

Experimental study of the interaction of concrete carbonization and chloride erosion under load

Zibao Lian

School of Architectural Engineering, Huanghuai University,
463000 Zhumadian, Henan, China

Received August 30, 2022

The influence of the interaction between carbonization and chloride on concrete corrosion was studied; an optimal design scheme for testing the interaction of carbonization and chloride corrosion of concrete under load is proposed, and simulation analysis has been made. The simulation results show that this algorithm has the accuracy, which is 9.34 % higher than that of the traditional algorithm. This allows the normal use function of a concrete structure to be properly assessed when the concrete structure is under the combined action of one or more environmental factors.

Keywords: load action, concrete, carbonation and chloride erosion.

Експериментальне дослідження взаємодії карбонізації бетону та хлоридної ерозії під навантаженням. *Zibao Lian*

Досліджено вплив взаємодії карбонізації та дії хлориду на корозію бетону, запропоновано оптимальну розрахункову схему випробувань взаємодії карбонізації та хлориду на корозію бетону під навантаженням, проведено імітаційний аналіз. Результати моделювання показують, що цей алгоритм має певну точність, яка на 9,34 % вище, ніж у традиційного алгоритму. Це дозволяє належним чином оцінити нормальну функцію використання бетонної конструкції, коли бетонна конструкція знаходиться під спільною дією одного або декількох факторів навколишнього середовища.

1. Introduction

In the 1920s, with the appearance of cement material, a new material appeared — concrete. Due to its good characteristics, concrete became one of the preferred materials in the field of civil engineering. However, in environmental conditions (carbonation, chloride-ion erosion, freeze-thaw cycle, etc.), the durability of concrete structures is limited, which leads to huge economic losses [1]. The durability of concrete structures during operation is affected not only by the external environment, but also by the load [2]. Loading often causes the formation and development of microcracks in the concrete, improves the cohesion of the pores, and creates more channels for the transfer of corrosive media, such as chlo-

ride ions and carbon dioxide, into the concrete, thereby accelerating the deterioration of concrete durability [3–5].

This paper investigates the interaction between concrete carbonization and chloride erosion as a function of load in order to reduce the cost of running the algorithm. Practice has proved that this combination can not only reduce the calculation time, but also improve the quality and efficiency of the test optimization of the interaction between concrete carbonation and chloride erosion.

This paper proposes a visual model for reconstructing signs of the interaction between concrete carbonization and chloride erosion; test optimization design is set. In test optimization design, the horizontal

depth and vertical depth of the interaction between concrete carbonization and chloride erosion are compared in a visual reconstruction process; and when optimizing tests, a fuzzy value of the sign of the interaction of carbonization and chloride erosion of concrete was obtained. Its innovation lies in:

(1) In this paper, the carbonation area of concrete is determined by several methods; the relationship between carbonization products and depth is obtained and the parameters in the model are determined.

(2) In this paper, a model of chloride-ion erosion under the influence of carbonation of unsaturated concrete is established, and the effect of different crack widths on the degree of carbonation in vertical and depth directions is discussed.

(3) The effect of carbonation on chloride diffusion in concrete was studied by determining the chloride ion content at different depths of concrete in the mode of alternating immersion in a salt solution and carbonization.

In this paper, the optimal design of the interaction test between concrete carbonation and chloride erosion is studied.

At present, a great deal of research has been carried out at home and abroad on the durability of concrete under the action of various single factors, and fruitful results have been achieved. Many of the conclusions and empirical formulas have reached consensus in academic circles, and have been well applied and verified in engineering practice.

In [6], the deterioration law of concrete performance under different sulfate concentrations was studied, and it has been found that when the concentration of sodium sulfate is lower, the performance of the concrete is less affected by the concentration of sulfate ions, i.e. increasing the concentration of sulfate will not significantly accelerate the penetration of the candle invasion of concrete. The article [7] shows that when the concentration of sulfate solution is lower, increasing the concentration of sulfate solution will obviously improve the acceleration of concrete candle penetration. When the concentration of sulfate solution is greater, with an increase in the concentration, the deterioration rate of concrete performance gradually slows down. In [8], candle damage was introduced as an equivalent porosity into the effective diffusion coefficient, a nonlinear equation for the diffusion of sulfate ions based on the evolution of erosion damage was established, and the

symmetrical effect of candle damage on ion diffusion was studied. In [9] the mechanism of stress and fatigue damage caused by the expansion product of rotten candle in concrete under alternating load was proposed, and a constitutive stress-strain model was derived, and a model was created for predicting the durability of concrete with a symmetrical interaction of sulfate and alternating load. On the basis of neural network technology, in article [10], neural network models were established for sulfate ion distribution in concrete under the action of single-factor and double-factor sulfate candle, and the experimental values were compared with the predicted values, which were in good agreement with each other, with high accuracy. In [11], the basic equation was reduced to a virtual crack size based on the analysis of the stress field in the area of the concrete failure process and a mathematical programming method was applied to determine the corresponding size of the area of the destruction process and the intensity of the applied load when the crack is in a critical state of propagation, which provided convenience for solving practical engineering problems. The authors of [12] used virtual crack model to study the fracture process area of concrete, and analyzed the influence of material parameters on the displacement, cohesion, length of fracture process area and peak external load. In [13], the effect of transverse cracks in concrete on chloride ion diffusion was predicted by a graphic method. At the same time, compared with the experimental data of saturated concrete, it was found that the combination of cement paste and chloride ions plays an important role in slowing down the entry of chloride ions into concrete. The authors of [14] used the numerical simulation analysis method to study the behavior of chloride ion penetration into cracked and undamaged concrete under saturated and unsaturated conditions, and created a chloride ion diffusion model with independent variables of crack width and concrete cover thickness.

As a matter of fact, many concrete structures often work under the dual action of carbon dioxide and chloride ions. However, there are few studies on these aspects in the reports. In this paper, an optimal design scheme of testing interaction between concrete carbonation and chloride erosion under load is proposed.

2. Experimental

2.1 Corrosion effect of chloride on concrete

The main causes of rebar corrosion can be divided into the following three types: concrete carbonization, rebar passivation caused by chloride ion erosion and rebar corrosion caused by acidic substances.

Chloride will not only corrode the steel bars in concrete, but also destroy the concrete itself. The results show that when calcium chloride is added into cement slurry, it will swell greatly with an increase in the calcium chloride content, which will lead to the destruction of the specimens to various degrees. This is because calcium chloride takes part in the hydration reaction of cement, producing some hydration substances containing chlorine, which increases the volume of the hydration product gel. This kind of atmosphere-containing substance is calcium oxychloride, therefore, the chloride salt at a high concentration has a corrosive effect on the cement. Adding calcium chloride will increase the drying shrinkage of cement slurry by several times, but the drying shrinkage effect caused by different curing conditions is very different. The irreversibility of cement paste mixed with calcium chloride in the cycle of dry shrinkage and wet expansion is more obvious than that of pure cement paste.

Chloride ions can enter concrete in two ways, one is in the composition of the concrete mixture, and the other is infiltration from the outside. The first way can be avoided by strict quality control, so the research on ion-trapping permeability usually focuses on the second one. In the natural state, the transfer of atmospheric ions in concrete generally has the following mechanisms: diffusion, infiltration, capillary adsorption, physical or chemical adsorption. Diffusion refers to the transmission and penetration of atmospheric ions in concrete when the concrete is saturated or has a high water content, the transmission and capillary adsorption of atmospheric ions and water in concrete under the pressure gradient of water, and the transmission characteristics of chloride ions in low moisture concrete due to negative capillary adsorption pressure. When considering the transport behavior of grasping ions in concrete, the infiltration of grasping ions combined with water under the action of water head is rarely considered, because only under the action of high water pressure, this kind of influence will be more significant; and even

under the action of water pressure, the water infiltration can be dealt with according to the diffusion problem. One of them, that is, the problem of infiltration of core-hardened soil, can be considered as the diffusion of water in concrete. For one-dimensional problems, it can be described by the diffusion equation:

$$\frac{\partial P}{\partial t} = \beta^2 \frac{\partial^2 P}{\partial x^2}, \quad (1)$$

where P is the water pressure; t is time; x is the distance of water flow; β^2 is the diffusion coefficient of water; and the diffusion coefficient of water in concrete is generally 1,000,000 times of the permeability coefficient. The water diffusion coefficient and permeability coefficient are as follows.

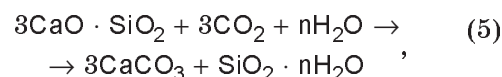
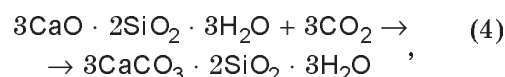
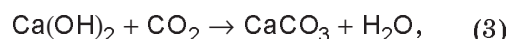
$$\beta^2 = k \frac{p_w \partial h}{p_s \partial u}, \quad (2)$$

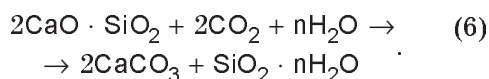
where p_w , p_s is the apparent density of water and medium respectively; u is the material water content; k is the permeability coefficient; w is the water content of the material.

2.2 Effect of carbonization on concrete

Concrete carbonization consumes the reducing substances in the concrete and generates neutral carbonates, which reduces the value of the concrete, and the concrete is completely carbonized. In this case, the concrete loses its protective effect on the reinforcement; as a result, the steel bar becomes open. Under the action of oxygen, water and other corrosive media, the steel bar begins to rust, which leads to a decrease in the strength of concrete.

When the cement is fully hydrated, the pore fluid of concrete is saturated with calcium hydroxide; the pH value is about 12 ~ 13 indicating strong alkalinity. The decrease in the pH value leads to the destruction of the passivation film of the reinforcement and corrosion of the reinforcement. The main chemical reaction equation of the concrete carbonation process is as follows.





The diffusion rate of carbon dioxide gas is related to the compactness of concrete itself, the concentration of carbon dioxide gas, the temperature and humidity and other environmental factors, which can be attributed to external factors related to the environment and internal factors related to concrete itself.

(1) *Influence of environmental temperature and humidity*

This factor has a great influence on the rate of destruction of concrete. The change of relative humidity determines the pore water saturation of concrete. When the humidity is low, the concrete is in a dry or low water content state. Although the diffusion rate of CO_2 gas is faster, the carbonation rate is slower due to the lack of water required for carbonation reaction.

The formula of the effect of environmental relative humidity on carbonization is

$$\frac{k_{RH_1}}{k_{RH_2}} = \frac{1 - RH_1}{1 - RH_2}, \quad (7)$$

where RH_1 and RH_2 are the relative humidity of two environments respectively. In addition, the diffusion rate and carbonization reaction of gas are greatly affected by temperature, so the carbonization rate increases with an increase in temperature. The formula of the influence of temperature on concrete carbonation is:

$$\frac{k_{T_1}}{k_{T_2}} = \frac{T_1^{1/4}}{T_2^{1/4}}, \quad (8)$$

where T_1 , T_2 is the absolute temperature of the environment.

(2) *Influence of concrete quality; water-cement ratio*

CO_2 diffuses through the internal capillary structure or pores of the concrete and its diffusion rate is highly dependent on the microstructure of the concrete. The water-cement ratio is an important parameter to determine the performance of concrete. The water-cement ratio basically determines the pore structure of concrete, which to some extent also determines the diffusion rate and depth of CO_2 in the concrete.

Dosage and grades of cement

The amount of cement directly affects the amount of absorbed CO_2 in the concrete,

so it has a certain influence on the carbonation of the concrete. Fan Ziyang's research shows that the amount of CO_2 absorbed by concrete depends on the amount of cement and the hydration degree of the concrete. The greater the amount of cement, the slower the rate of carbonization. Different cement grades, different contents of alkaline substances in cement hydration reactants, and different amounts of CO_2 absorbed by concrete, have a certain influence on the carbonization rate of concrete.

Admixtures

Under the condition of the same cement dosage and water-binder ratio, the higher the content of CO_2 in cement, the more $\text{Ca}(\text{OH})_2$ will be produced in hardened cement stone, therefore, the degree of concrete shrinkage will be slower, so the carbonization rate of cinnamate cement concrete is slower than that of concrete mixed with active admixture. This is because the latter has a secondary hydration process, which will consume a part of $\text{Ca}(\text{OH})_2$, so its carbonization speed is faster.

3. Results and discussion

Carbonization and chloride ion invasion of concrete are the two main factors that cause steel frying and corrosion in concrete structures. In the general atmospheric environment, only the role of carbon dioxide is generally considered, while the concrete structures in the atmospheric area, splash area and tidal sand area of marine environment are simultaneously destroyed by chloride ions and carbon dioxide. Although chloride ion is the main cause of steel bar rust candle, on the one hand, carbonation can not only cause steel bar candle suppression, but also affect the transmission of chloride ion in concrete to a certain extent. On the other hand, chloride ion candle invasion also has a certain degree of influence on concrete carbonization.

Through the analysis of chloride ion concentration in different depth ranges of crack and its adjacent section of a cracked concrete specimen, the influence of load level, erosion time and the bearing strain state of concrete around the crack on the chloride ion concentration in cracked concrete was explored.

Important factors of chloride ion diffusion in cracked concrete: the magnitude of the load, the possibility of introducing a wedge into cracks in precast concrete after loading, and the time of chloride ion erosion. The magnitude of the load and the

Table 1. Parameters of specimen

Group	Test piece number	Load value	Is there wedge after unloading	Is there a crack
1	S-CL-D	Crack initiation load	Without	No
2	C-CL-D	Crack initiation load	Have	No
3	S-PL-D	Peak load	Without	Yes
4	C-PL-D	Peak load	Have	Yes

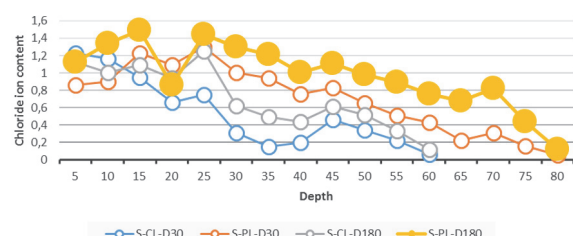


Fig. 1. Changes of chloride ion content with depth under load.

possibility of introducing a wedge into cracks after loading are considered in the concrete loading test. See Table 1 for the detailed loading scheme of the specimen.

In order to study the influence of the load level on the chloride ion concentration in cracked concrete, especially for the process of crack development before the concrete is unstable under load, the critical cracking state and the load action in the unstable failure state of concrete are studied, and the diffusion of chloride ions in cracked concrete under the initial cracking load is comparatively analyzed.

As can be seen from Fig. 1, the wedge inserted into the crack does not keep the bearing strain state, and the load level has a certain influence on the chloride ion diffusion in cracked concrete. At the same depth, the chloride ion content in the concrete with wedge inserted to keep the strain state under loading is significantly higher than that in the concrete without wedge inserted. It shows that the load level has a great influence on chloride ion diffusion rate in concrete in the early stage of erosion; and with increasing erosion time, the effect of the load level on the rate of diffusion of chloride ions in concrete gradually becomes stable. The raw data of carbonation depth measurement are shown in Table 2. In the table, the sample numbers *P* and *M* indicate pure cement concrete and concrete mixed with fly ash and mineral powder, respectively, and I–IV indicates circulation system.

Two groups of experimental data of PIV

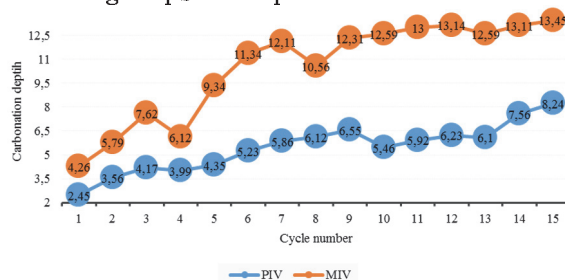


Fig. 2. Curves of carbonization depth of PIV and MIV with cycle period.

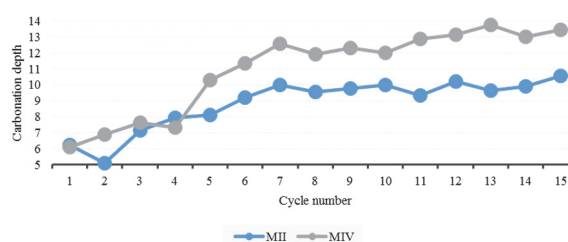


Fig. 3. Curves of carbonization depth of MII and MIV with cycle period.

and MIV were selected to analyze the influence of mineral admixtures on concrete carbonization, as shown in Fig. 2.

Under the same cycle period, the carbonization ages of PIV and MIV are the same. It can be seen from Fig. 2 that under the same cycle period, the carbonization depth of MIV is obviously higher than that of PIV, which indicates that the anti-blocking performance of MIV is not as good as that of PIV. This is mainly due to the fact that after replacing cement with mineral additives in equal amounts, the content of carbonizing substance $\text{Ca}(\text{OH})_2$ in concrete decreases, and the rate of carbonization of concrete increases, which means that the depth of carbonization increases. Since the secondary hydration reaction of mineral admixtures is a long-term process under these experimental conditions, the carbon dioxide concentration of rapid carbonization test is high, and the carbonization rate of concrete

Table 2. Raw data of measuring carbonation depth by phenolphthalein titration

Test piece number	Cycle period				
	3	6	9	12	15
PI	2.12	3.12	4.12	4.32	4.12
PII	3.15	4.81	6.13	6.49	7.65
PIV	4.17	5.23	6.55	6.23	8.24
MI	5.64	7.45	8.32	8.12	9.11
MII	7.13	9.22	9.78	10.22	10.56
MIV	7.62	11.34	12.31	13.14	13.45

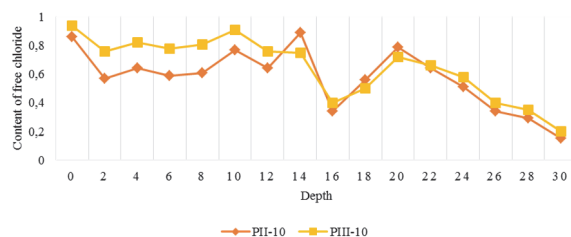


Fig. 4. Distribution curve of chloride ion content in pure cement concrete.

is fast, therefore, the improving effect of the secondary hydration reaction of mineral additives on the porous structure of concrete cannot be reflected in time. On the contrary, the reduction of the content of carbonizing substances $\text{Ca}(\text{OH})_2$ caused by replacing cement with mineral admixtures plays a leading role, making the carbonization depth of concrete mixed with fly ash and mineral powder greater than that of pure cement concrete.

Two groups of test data of MII and MIV were selected to analyze the influence of chloride ion on concrete carbonation, as shown in Fig. 3.

In the same cycle, the degree of carbonization of MII and MIV is the same, while MII is soaked in a chloride solution, and MIS is soaked in pure water. It can be seen from Fig. 3 that in the same cycle, the depth of carbonization of sample MII is less than that of sample MIV, indicating that the carbonization resistance of the concrete improves after soaking in the chloride solution in the cycle. After 15 cycles, the carbonization depth of MIV is 13.45 mm, while that of MII is 10.56 mm. The main reason for this phenomenon is that in the process of circulation, concrete has been dried for a long time after being taken out of the chloride solution, and the surface water of concrete evaporates outward, while the surface

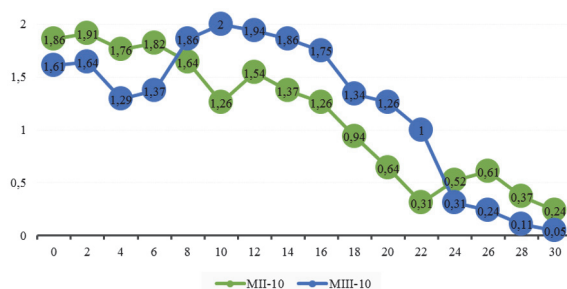


Fig. 5. Distribution curve of chloride ion content in concrete mixed with fly ash and mineral powder.

chloride ions still exist in the form of crystals, which fill the concrete pores.

The distribution curves of chloride ion content of test pieces PII and PIII and test pieces MII and MIII in the 15th cycle are shown in Fig. 4 and 5. The carbonization test was added in cycle II, but not in cycle III.

It can be seen from Fig. 4 and Fig. 5 that the distribution of chloride ion content in concrete with and without carbonization in circulation shows some differences. The distribution curve of chloride ion content in unbroken concrete is relatively smooth, while in carbonized concrete it varies from 0.05 mm to 2 mm in depth. There is an obvious "intersection" between the distribution curves of chloride ion content in carbonized and non-carbonized concrete. In Fig. 4, the intersection point of the distribution curves of chloride ion content in carbonized and non-carbonized concrete appears at the depth of 0.4 mm. When the depth is less than 0.7 mm, the chloride ion content is higher in non-carbonized concrete. At a depth of more than 0.7 mm, the chloride ion content is higher in carbonized concrete. Figure 5 shows a similar rule, and its "intersection point" appears at about 1.7 mm. It can be concluded that the effect of carbonization on the content of chloride

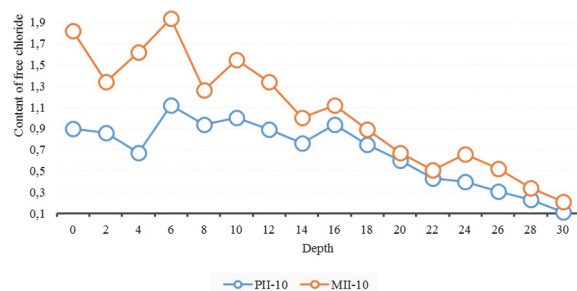


Fig. 6. Distribution curve of chloride ion content in carbonization.

ions in concrete is first decreased and then increased, and its influence is related to carbonation depth.

From the above, it can be seen that the influence of carbonation on the content of chloride ions in concrete is mainly manifested in two aspects. One is the influence on chloride ion diffusion, which improves the compactness of concrete in the carbonization area, reduces the porosity of concrete and hinders the diffusion of chloride ions. Second is the effect on the binding capacity of chlorine ions. Carbonization reduces the binding capacity of concrete to chloride ion, and causes the Friedel salt in the concrete to decompose in a limited area, releasing the originally bound chloride ions into free chloride ions, increasing the concentration gradient of free chloride ion dispersion, and promoting the migration of chloride ions from the carbonized area to the non-carbonized area.

The distribution curves of chloride ion content of samples PII and MII and samples MIII and PIII in the 15th cycle are shown in Fig. 6 and Fig. 7. *P* is pure cement concrete, and *M* is concrete mixed with fly ash and mineral powder.

From Fig. 6 and Fig. 7, it can be found that mineral admixtures increase the chloride ion content of the concrete surface layer; therefore, mineral admixtures change the pore structure of concrete, thus affecting the deposition of chloride ion on the concrete surface layer. Fig. 6. For the concrete with carbonized fly ash and mineral powder added in the cycle, the chloride ion content in the surface layer increased significantly.

Comparing Fig. 6 and Fig. 7, it is found that mineral admixtures not only increase the chloride ion content in the concrete surface layer, but also have a certain influence on the chloride ion transmission in concrete (Fig. 7). In non-car-

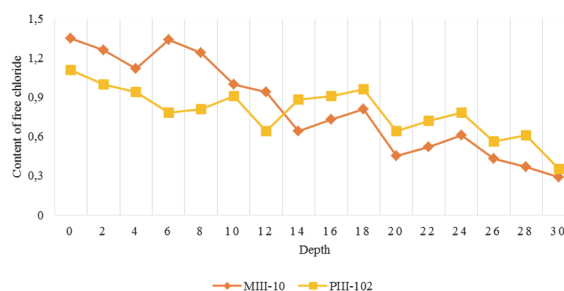


Fig. 7. Distribution curve of chloride ion content in non-carbonization.

bonized concrete, although mineral admixture increases the chloride ion content in the surface layer, it decreases the chloride ion content in the interior; thus, the admixture has a positive effect on the chloride ion permeability resistance of concrete (Fig. 6). For the carbonized Panning soil specimen, the chloride ion content of concrete mixed with fly ash and mineral powder is higher than in pure cement concrete, because the carbonization depth of concrete mixed with fly ash and mineral powder is greater. Due to migration of chloride ions by carbonization, chloride ions are more easily transported into concrete, which leads to the fact that the chloride ion content in concrete mixed with fly ash and mineral powder is higher than in pure cement concrete.

4. Conclusions

In this paper, an optimal design scheme to test the interaction between carbonation and chloride corrosion of concrete under load is proposed. As the most important factors of carbonization and chloride corrosion of concrete, the interaction between carbonization and chloride in concrete is studied under load conditions, and finally, simulation tests are analyzed. The simulation results show that this algorithm provides an accuracy that is 9.34 % higher than that of the traditional algorithm. This result fully shows that the carbonization depth determined by the experimental results, is larger than that measured by phenolphthalein titration; also, it is found that the carbonization time increases and the length of some carbonization zones increases. At the same time, experiments revealed the microscopic effects of carbonization on the pore structure of concrete and the migration of chloride ions; the change of porosity and the migration of chloride ions due to carbonization provide

some experience and experimental results for the study of concrete carbonization. Since there are many factors that affect the durability of concrete, some effective methods are needed to achieve the research purpose. The basic methods of durability research include: establishing the degree and significance of various types of damage; determining the characteristics of the product; establishing each type of mechanisms; establishing the properties which can be used to indicate that damage has occurred; how to measure it; designing test instruments to simulate the failure mechanism in the laboratory; finally, the laboratory data and field data should be connected and used in practice, which allows us to discuss in detail the problems of the relationship between different carbonization times and the time of action of the chloride salt, as well as consider the multifield problems of different ratios of moisture and dryness and different boundary conditions.

References

1. F.Jiang, G.Jiang, W.Song et al., *Funct. Mater.*, **27**, 730 (2020).
2. Luo Yeke, YU Zhouping, *Funct.Mater.*, **29**, 135 (2022).
3. G.L.Golewski, *Energies*, **14**, 668 (2021).
4. B.Lei, W.Li, Z.Li et al., *Journal of Materials in Civil Engineering*, **30**, 04018220.1-04018220.10 (2018).
5. F.Mu, J.M.Vandenbossche, *International Journal of Fatigue*, **158**, 106665 (2022).
6. Q.H.Xiao, Q.Li, Z.Y.Cao et al., *Construction and Building Materials*, **200**, 344 (2019).
7. W.Grzmil, W.Raczkiewicz, *Cement, Wapno, Beton*, **4**, 311 (2017).
8. L.Mo, Z.Feng, D.Min, *Cement and Concrete Composites*, **83**, 138 (2017).
9. Y.Kim, A.Hanif, M.Usman, *Journal of Cleaner Production*, **172**, 3056 (2018).
10. J.Chao, X.Gu, Q.Huang, *Cement and Concrete Composites*, **93**, 140 (2018).
11. G.Chen, Y.Lv, Y.Zhang, *Engineering Failure Analysis*, **119**, 104990 (2021).
12. J.Ying, Z.Han, L.Shen, *Materials*, **13**, 4631 (2020).
13. N.D.Van, E.Kuroiwa, J.Kim, *J. Materials*, **13**, 2136 (2020).
14. B.Zheng, T.Li, H.Qi et al., *Construction and Building Materials*, **326**, 126632.1-126632.15 (2022)