A Study of the deterioration law and mechanism of aeolian-sand powder concrete in the coupling environments of freeze-thaw and carbonization

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In this study, aeolian-sand powder was used for replacing cement-based gelling material in order to prepare aeolian-sand powder concrete in C25 and C35 strength grades. Through relative dynamic elastic modulus and carbonization depth changes, the deterioration laws of the aeolian-sand powder concrete under the coupling effects of freeze-thaw + carbonization and carbonization + freeze-thaw were studied. Then, field emission scanning electron microscopy, X-ray diffraction, and nuclear magnetic resonance porosity measurement technology were applied to analyze the microstructure, hydration products, and porosity changes. The results show that the Carbonation Mechanism of aeolian sand powder concrete is different from that of ordinary concrete. The carbonation of ordinary concrete results in calcium carbonate, and the carbonation of aeolian sand powder concrete results in calcium sulfate and calcium carbonate; The decrease of relative dynamic elastic modulus of aeolian sand powder concrete under freeze-thaw and carbonation environment is lower than that of ordinary concrete, and the results indicated that the relative dynamic elastic modulus of the aeolian-sand powder concrete under the freeze-thaw + carbonization effects was higher than that under the carbonization + freeze-thaw effects by 1.5 times. Also, the carbonization depth was less than that under the carbonization + freeze-thaw effects by 5.0%. Under the freeze-thaw + carbonization effects, the internal harmless pores of the aeolian-sand powder concrete were higher than carbonation + freeze-thaw by 16.85%, higher than those of the ordinary concrete by 15.35%, the multi-harm pores were observed to be less than that of carbonization + freeze-thaw by 22.5%, which is lower than that of ordinary concrete by 22.25%. At the same time, the irreducible fluid saturation and permeability of aeolian sand powder concrete are 0.34 and 1.5% higher than those of ordinary concrete under the action of carbonization and freeze-thaw, thus the deterioration of aeolian sand powder concrete is significantly lower than that of ordinary concrete, while that of aeolian sand powder concrete under the action of carbonization and freeze-thaw is significantly higher.

Key-words : Aeolian-sand powder concrete, Freeze-thaw, Carbonization, Nuclear magnetic resonance, Calcium carbonate, Calcium sulfate, Harmless pores, Multi-harm pores

1. Introduction

In recent years, many research studies have been conducted from the perspectives of waste resource utilization, ecological restoration, and environmental protection. As a result, research achievements have been made in the development of new building materials, such as the applications of recycled aggregate concrete;¹,² durability research for rubber concrete;³,⁴ and the applications of fiber concrete;⁵,⁶ Additionally, a large number of research teams have prepared mortar and concrete with aeolian sand as the raw material, from the perspective of the use and management of desert resources, and relevant performance have been discussed. For example, Li et al.⁷ discussed the design and optimization of aeolian-sand and mortar mix proportions in the Maowusu Desert; Dong et al.⁸ presented the freeze-thaw characteristics of aeolian-sand lightweight aggregate concrete, and created a damage prediction model; Padmakumar et al.⁹ determined the characteristic parameters for aeolian sand in the deserts of India; and Wu et al.¹⁰ studied the deterioration mechanism and durability of aeolian-sand concrete in freeze-thaw and brining coupled environments. Although there have been previous studies completed regarding the development and applications of aeolian sand resources, the majority of the studies have focused on potential applications based on the physical and chemical properties. However, studies regarding the gelation properties of aeolian-sand silicon oxides are still lacking. Therefore, the current data have been insufficient to fundamentally develop the engineering value of aeolian sand, which has
not been beneficial to desert ecological restoration and management. In addition, a growing demand has emerged for high-durability concrete material. Therefore, the durability problems of concrete material have become an important topic for reducing social operating costs, as well as improving resource utilization. Researchers in China and throughout the rest of the world have conducted many practical research studies on this subject. The existing theoretical models and research methods have essentially been focused on the durability qualities of concrete material, such as anti-freezing and anti-carbonization performances in a single environmental condition. However, less research results have been made available which reflect the durability of concrete material in the actual service environments where concrete materials are utilized under composite working conditions. For example, Mamoru Matsumoto et al.\textsuperscript{11} established a transient humid-heat transfer control equation for moisture among solids, liquids, and vapor in a single freeze-thaw environment. Richardson A\textsuperscript{12} studied the effects of the particle sizes of rubber on the anti-freezing performances of concrete in a single freeze-thaw environment, and concluded that rubber powder with a grade of 0.5 mm was the optimal use size. Basyigit C. et al.\textsuperscript{13} discussed the radiation shielding performances of concrete materials under the conditions of a single freeze-thaw cycle. Wang Zhenjun et al.\textsuperscript{14} examined the variation law of the electromagnetic reflectance of carbon fiber cement matrix composites under single freeze-thaw conditions. Shamsad Ahmad et al.\textsuperscript{15} investigated the effects of the pressure and duration of carbonization on the strength of concrete under the conditions of single carbonization. Talukdar S. et al.\textsuperscript{16} established a prediction model of concrete damages based on a single carbonization environment. Chao Jiang et al.\textsuperscript{17} found that in a single carbonization environment, the ratio of the carbonation depth to the square root of the carbonization time also applied to concrete after fatigue damages occurred. All of the aforementioned discussions were focused on the deterioration mechanism and durability of concrete materials in single freeze-thaw or carbonization environments. Therefore, the results did not accurately reflect the actual service conditions of the concrete materials. In addition, some Chinese and international researchers have discussed the durability of concrete materials under complex working conditions. For example, He Z. et al.\textsuperscript{18} studied the deterioration mechanism of concrete materials in carbonization environments after imposing freeze-thaw actions along the 3D and 1D. The results of that study revealed that the freeze-thaw and carbonization coupling effects had more obvious deterioration significance than the single working conditions. However, to date, the deterioration mechanisms of concrete under complex working conditions have not yet been thoroughly studied. In addition, the effects of the order of the composite working conditions on the durability of concrete haven’t already to be considered. These could be quite different from the actual service conditions of the concrete, resulting in a low use value.

Due to the fact that the anti-freezing performances are often important indexes of the durability of the concrete material in cold regions, these performance results were included in the calculation. It is known that carbonization is the ultimately the most common physical and chemical reaction within concrete materials in natural environments. Meanwhile, according to the principles of resource development, environmental protection, and economic accountability, aeolian sand was taken as the raw material to prepare the aeolian-sand powder utilized in this study, rather than cement-based gelled material. At the same time, the deterioration mechanism and durability of the aeolian-sand powder concrete were discussed under two working conditions: freeze-thaw + carbonization, and carbonization + freeze-thaw. The goal was to develop a new type of concrete which would suitable for special environments (such as cold regions) under the premise of aeolian-sand resource development and utilization, ecological restoration and management, and project cost reduction.

2. Experimental testing

2.1 Material used in this study’s testing process

Table 1 details the experimental test results of the raw materials examined in this study. The aeolian sand was collected from the widely distributed aeolian sand in the Kubuqi Desert of Inner Mongolia. The ordinary sand was sourced from the surrounding sand fields of Hohhot. The physical and chemical parameters of the sand types are shown in Table 1(a). A WEM-10 superfine grinding vibromill was used to prepare the aeolian-sand powder. A BT-1800 dynamic image particle analysis system, along with a BT-2002 laser sedimentograph and a RIGKU ZSX Primus II X-ray fluorescence spectrometer were applied to measure the physical and chemical parameters, as shown in Table 1(b). The physical and chemical parameters of the P·O42.5 cement used in this study’s experimental process are listed in Table 1(c), and those of the Coarse aggregate are shown in Table 1(d). The parameters of the secondary fly ash obtained from the Jinqiao Power Plant for the experimental testing are shown in Table 1(e). The experimental admixture was a high-performance water reducing agent from a polycarboxylic acid system of Inner Mongolia Rongshengda New Material Co., Ltd., and its physical and chemical parameters are shown in Table 1(f). Also, the physical and chemical properties of the aeolian-sand powder-cement gel system are shown in Table 1(g). The air entrant was an SJ-3 high-efficiency air entrant, and the test water was ordinary tap water.

2.2 Experimental testing method

In order to ensure that the aeolian-sand powder concrete can achieve good workability for engineering practice, the testing method in this study was conducted in accordance with the \textit{Specification for Hydraulic Concrete Construction} (SL677-2014); \textit{Mix Proportion Design Regulation of Ordinary Concrete} (JGJ55-2011); and the relevant regulations regarding the C25 and C35 concrete proportioning.
Table 1. The test results of aeolian sand powder concrete raw materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Apparent Density /kg·m⁻³</th>
<th>Fineness modulus</th>
<th>Moisture content /%</th>
<th>Bulk density /kg·m⁻³</th>
<th>Sediment percentage /%</th>
<th>Organic matter content /%</th>
<th>Chlorine content /%</th>
<th>Sulfate and sulfide content /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeolian sand powder</td>
<td>2584</td>
<td>0.72</td>
<td>0.3</td>
<td>1579</td>
<td>0.41</td>
<td>Lighter than standard color</td>
<td>0.025</td>
<td>0.37</td>
</tr>
<tr>
<td>Sand</td>
<td>2576</td>
<td>2.91</td>
<td>2.2</td>
<td>1790</td>
<td>3.48</td>
<td>Lighter than standard color</td>
<td>0.29</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Note: D50 indicates that the proportion of particles with diameter of 25.31 μm is 50%, D90 and D98 are the same.

b. Physical and dynamic parameters of experiment Aeolian sand powder

<table>
<thead>
<tr>
<th>Type</th>
<th>Apparent Density /kg·m⁻³</th>
<th>Aspect ratio</th>
<th>Roundness</th>
<th>D50 /μm</th>
<th>D90 /μm</th>
<th>D98 /μm</th>
<th>SiO₂ /%</th>
<th>Al₂O₃ /%</th>
<th>CaO /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeolian sand powder</td>
<td>2640</td>
<td>1.36</td>
<td>0.93</td>
<td>25.31</td>
<td>118.21</td>
<td>216.68</td>
<td>74</td>
<td>9</td>
<td>4</td>
</tr>
</tbody>
</table>

c. Basic performance index of cement

<table>
<thead>
<tr>
<th>Type</th>
<th>Surface area /m²·kg⁻¹</th>
<th>Standard consistency water consumption /%</th>
<th>Density /kg·m⁻³</th>
<th>Standard consistency water consumption /%</th>
<th>Density /kg·m⁻³</th>
<th>Volume stability</th>
<th>Screening residual (80 μm) /%</th>
<th>Needle plate content /%</th>
<th>Crushing value /%</th>
<th>Roundness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>384</td>
<td>27.25</td>
<td>3109</td>
<td>conformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gravel 2669 4.75–20 3 1650 0.37 0 Lighter than standard color 2.8 3.7 5.1

e. Physical and chemical properties of fly ash

<table>
<thead>
<tr>
<th>Type</th>
<th>Ignition loss /%</th>
<th>Surface area /m²·kg⁻¹</th>
<th>Solid content /%</th>
<th>Density /g·cm⁻³</th>
<th>PH</th>
<th>Gas content /%</th>
<th>Water reducing rate /%</th>
<th>Setting time/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash</td>
<td>3.05</td>
<td>354</td>
<td>97.2</td>
<td>2150</td>
<td>9.7</td>
<td>93.3</td>
<td>26</td>
<td>57</td>
</tr>
</tbody>
</table>

f. Indicator list of polycarboxylate superplasticizer

<table>
<thead>
<tr>
<th>Type</th>
<th>Chloride ion content /%</th>
<th>Total alkalinity /%</th>
<th>Solid content /%</th>
<th>Density /g·cm⁻³</th>
<th>PH</th>
<th>Gas content /%</th>
<th>Water reducing rate /%</th>
<th>Setting time/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water reducer</td>
<td>0.42</td>
<td>11.2</td>
<td>40</td>
<td>1.015</td>
<td>6</td>
<td>2.9</td>
<td>26</td>
<td>57</td>
</tr>
</tbody>
</table>

g. Physical and dynamic parameters of experiment cement

<table>
<thead>
<tr>
<th>Type</th>
<th>Apparent Density /kg·m⁻³</th>
<th>Standard consistency water consumption /%</th>
<th>Density /kg·m⁻³</th>
<th>Standard consistency water consumption /%</th>
<th>Density /kg·m⁻³</th>
<th>Volume stability</th>
<th>Screening residual (80 μm) /%</th>
<th>Setting time/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>384</td>
<td>27.25</td>
<td>3109</td>
<td>conformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aeolian sand powder-cement</td>
<td>375</td>
<td>26.5</td>
<td>2970</td>
<td>conformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

design presented in the *ACI Method of Proportioning Concrete Mixes*. The C25 (water/cement ratio of 0.50, sand ratio of 40.0%, and fly ash content of 20%) and C35 (water/cement ratio of 0.40, sand ratio of 35.0%, and fly ash content of 20%) aeolian-sand powder concrete were prepared with aeolian-sand powder to equal-mass replace the cement (15%) and activator (sodium sulfate) content (2.0%) of the mass of aeolian-sand powder. The details of the proportions are shown in Table 2. A LA-0316 direct-reading air entrainment meter for concrete was used to measure the air content. Then, a WHY-3000 press and a WAW-3000 universal testing machine were used to measure the compressive strength and splitting tensile strength of the aeolian-sand powder concrete, respectively. Meanwhile, according to The Test Method and Standard of Long-term Performance and Durability Performance of Ordinary Concrete (GB/T50082-2009); *Hydraulic Concrete Test Procedures* (SL352-2006); and ASTM C 666/C 666M-2003 requirements of Standard Test Method for the hold state of Concrete to Rapid Freezing and Thawing, were used as reference materials. A concrete fast freeze-thaw test meter, along with a carbonization test meter, were used for macroscopic testing. The specifications were as follows:

**Freeze-thaw test**: A TDR-16 concrete fast freeze-thaw test machine was applied. In accordance with the standards, at the completion of the preprocessing of a group of three
100 mm × 100 mm × 400 mm prism specimens, the initial relative dynamic elastic modulus was measured. Meanwhile, \( \varphi 50 \times H50 \text{mm} \) core samples were collected for the accompanying test with a pretreatment process consistent with the prism specimens, in which 25 freeze-thaw cycles were taken as a test cycle. When the relative dynamic elastic modulus decreased to 60% of the initial value, the test was stopped. Subsequently, a nuclear magnetic resonance (NMR) test was conducted on the core samples of the accompanying test at the completion of each test cycle.

**Carbonization test:** In accordance with the standards, a group of three 100 mm × 100 mm × 400 mm prism specimens were preprocessed. At the completion of the preprocessing, the specimens were placed into a carbonization test chamber. Meanwhile, \( \varphi 50 \times H50 \text{mm} \) core samples were collected for the accompanying test with a pretreatment process consistent with prism specimens, in which three days was set as the carbonization cycle. In the meantime, an LR-1 cutting machine was used to harvest 100 mm × 100 mm × 100 mm cube specimens, which was followed by the determination of the carbonization until an average carbonization depth \( d_i \) was reached at each stage. At the completion of each test cycle, a NMR test was conducted on the core samples of the accompanying test.

**Working condition 1:** Freeze-thaw + carbonization test (freeze and thaw plus carbonization, F-C)

First, the prism specimens and core samples of the aeolian-sand powder concrete C25 and C35 were selected for the freeze-thaw tests (25 times), which were alternately followed by the carbonization tests (3-day), and two major cycles were completed. At the completion of each individual test project, both the relative dynamic elastic modulus and carbonization depth of the prism specimens were measured for a NMR analysis of the core samples. After two cycles, the cement paste was taken at depths of 0–5 mm, 5–10 mm and 10–15 mm to stop hydration with ethanol and analyzed by field emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD).

**Working condition 2:** Carbonization + freeze-thaw test (carbonization plus freeze and thaw, C-F)

The prism specimens and core samples of the aeolian-sand powder concrete C25 and C35 were first selected for the carbonization test (3-day). This was alternately followed by freeze-thaw tests (25 times), and two major cycles were completed. At the completion of each individual test, both the relative dynamic elastic modulus and carbonization depths of the prism specimens were measured for a NMR analysis of the core samples, in order to study the total-process porosity change rules of the aeolian-sand powder concrete under the conditions of the carbonization + freeze-thaw effects. After two cycles, the cement paste was taken at depths of 0–5 mm, 5–10 mm and 10–15 mm to stop hydration with ethanol and analyzed by FESEM and XRD.

### 2.3 Test instrument

**NMR:** The pore characteristics of concrete were measured by MesoMR NMR analysis system. During the testing process, the H proton resonance frequency was 23.320 MHz, the magnet strength was 0.55 T, and the temperature of the magnet was 32°C.

**FESEM:** Sigma 5000 FESEM with resolution of 0.8 mm, \( @15 \text{kV}, 16 \text{nm, amplification factor of } 1000000 \times \), acceleration voltage of 0.02–30 kV, probe current of 4 pA–20 nA, low vacuum range of 2–133 Pa.

**XRD:** Ultima IV X-ray diffractometer of Nippon Science Company was used to measure the XRD under the following conditions: CuKa, rated power 3 KW, tube pressure 40 kV, 1 KV/step, tube current 40 mA, 1 mA/step, scanning speed \( 4°/\text{min} \), scanning range (2θ) 5–90°, stability: \( \pm 0.01\% \).

### 3. Results and analyses

#### 3.1 Analysis of the results of the mechanical performance tests

The mechanical performance test results for the aeolian-sand powder concrete are shown in Fig. 1. It was determined that the mechanical performance of the aeolian-sand powder concrete satisfied the requirements of the standards. The splitting tensile strengths of the C25 and C35 groups of aeolian-sand powder concrete had increased by 40.0 and 33.6%, respectively, over the standards. These results were mainly due to the unique hydration mechanism of the aeolian-sand powder concrete, which led to the generation of ettringite and other hydration products. This resulted in improvements to the bond effects of cement paste and aggregate, as well as reductions in the porosity to a certain extent, and upgrading of the mechanical properties of the interface transition zone. Additionally, since the C25 and C35 groups of the aeolian-sand powder concrete were able to satisfy the requirements of the macro mechanical properties (the C35 group was found to be superior to the C25 group in this regard), in
the follow-up analysis, the C25 group of the aeolian-sand powder concrete was taken as a case for further analysis.

3.2 Analysis of the freeze-thaw and carbonization test results

3.2.1 Change rules and the mechanism analysis of the relative dynamic elastic modulus

The change rules of the relative dynamic elastic modulus and carbonization depths of the aeolian-sand powder concrete under the actions of the freeze-thaw and carbonization are shown in Fig. 2. As can be seen in Figs. 2(a) and 2(b), the relative dynamic elastic modulus of the aeolian-sand powder concrete had a lower declining trend than the ordinary concrete, and the decrease of freeze-thaw + carbonization is lower than that of carbonization + freeze-thaw. Furthermore, for the cases under the actions of the freeze-thaw and carbonization, lower declining trends than those under the actions of the carbonization and freeze-thaw were observed. When two cycles were completed under the actions of the carbonization and freeze-thaw, the relative dynamic elastic modulus of the C25 group of the aeolian-sand powder concrete was determined to be 59.6%, which was less than that under the action of the freeze-thaw + carbonization by 1.5 times. Meanwhile, under the actions of the freeze-thaw + carbonization, the relative dynamic elastic modulus first decreased, followed by a increasing trend, and then declined until damages occurred, but the relative dynamic elastic modulus of carbonization + freeze-thaw increases first, then decreases, and then decreases to failure.

These results were due to the fact that Carbonation makes the relative dynamic elastic modulus of aeolian sand concrete increase, freeze-thaw makes it lower. The freezing generally occurred in the outermost concrete layers, and only when the temperature fell further did the freezing extend to the internal layers. The internal frost heave led to pore development, and the surface cracks were also further expanded. Carbonization is a complex process of physical and chemical changes, in which carbon dioxide enters inside the concrete through the internal complex pore system of concrete under the action of a concentration gradient, and then reacts with alkali carbide causing carbonization generated calcium carbonate. It was determined that the calcium carbonate led to a 11% volume expansion in the concrete.21,22) Under the actions of the freeze-thaw + carbonation, the initial frost heave effects resulted in increased porosity, as well as the reduction of the relative dynamic elastic modulus. Then, the swelling of calcium carbonate generated by following carbonization was able to reduce the porosity, refine the pore structures, and increase the relative dynamic elastic modulus. As the experimental testing progressed, the pore structures became increasingly damaged due to the internal frost heave of the aeolian-sand powder concrete and the swelling of calcium carbonate crystallization. Also, the surface cracks were further expanded with the gradual decrease of the relative dynamic elastic modulus. Under the actions of the carbonization + freeze-thaw, the initial carbonization was able to reduce the porosity and increase relative dynamic elastic modulus. Then, the frost heave effects led to increases in the porosity, and the relatively dynamic elastic modulus became reduced until damages occurred.

3.2.2 Change rules and mechanism analysis of the carbonization depths

Figures 2(c) and 2(d) illustrate that the carbonization depths of the aeolian-sand powder concrete increased with cycle increases under the actions of the freeze-thaw + carbonization. The C25 group of the aeolian-sand powder concrete under the actions of carbonization + freeze-thaw
displayed higher carbonization depths than that under the actions of the freeze-thaw + carbonization by 5.0%. Meanwhile, the C25 group of the ordinary concrete under the actions of the carbonization + freeze-thaw had higher carbonization depths than that under the actions of freeze-thaw + carbonization (by 2 times).

These results were due to the fact that the aeolian-sand powder concrete had a somewhat different carbonization mechanism from the ordinary concrete. During carbonization, the ordinary concrete had mainly reacted with carbon dioxide due to the calcium hydroxide and hydrated calcium silicate and had then produced calcium carbonate, which was consistent with the results of previous related studies.\textsuperscript{23–25} However, the swelling properties of the calcium carbonate underwent more stress during the subsequent freeze-thaw actions, which created more pore channels for the subsequent carbonization process. However, for the aeolian-sand powder concrete, a process of calcium hydroxide, hydrated calcium silicate, and ettringite had reacted with carbon dioxide. Following the decalcification, the ettringite released sulfuric acid root ions, and after carbonization, the average pH values had decreased from 12 or 14, to 8 or 9.\textsuperscript{26} The sulfuric acid root ions reacted with the carbide product in the alkaline environment following the carbonization and calcium sulphate had been generated. This prevented further carbonization. The reduction of the calcium carbonate in the swelling carbide products led to declining stresses during the subsequent

![Fig. 2. Experimental results of macroscopic performance of aeolian sand powder concrete under freezing thawing and carbonization coupling environment.](image-url)
freeze-thaw actions, which were insufficient to destroy the pore structures. At the same time, when freeze-thaw + carbonization occurs, the initial frost heave is insufficient to destroy the internal pore structure and promote the pore development during subsequent carbonization, thus the carbonization depth of ordinary concrete under the action of carbonization + freeze-thaw is twice as high as that under the action of freeze-thaw + carbonization, while that of aeolian sand powder concrete is only 5%.

Note: The initial state (I) indicates the initial state of the concrete without external actions; C denotes the carbonization; C1 and C2 indicate the first and second carbonization cycles, respectively; F represents the freeze-thaw; and F1 and F2 indicate the first and second freeze-thaw cycles, respectively.

3.3 FESEM, and the analysis of the XRD test results

The FESEM and XRD test results for the aeolian-sand powder concrete under the actions of the freeze-thaw + carbonization are shown in Figs. 3 and 4, respectively. Relative to the baseline groups 3a and 3b, the prismatic or rhombic products were found in the ordinary concrete within the ranges of 0 to 5 mm, 5 to 10 mm, and 10 to 15 mm following the actions of the freeze-thaw + carbonization. Then, when combined with the XRD analysis, it

![Figure 3](image-url)

**Fig. 3.** Electron microscope test results of aeolian sand powder concrete before and after freezing thawing-carbonization.
was determined that the product was calcium carbonate crystal ($2\theta \approx 29.6^\circ$), and also ammonium gypsum had been found in the range of 5 to 10 mm. In the aeolian-sand powder concrete within the range of 0 to 5 mm, the clustered-column calcium carbonate crystal was observed to be aggregated into a prism-shape, and fibrous products were also found in the range of 5 to 10 mm. When combined with the XRD analysis, it was determined that the product was gypsum, and fiber meshed calcium sulphate ($2\theta \approx 27.9^\circ$) was also densely distributed in the range of 10 to 15 mm.

The FESEM and XRD phase test results of the aeolian-sand powder concrete under the actions of the carbonization + freeze-thaw are shown in Figs. 5 and 6. Relative to the baseline groups 3a and 3b, clustered calcium carbonate crystals were found in the ordinary concrete within the ranges of 0 to 5 mm, and prism calcium carbonate crystal and hexagonal-tabular potassium alum ($2\theta \approx 24.6^\circ$) were observed in the range of 5 to 10 mm. Furthermore, prism calcium carbonate crystal was locally found as a cobweb-like product in the range of 10 to 15 mm. When combined with the XRD analysis, it was determined that the product was ettringite ($2\theta \approx 9.3^\circ$).

Following the actions of the carbonization + freeze-thaw, leaf-shaped calcium hydroxide ($2\theta \approx 36.6^\circ$) and rhombic calcium carbonate were observed in aeolian-sand powder concrete within the range of 5 to 10 mm. Also, prismatic calcium carbonate crystal was found in the range of 5 to 10 mm, and needle bar ettringite was located in the range of 10 to 15 mm.
Since the aeolian-sand powder concrete differed from the ordinary concrete in regard to its carbonization mechanism, the carbide products of the ordinary concrete under the environment of freeze-thaw, carbonization were observed to be dominated by calcium carbonate, as shown in Eq. (1), and more carbide products existed along the direction of the carbonization depth. However, the carbide products of the aeolian-sand powder concrete were found to be dominated by calcium carbonate and calcium sulfate, as shown in Eq. (2), while the carbide products were observed to be gradually reduced along the direction of the carbonization depth. Within the range of 10 to 15 mm, a mixed zone existed between the calcium carbonate as a variable material of carbide product, and the ettringite without carbonization. The less expansive products such as calcium carbonate, the smaller the expansive pressure on the internal pore structure of aeolian sand powder concrete, the higher the integrity of pore structure, and the better the durability. These results further emphasized the fact that the deterioration significance of the aeolian-sand powder concrete in the freeze-thaw, carbonization environment was lower than that of the ordinary concrete.

\[
\text{CO}_2 + \text{Ca(OH)}_2 = \text{CaCO}_3 \downarrow + \text{H}_2\text{O} \quad (1)
\]

\[
\text{CaCO}_3 + \text{H}_2\text{SO}_4 = \text{CaSO}_4 + \text{CO}_2 \uparrow + \text{H}_2\text{O} \quad (2)
\]

3.4 Analysis of the NMR test results

The pore structures of concrete have crucial influences on the resistance to the coupling effects of freeze-thaw + carbonization. In order to gain a more intuitive understanding of the changes in the internal pore structures of the aeolian-sand powder concrete under the effects of the freeze-thaw + carbonization environment, NMR technology was used in this study to test the pore characteristics of the aeolian-sand powder concrete. The test results are shown in Figs. 7 and 8. According to the principle of NMR, the relationship between pore radius and pore size distribution, \(T_2\) relaxation time and total signal volume of aeolian sand powder concrete specimens, and the pore characteristic parameter diagram of aeolian sand powder concrete under freeze-thaw, carbonation environment are obtained.

In concrete, the smaller the pore size is, the shorter the \(T_2\) relaxation time will be. Also, the larger the pore size, the smaller the constraint degree of the porous water, and the longer the \(T_2\) relaxation time. As detailed in Figs. 7(a), 7(b), 8(a), and 8(b), the \(T_2\) map of the aeolian-sand powder concrete was distributed in the range of 0.01 to 10,000 ms, which corresponded to the three peaks of the micro, meso, and macro pores. During the process of the freeze-thaw + carbonization, the \(T_2\) map of the C25-0 group of the ordinary concrete at the completion of the final carbonization showed that the peak proportions of the micro and macro pores were 28.63 and 71.37\%, respectively, and the peak of middle aperture disappeared. Those of the C25-15 group of the aeolian-sand powder concrete were determined to be 50.27 and 40.45\%, respectively. It was determined that after the freeze-thaw + carbonization, the proportions of the internal micro and macro pores in the aeolian-sand powder concrete were higher than those of the ordinary concrete by 21.64 and 70.92\%, respectively. During the process of the carbonization + freeze-thaw, the \(T_2\) map of the C25-0 group of the ordinary concrete at the completion of last freeze-thaw cycle showed peak proportions of micro and macro pores measuring 29.49 and 11.85\%, respectively, and those of the C25-15 group of the aeolian-sand powder concrete were determined to be 17.99 and 9.18\%, respectively. It was observed in this study that following the carbonization + freeze-thaw, the proportions of the internal micro and macro pores in the aeolian-sand powder concrete were lower than those of the ordinary concrete by 11.5 and 2.67\%, respectively.

Academician Wu et al. divided the internal pores of concrete according to pore sizes into harmless (<20 nm); less harmful (20 to 50 nm); harmful (50 to 200 nm); and multi-harm pores (>200 nm), which was of great significance to a deeper examination of the internal pore structural changes of concrete. As can be seen in the distribution maps of the harmless and multi-harm pores in the aeolian-sand powder concrete [Figs. 7(c) and 8(c)], under the actions of the freeze-thaw + carbonization, along with the testing process, the internal harmless pores in the C25-0 and C25-15 groups of the ordinary concrete showed a change rule of first increasing and then decreasing, while...
The multi-harm pores showed a change rule of first decreasing and then increasing. At the end of the final carbonization cycle, in the C25-15 group of the aeolian-sand powder concrete, the proportions of the harmless and multi-harm pores were 22.06 and 44.53%, respectively. In the C25-0 group of the ordinary concrete, the proportions of the harmless and multi-harm pores were determined to be 6.71 and 66.78%, respectively. Therefore, it was...
Fig. 8. NMR test results of aeolian sand powder concrete after Carbonization and Freeze-thaw.

Note: I, Initial state, indicating no freeze-thaw or carbonization test; F1, Indicates the first freeze-thaw action; C2, Indicates the second dry and wet action.

C1, Indicates the first dry and wet action; F2, Indicates the second freeze-thaw action.

Fig. 8. NMR test results of aeolian sand powder concrete after Carbonization and Freeze-thaw.
confirmed that following the freeze-thaw + carbonization, the internal harmless pores of the aeolian-sand powder concrete were higher than those of the ordinary concrete by 15.35%. Meanwhile, the multi-harm pores of the aeolian-sand powder concrete were lower than those of the ordinary concrete by 22.5%, and presented a significant durability performance. Under the actions of the carbonization + freeze-thaw, the internal harmless pores in the C25-0 group of the ordinary concrete and the C25-15 group of the aeolian-sand powder concrete both displayed the change rule of an increase/decrease/increase/decrease. The multi-harm pores of the ordinary concrete showed a change rule of a decrease/increase/decrease/increase, while that of the aeolian-sand powder concrete displayed a change rule of a decrease/increase/increase/increase. At the end of the last freeze-thaw cycle, the proportions of the harmless and multi-harm pores in the ordinary concrete were 5.26 and 89.53%, respectively, and those in the aeolian-sand powder concrete were determined to be 5.21 and 67.03%, respectively. Therefore, it was confirmed that under the actions of the carbonization + freeze-thaw, the internal harmless pores of the aeolian-sand powder concrete were lower than those of the ordinary concrete by 0.5%, while the multi-harm pores of the aeolian-sand powder concrete were higher than those of the ordinary concrete by 22.5%. Moreover, harmless pores were lower than freeze-thaw + carbonization by 16.85%, and the multiple damage holes were higher than freeze-thaw + carbonization by 22.5%.

In concrete, the higher the bound fluid saturation, the smaller the porosity was, lower the permeability would be, and the better the durability of the concrete would be. As can be viewed from the pore characteristic maps of the aeolian-sand powder concrete detailed in Figs. 7(c) and 8(c), under the actions of the freeze-thaw + carbonization, the bound fluid saturation in the C25-0 group of the ordinary concrete showed a change rule of an increase/decrease/increase/decrease. Meanwhile, the porosity showed a change rule of an increase/increase/increase/increase. The bound fluid saturation in the C25-15 group of the aeolian-sand powder concrete displayed a change rule of an increase/increase/increase/decrease, while the porosity showed a change rule of an increase/decrease/increase/decrease. These results were due to the combined actions of the frost heave stress, and the calcium carbonate swelling properties. Since the aeolian-sand powder concrete had a different carbonization mechanism from the ordinary concrete, the generated swelling carbide products were reduced, and both types of concrete showed completely different laws and patterns. Under the coupling effects of the freeze-thaw + carbonization, the aeolian-sand powder concrete mainly underwent frost heave stress, while the ordinary concrete was subject to the combined actions of the frost heave and calcium carbonate swelling stresses, and presented a large change range of porosity. At the end of the last carbonization cycle, the porosity of the aeolian-sand powder concrete was observed to be lower than that of the ordinary concrete by 3.13%, and its bound fluid saturation was higher than that of the ordinary concrete by 21.86%. In the meantime, the permeability of the C25-0 group of the ordinary concrete had gradually increased, while that of the C25-15 group of the aeolian-sand powder concrete presented a certain fluctuation. At the end of the final carbonization cycle, the permeability of the aeolian-sand powder concrete was 374.645 mD, which was far below that of the ordinary concrete at 18,689.97 mD by nearly 50 times. During the action process of the carbonization + freeze-thaw, the aeolian-sand powder concrete basically maintained the same change rules of the bound fluid saturation, permeability, and porosity as the ordinary concrete. At the end of the last freeze-thaw action cycle, the bound fluid saturation of the aeolian-sand powder concrete was observed to be higher than that of the ordinary concrete by 0.34%. In addition, its porosity was higher by 0.63%, and its permeability was 1.5% higher, which could almost be neglected.

In summary, in this study it was elucidated that the deterioration significance of the aeolian-sand powder concrete was lower than that of the ordinary concrete, and the deterioration significance of the aeolian-sand powder concrete under the actions of the freeze-thaw + carbonization was lower than that under the actions of the carbonization + freeze-thaw.

4. Conclusions

(1) Under the action of freeze-thaw and carbonization, the relative dynamic elastic modulus of aeolian sand powder concrete decreases was less than that of ordinary concrete. Through comparing the coupled actions of the freeze-thaw + carbonization and carbonization + freeze-thaw, it was found that the relative dynamic elastic modulus of the aeolian-sand powder concrete under the actions of the freeze-thaw + carbonization was higher than that under the actions of the carbonization + freeze-thaw by 1.5 times. Meanwhile, the carbonization depths of the aeolian-sand powder concrete under the actions of the freeze-thaw + carbonization were observed to be higher than those under the actions of the carbonization + freeze-thaw by 5.0%.

(2) The freeze-thaw actions produce frost heave stress, along with damages to the internal pore structures of aeolian-sand powder concrete. The actions also tend to promote pore development and increase porosity. Carbonization leads to the formation of calcium carbonate, refined pore structures, and reduced porosity. Meanwhile, the results of related studies have indicated that aeolian-sand powder concrete has a different carbonization mechanism from that of ordinary concrete. The carbonization of ordinary concrete results in the formation of calcium carbonate, while that of aeolian-sand powder concrete tend to lead to the generation of calcium sulfate and calcium carbonate.

(3) The results of this study revealed the pore structure change rules of the aeolian-sand powder concrete under the actions of the freeze-thaw, carbonation. Also, under the actions of the freeze-thaw + carbonation, the bound
fluid saturation of the aeolian-sand powder concrete was higher than that of the ordinary concrete by 21.86\% and its permeability was observed to be 50 times lower than that of ordinary concrete. Furthermore, its porosity was lower than that of the ordinary concrete by 3.06\%, its harmless pores were greater in number than those of the ordinary concrete by 15.35\%, and its multi-harm pores were fewer than those of the ordinary concrete by 22.25\%. Meanwhile, the harmless pore was higher than that of carbonization + freeze-thaw, by 16.85\%, and the damage hole was less than that of carbonation + freeze-thaw, by 22.5%. Under the actions of the carbonation + freeze-thaw, the irreducible fluid saturation and permeability of aeolian sand powder concrete were 0.34 and 1.5\% higher than those of ordinary concrete. Consequently, the deterioration of aeolian sand powder concrete was shown to be significantly lower than that of ordinary concrete, while the deterioration of aeolian sand powder concrete under the action of carbonization + freeze-thaw was significantly higher.

Acknowledgement This study was funded by National Natural Science Foundation Grant Project (51569021, 51769025).

Conflict of Interest Both Xiangdong Shen and Genfeng Li declare that we have no conflict of interest with any of the journal editors, reviewers and any person who may affect the review of the paper.

Reference