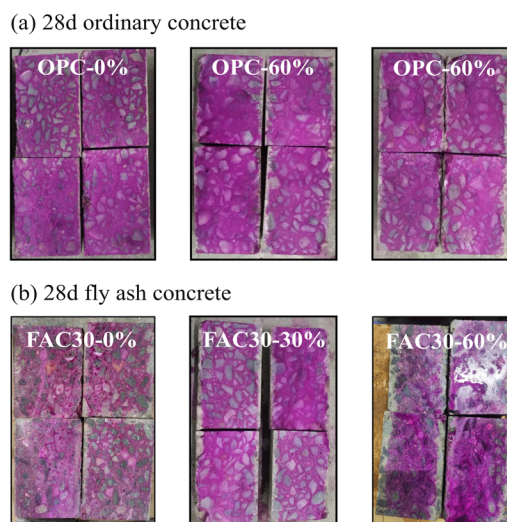
Figure 2: Carbonation depth of concrete under different load levels over time.



3.2.2 Carbonation Morphology Analysis

Figure 3 shows the phenolphthalein color development on the split surfaces of selected specimens after 28d of carbonation. It can be intuitively observed that the carbonated area (colorless) of FAC30 was much larger than that of OPC. Meanwhile, the carbonation front of specimens under high load (60%) was straighter and deeper, while that of unloaded or low-load specimens was relatively irregular, reflecting the “channeling” effect of load on CO₂ transport pathways.

Figure 3: Split surface morphology of concrete after 28d carbonation.

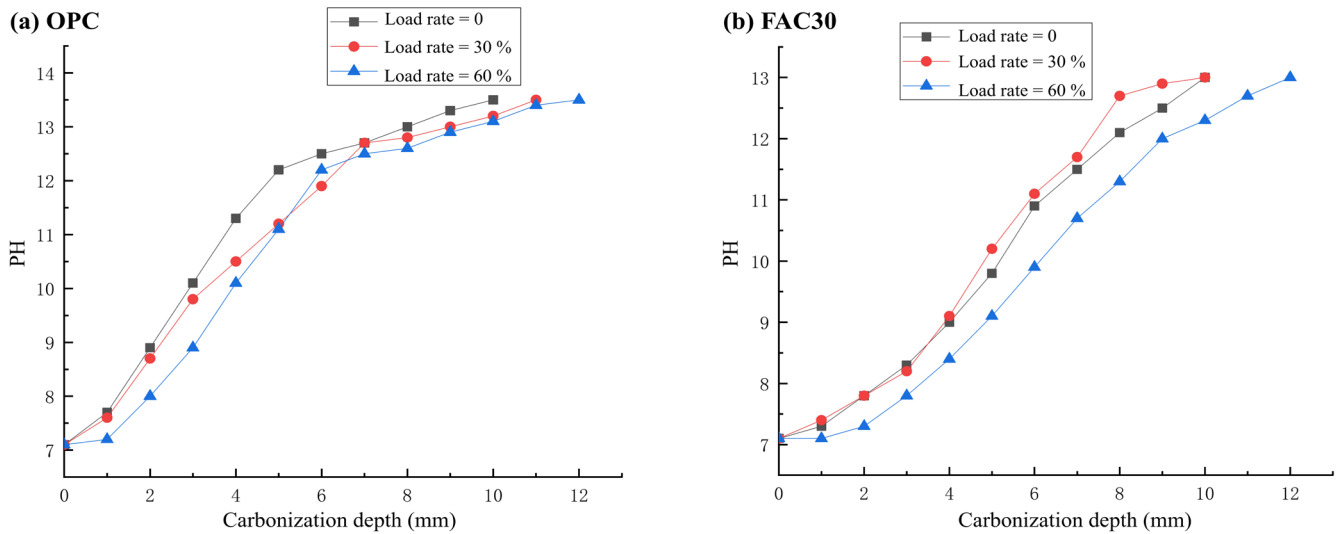


3.3 Internal pH Value and Calcium Carbonate Distribution

3.3.1 pH Value Distribution

Figure 4 shows the variation of internal pH value with depth after 14d of carbonation. It can be observed that: The pH value of FAC30 was lower than that of OPC at all depths, once again verifying its insufficient alkali reserve. For OPC, the higher the load, the lower the pH value at the same depth, indicating a deeper degree of carbonation. For FAC30, the pH value under 30% load within 4 mm depth was slightly higher than that of unloaded specimens, which corroborated the “inhibitory” phenomenon observed in the carbonation depth data. In contrast, 60% load caused a sharp decrease in pH value throughout the entire measured depth.

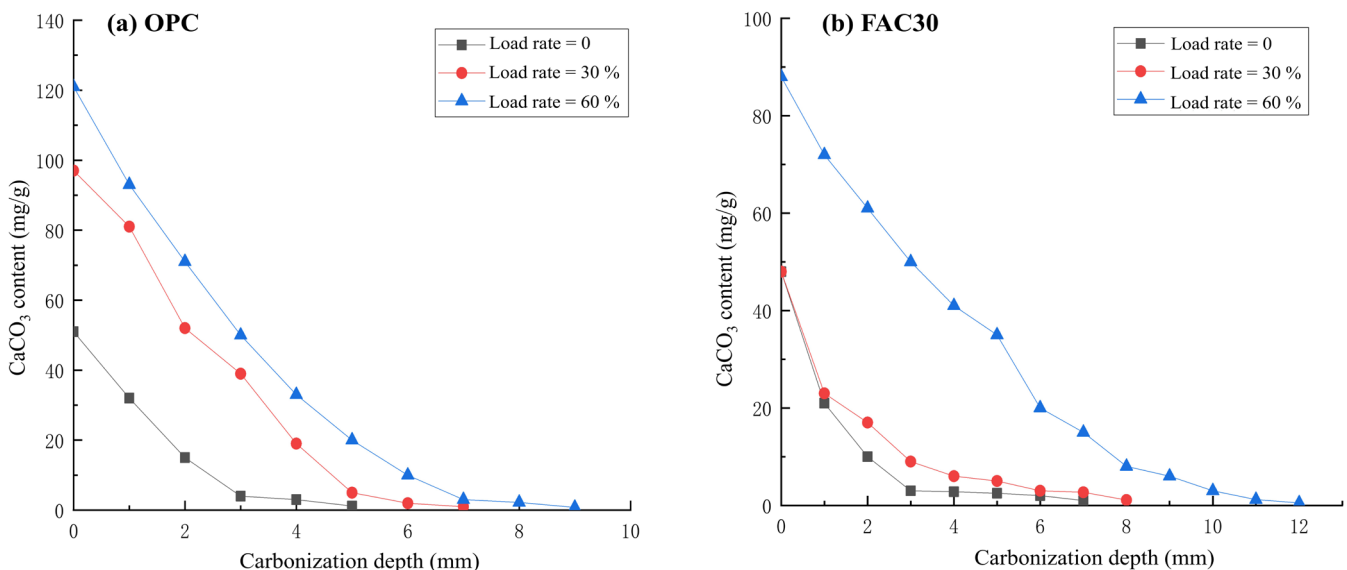
Figure 4: Internal pH value distribution with depth after 14d carbonation.



3.3.2 Calcium Carbonate Content Distribution

The calcium carbonate content distribution was obtained through layer-by-layer testing of specimens after 14d of carbonation (Figure 5). The calcium carbonate content was highest in the completely carbonated zone and gradually decreased with depth toward the non-carbonated zone. The CaCO₃ content in each layer of OPC was generally higher than that of FAC30, because OPC contained more carbonatable substances (Ca(OH)₂). The increase in load, especially 60% load, led to a higher CaCO₃ content at the same depth, indicating that more CO₂ had diffused to that location and participated in the reaction. This intuitively reflected the accelerating effect of load on the carbonation process.

Figure 5: Calcium carbonate content distribution after 14d carbonation.



3.3 Internal pH Value and Calcium Carbonate Distribution

3.4 Carbonation Depth Prediction Model

Based on Fick's first law, carbonation depth is generally proportional to the square root of carbonation time, namely:

$$X_c = K\sqrt{t} \quad (1)$$

In this study, the axial compressive load ratio S ($S = \text{Applied load}/\text{ultimate axial compressive load}$) was introduced as an influencing coefficient, and the following modified model was proposed:

$$X_c = X_0(1 + kS^m) \quad (2)$$

where, X_0 is the carbonation depth under unloaded condition, which can be fitted by $X_0 = Kt^a$, k and m are model parameters related to the material properties of concrete.

Fitting was performed using the 28d carbonation depth experimental data, yielding:

$$\text{For OPC: } X_0 = 0.15t^{0.91}, k = 0.18, m = 1.36$$

$$\text{For FAC30: } X_0 = 0.45t^{1.16}, k = 1.62, m = 2.6$$

For fly ash concrete at a carbonation age of 14d: when $S = 0.3$, $X_c = 10.34$; when $S = 0.6$, $X_c = 13.25$. Substituting these into the formula gave $k = 1.62$ and $m = 2.6$. The theoretical carbonation depth at 28d under 60% load ratio was calculated to be 30.69 mm, which was close to the experimental result of 30.41 mm, with an error of 1%. Therefore, this model could be applied to this experiment. The carbonation model for fly ash concrete under these conditions was $X_c = X_0(1 + 1.62S^{2.6})$. Similarly, the carbonation model for ordinary concrete under the same conditions was $X_c = X_0(1 + 0.18S^{1.36})$.

4. Rebounding and Defensive Comprehensiveness

This study investigated the effect of axial compressive load on the carbonation resistance of fly ash concrete. The main conclusions are as follows: Axial compressive load exhibited a significant dual effect on the carbonation resistance of fly ash concrete. A low load level of 30% slightly inhibited carbonation through compaction, while a high load level of 60% significantly accelerated the carbonation process by inducing microcracks. At 28 days, the carbonation depth increased by more than 43% under high load. Fly ash content was the dominant factor affecting the carbonation resistance of concrete. Under the same conditions, the carbonation depth of concrete with 30% fly ash replacement was more than six times that of ordinary concrete. This was mainly attributed to the consumption of alkaline substances by the pozzolanic reaction. The underlying mechanism of the load effect was revealed. Load regulated the CO_2 diffusion rate by altering the pore structure and crack network of concrete. Low load optimized the structure, whereas high load damaged it. A carbonation depth prediction model was established, incorporating the effects of time, fly ash content, and axial compressive load ratio. The model showed high predictive accuracy and can serve as a quantitative tool for durability design and service life assessment of engineering structures. When applying fly ash concrete in practice, appropriate measures such as reducing the water-to-binder ratio, adding anti-carbonation admixtures, or applying surface protection are recommended to compensate for its limited carbonation resistance, especially in members subjected to high stress levels.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Papadakis, V. G., Vayenas, C. G., & Fardis, M. N. (1991). Fundamental modeling and experimental investigation of concrete carbonation. *ACI Materials Journal*, 88(4), 363-373. <https://doi.org/10.14359/1863>
- [2] Zhang, Y., Lu, L., & Yao, Y. (2016). Research on carbonation effect of fly ash concrete. *Construction Technology*, 45(S2), 526-529.
- [3] Liu, J. (2016). Research on the carbonation characteristics of concrete of different strength grades. *China Concrete and Cement Products*, (6), 24-28. <https://doi.org/10.19761/j.1000-4637.2016.06.006>

- [4] Nath, P., & Sarker, P. (2011). Effect of fly ash on the durability properties of high strength concrete. *Procedia Engineering*, 14, 1149-1156. <https://doi.org/10.1016/j.proeng.2011.07.144>
- [5] Zhao, Q., He, X., & Zhang, J. (2017). Effect of long-term loading on carbonation resistance of fly ash concrete. *Journal of The Chinese Ceramic Society*, 45(2), 86-91. <https://doi.org/10.14062/j.issn.0454-5648.2017.02.12>
- [6] Tu, Y., & Lu, Z. (2003). Experiment and research of prestressed concrete structure in carbonation corrosive environments. *Journal of Southeast University (Natural Science Edition)*, 33(5), 573-576.
- [7] Chen, W., Xu, Y., & Geng, J. (2003). Effect of carbonization and stress on performance of concrete resistance to chloride ion penetration. *Bulletin of the Chinese Ceramic Society*, 33(5), 573-576. <https://doi.org/10.16552/j.cnki.issn1001-1625.2015.05.003>
- [8] Castel, A., François, R., & Arliguie, G. (1999). Effect of loading on carbonation penetration in reinforced concrete elements. *Cement and Concrete Research*, 29(8), 561-565. [https://doi.org/10.1016/S0008-8846\(99\)00017-4](https://doi.org/10.1016/S0008-8846(99)00017-4)
- [9] Hao, X., Zhang, W., & Liu, Y. (2017). The carbonation properties of the fly ash concrete under the axial compression load. *Journal of Agricultural University of Heibei*, 40(6), 108-112. <https://doi.org/10.13320/j.cnki.jauh.2017.0134>