Experimental Study on the Durability of Alkali-Activated Slag Concrete after Freeze-Thaw Cycle

Bin Chen and Jun Wang

College of Civil Engineering, Northeast Forestry University, Harbin 150040, China

Correspondence should be addressed to Jun Wang; jun.w.619@nefu.edu.cn

Received 24 March 2021; Accepted 3 July 2021; Published 12 July 2021

Copyright © 2021 Bin Chen and Jun Wang. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A freeze-thaw resistance is an important indicator of the durability of alkali-activated slag concrete, which causes structural failure when the performance is low, especially in severely cold areas. In this study, solid sodium aluminate and sodium silicate were used as composite alkaline activators, while slag was used as the raw material to prepare alkali-activated slag concrete, whose freeze-thaw resistance, as well as that of ordinary cement concrete, was experimentally studied by varying the freeze-thaw cycles. The effects of the mass, compressive strength, and dynamic elastic modulus of the sample were investigated by considering the influence of different water-to-slag ratios and slag contents, while the damage variables and model were also analyzed. The results showed that alkali-activated slag concrete had an excellent freeze-thaw resistance, which was significantly affected by the water-to-slag ratio and compressive strength; specifically, the higher the water-to-slag ratio, the lower the freeze-thaw resistance, and the higher the compressive strength, the better the freeze-thaw resistance. The freeze-thaw durability, microstructure, and damage mechanism were studied via microscopic analysis. When analyzed via the microstructure test, crack pores and microcracks with narrow spaces and large surface areas were generated under freeze-thaw damage conditions, but the dense hydration structure and high-bonding-strength hydration products led to a better freeze-thaw resistance. The damage model was established using compressive strength and relative dynamic elastic modulus as damage variables, and the attenuation exponential and accumulative damage power function model had a high accuracy, which could better reflect the freeze-thaw damage law and damage degree and predict the lifetime of alkali-activated slag concrete.

1. Introduction

Cement and concrete have been widely used in construction and civil engineering for over a century, while the production of cement entails several challenges that are environmentally detrimental, such as intensive carbon dioxide emissions and high energy consumption [1, 2]. These environmental problems have become more prominent with societal development, and more attention has been paid to alkali-activated slag and alkali-activated slag concrete (AASC) as new green materials [3, 4]. The alkali-activated slag gel material consumes less energy and emits less carbon dioxide than cement in terms of production [5–8]. Furthermore, the alkali-activated slag gel material provides a feasible approach toward recycling industrial solid waste because slag is an industrial by-product, and the annual output has increased with continuous industrial development [9, 10].

Currently, the basic properties of AASC have been widely reported, and some studies have focused on frost resistance [11, 12], while research on the relationship between the microstructure and frost resistance of AASC is lacking, and studies on freeze-thaw damage laws and models are rare. Concrete freeze-thaw damage entails a phenomenon whereby concrete is peeled off from the surface, such that the structure becomes loose, and the strength is reduced until the structure is destroyed under alternating positive and negative temperature cycles. All concrete structures in severely cold areas suffer from various degrees of freeze-thaw damage, which indicates the main factor of concrete...
structure deterioration in severely cold areas. Krivenko [13] studied the influence of different liquid alkalis activated on the freeze-thaw resistance of AASC and found that AASC with any activated liquid alkali could withstand 300–1300 freeze-thaw cycles, while ordinary cement concrete (OCC) could only withstand less than 300 cycles. Cai et al. [14] used response surface methodology and concluded that the water-to-slag ratio and sand content influenced AASC frost resistance. Fu et al. [15] reported that AASC had a better freeze-thaw resistance and built the AASC dynamic elastic modulus attenuation model; however, the influence of the loss of compressive strength was not considered. Most research results showed that AASC had evident advantages in frost resistance compared with OCC, but there were also different research conclusions. Bilek et al. [16] reported that because AASC had higher free water, which was available for freezing, their freeze-thaw resistance was lower than that of OCC.

Although previous studies on the freeze-thaw properties of AASC achieved some groundbreaking accomplishments, the conclusions were haphazard and several aspects could be improved upon. On the one hand, the existing research on AASC mostly adopts the steam curing method, which has a certain effect on improving the resistance of AASC to freeze-thaw damage, but it is inapplicable to all situations, except for prefabricated components, which presents a concern that needs to be considered to facilitate the wide use of AASC. On the other hand, research on freeze-thaw damage has been mostly focused on the state of instantaneous destruction; however, the destruction of materials is not a “start point to end point” type of damage, and it is more important to study the effect of changes in the material microstructures on the external macroscopic performance (damage theory). Furthermore, most of the previous studies used liquid alkaline activators to obtain the best mechanical properties of AASC, but the corrosive damage caused by the alkaline liquid in the preparation and curing process is also a problem that needs to be considered. Previous studies used a set of composite solid alkaline activators, which had been confirmed to present better mechanical properties at room temperature curing times but did not achieve the research objectives in terms of durability to reduce the corrosive damage generated during the preparation and curing processes.

In this study, the effects of different slag contents and water-to-slag ratios on the freezing resistance properties of AASC were studied. Systematic research on the freeze-thaw durability, microstructure, and damage mechanism of AASC was conducted via microscopic analysis methods, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and nitrogen adsorption. Additionally, the importance of the damage theory regarding freeze-thaw damage was considered, and combined with mathematical simulation, AASC freeze-thaw damage models were established, which provided basic data for the prediction of AASC freeze-thaw damage in severely cold regions.

2. Test Overview

2.1. Test Material. The slag used was obtained from the granulated blast furnace, and it satisfied the S95 level in the GB/T-18046 standard [17]. The specific surface area and density of the slag are 408 m²/kg and 2.92 g/cm³, respectively, while its chemical compositions are presented in Table 1. The alkaline activator was a mixture of solid sodium silicate and solid sodium aluminate. The solid sodium silicate was Na₂SiO₃·9H₂O (the ratio of Na₂O and SiO₂ content was 1.03 ± 0.03), and the solid sodium aluminate was of analytical grade. The sand used had an apparent density of 2620 kg/m³, bulk density of 1506 kg/m³, mud content (by mass) of 0.5%, and mud block content (by mass) of 0.2%, whereas the coarse aggregate had a continuous gradation of 5–20 mm, maximum particle size of 20 mm, apparent density of 2600 kg/m³, bulk density of 1600 kg/m³, mud content (by mass) of 0.4%, and mud block content (by mass) of 0.2%. The cement control group used was a PO level 42.5 cement.

2.2. Mix Proportion and Sample Production. To investigate the effect of different slag contents and water-to-slag ratios on the properties of AASC after various freeze-thaw cycles, we designed a test using four different slag contents and three different water-to-slag ratios in this study, and the target number of the freeze-thaw cycles was 300. Meanwhile, to compare the difference between the freeze-thaw resistance of AASC and OCC, a control group — OCC-1 — was set. The mass of alkali activator is calculated according to the mass of Na₂O in the alkali activator and based on the Na₂O content of 5% of the slag to obtain the mass of alkali activator. The sodium silicate and sodium aluminate are calculated according to the Na₂O content of 4 : 1. The mix proportions of AASC and OCC after 28 d of compressive strength application are presented in Table 2, and the compressive strength results correspond to the average of three specimens.

The production process of AASC entailed the following: first, the slag and the activated composite solid alkali were mixed and stirred for 2 min and placed as a powder gel material for retention. Thereafter, the weighed sand and coarse aggregate were placed into a 60 L forced mixer, dry-mixed for 2 min, put in the premixed powder gel material, with dry mixing being continued for 2 min, poured into water, and stirred for 3 min, and finally the mixture was poured into the corresponding mold. Next, the mixture was vibrated for 90 s on a standard vibrating table (vibration frequency of 50 ± 2 Hz). After the vibration process was completed, the surface paste was wiped off, wrapped with plastic to prevent evaporation, and cured in a curing room (temperature 20 ± 2°C, relative humidity > 95%). After curing for 2 d, the mixture was demolded, wrapped with plastic, and placed in a curing room until the test age. The control group preparation and curing process of the OCC were the same as those of the AASC. Each code of the mix proportion
of the AASC was used to prepare 21 samples with dimensions of 100 mm × 100 mm × 100 mm to measure the 28 d compressive strength every 50th freeze-thaw cycle. Each code of the mix proportion of the AASC was used to prepare three samples with dimensions of 100 mm × 100 mm × 400 mm to measure the quality and transverse fundamental frequency every 25th freeze-thaw cycle. The corresponding dynamic elastic modulus could be obtained by measuring the transverse fundamental frequency, and the loss of the dynamic elastic modulus could be obtained by measuring the transverse fundamental frequency of the prismsample wasmeasuredevery25thfreeze-thawcycle. The corresponding dynamic elastic modulus could reflect the internal damage of the AASC under the freeze-thaw cycle to evaluate the freeze-thaw damage.

### Table 1: Chemical composition of slag (%).

| Material | CaO | SiO₂ | MgO | Al₂O₃ | MnO | TiO₂ | SO₃ | FeO |
|----------|-----|------|-----|-------|-----|------|-----|-----|
| Slag     | 40.91 | 32.82 | 7.87 | 14.93 | 0.48 | 0.92 | 0.91 | 1.16 |

2.3. **Test Methods.** According to the GB/T 50081 standard [18], the sample cube compressive strength was tested in the YEW-2000B universal testing machine, and the loading speed ranged from 0.5 to 0.8 MPa, while the mean value of three samples in each group was recorded as the representative cube compressive strength value.

The freeze-thaw cycle test was performed using the BC-10 freeze-thaw test box, and the transverse fundamental frequency and dynamic elastic modulus were measured using a DT–20 dynamic bomb instrument, while the quality value was measured using an electronic scale with an accuracy of 0.001 kg, which was based on the GB/T 50082 standard [19]. The mass and transverse fundamental frequency of the prism sample was measured every 25th freeze-thaw cycle, with a cycle target of 300. The quality value is the mean value of the three quality samples in each group. The dynamic elastic modulus and relative dynamic elastic modulus values were the mean values of the three samples in each group. According to the standard, the test should be terminated if the following two situations occur: the sample mass loss rate reaches 5% or the relative dynamic elastic modulus drops to 60%

To observe the influence of freeze-thaw cycles on AASC, the microstructure, hydration product, and pore structure were analyzed via SEM/EDS (Hitachi S-4800, Japan) and a nitrogen adsorption apparatus (Micromeritics ASAP 2020 instrument, the United States). The broken specimen of the gel materials in the middle of the cross-section of the AASC sample was selected as the test specimen, and it was placed in absolute ethanol for 24 h to stop the hydration reaction; it was thereafter oven-dried at 60°C to a constant weight.

### 3. Experimental Phenomena

3.1. **Surface Morphology of the Prism Sample after the Freeze-Thaw Cycle.** Regarding the surface morphology after different freeze-thaw cycles, AASC exhibited minor changes, while OCC showed a large change. Here, AASC-1 and OCC-1 were used to analyze the surface morphology of the samples after the freeze-thaw cycle. Figures 1 and 2 show the surface morphological changes of AASC-1 and OCC-1 after the freeze-thaw cycle.

The surface morphologies of AASC-1 and OCC-1 were smooth and flat, and the gel materials were densely packed before the freeze-thaw cycle; after 50 cycles, there was no evident change in AASC-1, and the gel materials on the surface of the OCC-1 began to fall off; after 100 freeze-thaw cycles, small parts of the gel materials on the AASC-1 surface began to fall off, and small holes appeared, while a certain amount of gel materials on the OCC-1 surface fell off, and small holes appeared; after 150 freeze-thaw cycles, the gel materials on the AASC-1 and OCC-1 surface continually fell off, and the amount of OCC-1 was significantly greater than that of AASC-1; after 200 freeze-thaw cycles, dense holes appeared on the surface of the AASC-1, and OCC-1 gel materials had large parts dropped, while the fine aggregates were peeled off with a small amount of coarse aggregates exposed; after 250 freeze-thaw cycles, the AASC-1 surface roughening was more intense and some fine aggregates fell off, while numerous coarse bones were apparent on OCC-1; after 300 freeze-thaw cycles, a small amount of coarse aggregates could be seen on the AASC-1, and the gel materials and aggregates were relatively tight. Notably, the OCC-1 coarse aggregates leaked critically, and large voids and pits began to appear. Moreover, the OCC-1 surface gel materials were more severely peeled than those of the AASC-1 sample. The surface gel materials were slacking, and a considerable amount of powder was removable by light touch.

The basic macroscopic damage law of AASC entails the following: First, microcracks appear on the surface layer, whereafter the gel materials on the surface are peeled off; afterward, the surface layer of the aggregate and mortar is separated and the coarse aggregate is exposed. Thereafter, fine cracks are generated in the gel materials, and finally the interface between the gel material and aggregate develops. From the overall observation of the test, the damage of the AASC prism sample surface morphology was less than that of the OCC for the same number of freeze-thaw cycles.

3.2. **Compressive Damage Morphology of the Cube Sample after the Freeze-Thaw Cycle.** Upon studying the compressive damage morphology of the AASC and OCC sample cubes after freeze-thaw cycles, we discovered that no cracks appeared on the surface of the samples at the early loading stage. The internal stress of the sample gradually increased with the load, and initial vertical cracks perpendicular to the loading surface appeared. Thereafter, the cracks continued to extend until they were formed from the top to the bottom. Owing to the constraints of the upper and lower platen devices, the cracks grew inward. Accompanied by large cracking noise, the concrete outer layer began to bulge and flake, and the final damage mode was a four-sided pyramidal destruction, which was basically the same as that of the AASC and OCC cube samples.

The compressive damage interface of OCC after the freeze-thaw cycle was analyzed, and it was established that the damage interface of the samples before the freeze-thaw cycle had a relatively flat form, while some coarse aggregates

| Material | CaO | SiO₂ | MgO | Al₂O₃ | MnO | TiO₂ | SO₃ | FeO |
|----------|-----|------|-----|-------|-----|------|-----|-----|
| Slag     | 40.91 | 32.82 | 7.87 | 14.93 | 0.48 | 0.92 | 0.91 | 1.16 |
were split; after 50 freeze-thaw cycles, small cracks appeared between the coarse aggregates and cement mortar, and the damage interface became rather rough; after 100 freeze-thaw cycles, a small number of coarse aggregates were split; after 150 freeze-thaw cycles, large cracks appeared between the coarse aggregates and cement mortar; after 200 freeze-thaw cycles, virtually no coarse aggregates were split; and after 250 and 300 freeze-thaw cycles, the damage interface was characterized as the separation of large pieces of cement mortar and coarse aggregates. It could be seen that the freeze-thaw cycle had serious impacts on the internal structure of OCC, which destroyed the bonding performance of the coarse aggregates and cement mortar.

The AASC compressive damage interface after the freeze-thaw cycle was analyzed, and it was determined that the damage before the freeze-thaw cycle and after 50 cycles mainly involved the following: the gels shed and the cross-section of the outer drum was flat and the coarse aggregates were split, while the bonding between the coarse aggregates and the gels was strong; after 100 freeze-thaw cycles, small cracks appeared between the coarse aggregates and gels, and most coarse aggregates in the cross-section were split; after 150 freeze-thaw cycles, the cross-section became rough; after 200 freeze-thaw cycles, the cracks between the coarse aggregates and the gels were enlarged, while some coarse aggregates were split; after 250 freeze-thaw cycles, the gels and coarse aggregates were separated and very few coarse aggregates were split; and after 300 freeze-thaw cycles, the separation phenomenon of the gels and coarse aggregates intensified. Through the analysis of the AASC damage

| Code     | AASC/slag (kg/m³) | Stand (kg/m³) | Coarse aggregate (kg/m³) | Water-to-slag (cement) (%) | 28d compressive strength (MPa) |
|----------|-------------------|---------------|--------------------------|---------------------------|--------------------------------|
| AASC-1   | 400               | 716           | 1074                     | 0.35                      | 51.5                           |
| AASC-2   | 420               | 716           | 1074                     | 0.35                      | 54.0                           |
| AASC-3   | 440               | 716           | 1074                     | 0.35                      | 55.1                           |
| AASC-4   | 460               | 716           | 1074                     | 0.35                      | 56.7                           |
| AASC-5   | 400               | 716           | 1074                     | 0.37                      | 55.5                           |
| AASC-6   | 400               | 716           | 1074                     | 0.39                      | 51.3                           |
| OCC-1    | 400               | 716           | 1074                     | 0.35                      | 46.6                           |

Figure 1: AASC-1 surface morphology after the freeze-thaw cycle.

Figure 2: OCC-1 surface morphology after the freeze-thaw cycle.
interface, it was observed that, under the same number of freeze-thaw cycles, the gel bonding performance of AASC was stronger than that of OCC. With the same number of freeze-thaw cycles, the bonding performance and loss rate of the mechanical properties of the AASC were lower than those of the OCC. In other words, the AASC exhibited a better frost resistance performance than the OCC.

3.3. Analysis of the Microstructure after the Freeze-Thaw Cycle. The gel materials inside the concrete from the crushed specimen after the sample cube compressive damage analyses were investigated via SEM and EDS, whereby AASC-1 and OCC-1 were the samples used, as presented in Figures 3 and 4, respectively.

The microstructure of the OCC after the freeze-thaw cycle was analyzed, and it was discovered that before the freeze-thaw test, the cement mortar had tiny cracks and the surface was smooth; after 100 freeze-thaw cycles, the cracks in the cement mortar developed further; and after 200 freeze-thaw cycles, the damage became severe as the number of cycles increased, and interpenetrating cracks were generated. Owing to the effects of frost heaving and hydration, the microstructural surface began to form reticulated or flocculent gel materials, and small voids appeared. Meanwhile, a small amount of needle-shaped ettringite (AfT) was found to affect the mechanical properties [20]; after 300 freeze-thaw cycles, different degrees of avulsion and breakage were generated in the cement mortar, which split, and the compressive strength decreased sharply. With the number of freeze-thaw cycles increased, the microstructure of the OCC was destroyed rapidly.

The microstructure of the AASC after the freeze-thaw cycle was also analyzed, and there were a few microcracks in the gel material before the freeze-thaw cycle, which had a relatively good integrity; after 100 freeze-thaw cycles, more microcracks were generated; after 200 freeze-thaw cycles, the cracks generated inside the gel materials were narrower and voids were fewer than those of cement mortar; and after 300 freeze-thaw cycles, the voids became bigger and more cracks were generated. With the number of freeze-thaw cycles increased, the microstructure of the destruction rate in AASC was significantly slower than that in OCCS. The gel materials of the AASC had a stronger binding ability than the cement mortars of the OCC, thereby resulting in higher compressive strength. Therefore, there was less damage to the AASC than OCC under the same number of freeze-thaw cycle conditions.

Based on the EDS analysis, it was found that the Ca/Si ratio inside the C–S–H gel generated from the AASC hydration product was approximately 1.0, which was considered to possess low Ca/Si, and was denoted as the C–S–H(I) gel [20]. This was different from the C–S–H (Ca/Si approximately 1.5) gel and the Ca(OH)\(_2\) generated in the OCC hydration product. The C–S–H(I) gel had a better buffering capacity, making it difficult for moisture to penetrate, which was beneficial for the material to resist freeze-thaw damage. The AASC EDS test data are presented in Figure 5 and Table 3. Considering the previous research results of our group on the hydration mechanism of the alkali-activated slag materials used in this study, the hydration products generated massive amounts of hydrotalcite and tetraxene zeolite [21], which formed a compact structure, caused less porosity, and complicated the infiltration of water into the material, thereby facilitating the deceleration of freeze-thaw damage. Therefore, the AASC maintained better freeze-thaw resistances than the OCC.

3.4. Pore Structure. The pore structure of concrete had a significant effect on freeze-thaw damage. The nitrogen adsorption test method was used to calculate and analyze the pore structure of AASC-4 based on the Barret–Joyner–Halenda method. The pore size distribution of the AASC was even and was mainly in the mesopore range. As shown in Table 4, with the increased freeze-thaw cycles, both the cumulative volume and surface area of pores increased, and the latter was evidently greater than the former. This explains why the increased pores of the AASC caused by freeze-thaw damage were mainly due to the crack pores and microcracks with narrow spaces, as well as large surface areas. To verify this perspective, the AASC adsorption and desorption curves were further established, and it was found that as the number of freeze-thaw cycles increased, the isotherm shifted upward and the hysteresis loop became wider, which also indicated a substantial increase in the number of crack pores and microcracks with narrow spaces and large surface areas, as shown in Figure 6. It is apparent that the microcracks grew significantly when the number of freeze-thaw cycles increased from 0 to 100, and the number of microcracks, as well as the total porosity increment, was evident when the number of freeze-thaw cycles was increased from 200 to 300.

As shown in Figure 7, through further analysis of the pore size distribution, we found that as the number of freeze-thaw cycles increased, the number of pores with diameters ranging from 2 to 10 nm increased, and the 0 to 100 freeze-thaw cycles showed the largest increase, thereby indicating that more microcracks and small pores were generated. As the number of freeze-thaw cycles increased, so did the number and proportion of pores with diameters of 20–50 nm and 50–200 nm, and the average pore diameter and the most probable pore diameter tended to increase, thereby indicating that the freeze-thaw damage to the interior of the specimen was intensified. The number of freeze-thaw cycles increased from 200 to 300, and the total porosity also increased significantly, indicating that the manifested freeze-thaw damage was more intensive at this stage. The porosity analysis results are consistent with the adsorption and desorption data. Pore structure analysis revealed that the AASC pore structure damage characteristics under the effect of the freeze-thaw cycle entailed the fact that microcracks and small pores mainly appeared in the AASC at the initial stage of the damage. As the number of freeze-thaw cycles...
Figure 3: Microstructure of the OCC specimens after different freeze-thaw cycles: (a) 0 cycles; (b) 100 cycles; (c) 200 cycles; (d) 300 cycles.

Figure 4: Microstructure of the AASC specimens after different freeze-thaw cycles: (a) 0 cycles; (b) 100 cycles; (c) 200 cycles; (d) 300 cycles.
increased, so did the connectivity between the pores, and the freeze-thaw damage gradually became more intensified as the average pore size and total porosity increased.

4. Result and Analysis

4.1. Mass Loss Rate after the Freeze-Thaw Cycle. The masses of the prism samples after different freeze-thaw cycles were measured. The mass of each 25th freeze-thaw cycle is presented in Table 5. The relationship between the prism sample mass loss rate and different numbers of freeze-thaw cycles is depicted in Figure 8.

\[
\Delta W_{ni} = \frac{W_{0i} - W_{ni}}{W_{0i}} \times 100\%,
\]

where \(\Delta W_{ni}\) represents the mass loss rate of the \(i\)-th sample after \(N\) freeze-thaw cycles (%); \(W_{0i}\) represents the initial value of the \(i\)-th sample mass before the freeze-thaw cycle (kg); and \(W_{ni}\) represents the \(i\)-th sample mass after \(N\) freeze-thaw cycles (kg).

As shown in Figure 8, as the number of freeze-thaw cycles increased, the mass loss rate of all the samples gradually increased. The main characteristics of the samples were damaged by the freeze-thaw cycle: first, microcracks, which gradually became larger, were generated on the surface; then, the gel materials fell off; and finally large amounts of coarse aggregates were leaked.

4.2. Compressive Strength Loss Rate of Cube Samples after the Freeze-Thaw Cycle. According to standard requirements, the freeze-thaw test used the sample under an overall saturated state such that not only the damage was on the sample surface, but the interior was also subjected to freeze-thaw cycles. The internal freeze-thaw damage was not directly responsible for peeling off the surface. Therefore, the freeze-thaw damage could not be evaluated only by quality loss; the internal damage had a significant impact on the properties of the concrete, and it was adverse. Because compressive strength is an important property of concrete materials, we...
used it to measure the specimens damaged during the freeze-thaw cycles.

The compressive strengths of the cube samples under different freeze-thaw cycles were tested. The results are presented in Table 6. The compressive strength loss rate of the cube sample after the freeze-thaw cycle was calculated according to (2). Table 7 shows the strength loss rate of the cube sample and freeze-thaw cycles is shown in Figure 9.

\[ \Delta f_{c,ni} = \frac{f_{c,0i} - f_{c,ni}}{f_{c,0i}} \times 100\% \]

where \( \Delta f_{c,ni} \) represents the compressive strength loss rate of the \( i \)-th sample after \( N \) freeze-thaw cycles (%); \( f_{c,0i} \) represents the initial value of the compressive strength of the \( i \)-th sample before the freeze-thaw cycle (MPa); and \( f_{c,ni} \) represents the \( i \)-th sample compressive strength after \( N \) freeze-thaw cycles (MPa).

With increasing freeze-thaw cycles, the sample got continuously damaged from the inside out. Figure 9 shows that the compressive strength decreased gradually, while the compressive strength loss rate increased constantly; both were affected by the increased freeze-thaw cycle. During the entire freeze-thaw cycle, the compressive strength loss rate of the AASC was much lower than that of the OCC. The slope of this line is shown in Figure 9, and it represents the compressive strength loss rate. The compressive strength loss rates of the AASC and OCC were basically the same before the 100th freeze-thaw cycle. The compressive strength loss rate of the AASC increased between the 100th and 200th freeze-thaw cycles but decreased between the 200th and 300th freeze-thaw cycles. However, for the OCC, the compressive strength loss rate increased sharply during the 100th to 300th freeze-thaw cycles, and there were cases where the individual sample had severely missing edges and corners upon removal from the test box after 300 freeze-thaw cycles. Considering the different effects of samples with different water-to-cement ratios on the test results, the sample with a higher water-to-cement ratio resulted in a more intensive compressive strength loss after 150 freeze-thaw cycles. This was mainly due to the noninvolvement of more residual free water in the hydration reaction in the sample with a higher water-to-cement ratio, making the sample damage more intensified, thereby leading to a greater compressive strength loss. Additionally, the sample with a higher compressive strength at 28d had a relatively low compressive strength loss rate after the freeze-thaw cycle test, which corresponded to the analysis presented in Section 4.1.

### 4.3 Dynamic Elastic Modulus Loss Rate of the Sample after the Freeze-Thaw Cycle

The compressive strength loss rate was able to reflect the degree and law of concrete damage from the perspective of compressive strength, and the dynamic elastic modulus was able to reflect the internal damage of the sample when it was subjected to various factors by

| Freeze-thaw cycle (n) | Cumulative volume of pores (mL/g) | Cumulative surface area of pores (m2/g) |
|-----------------------|----------------------------------|----------------------------------------|
| 0                     | 0.00675                          | 2.85                                   |
| 100                   | 0.03034                          | 13.93                                  |
| 200                   | 0.03302                          | 17.23                                  |
| 300                   | 0.04882                          | 20.45                                  |

Table 4: Pore structure parameter after the freeze-thaw cycle.
measuring the transverse fundamental frequency. Therefore, it is necessary to consider a method for measuring the dynamic elastic modulus by freeze-thaw cycles in concrete to evaluate the degree and damage regularity.

The transverse fundamental frequency of the prism sample under different freeze-thaw cycles was measured, and the dynamic elastic modulus loss rate of the prism sample after different freeze-thaw cycles was calculated using (3). The transverse fundamental frequency and dynamic elastic modulus of the prism sample after different freeze-thaw cycles are shown in Table 7. The relationship between the loss rate of the prism sample dynamic elastic modulus and freeze-thaw cycles is shown in Figure 10.

\[
\Delta E_{d,ni}^{\text{Ed}} = \left( \frac{E_{d,0i}^{\text{Ed}} - E_{d,ni}^{\text{Ed}}}{E_{d,0i}^{\text{Ed}}} \right) \times 100\%,
\]

where \(\Delta E_{d,ni}^{\text{Ed}}\) represents the dynamic elastic modulus loss rate of the \(i\)-th sample after \(N\) freeze-thaw cycles (%); \(E_{d,0i}^{\text{Ed}}\) represents the initial value of the dynamic elastic modulus of the \(i\)-th sample before the freeze-thaw cycle (GPa); and \(E_{d,ni}^{\text{Ed}}\) represents the dynamic elastic modulus of the \(i\)-th sample after \(N\) freeze-thaw cycles (GPa).

As the number of freeze-thaw cycles increased, as shown in Figure 10, the internal microcracks in the sample continuously developed and the number gradually increased; thus, the dynamic elastic modulus decreased and its loss rate gradually increased. The test results indicated that the AASC sample with a higher water-to-slag ratio had a higher dynamic modulus loss rate after the freeze-thaw cycle because more unreacted free water remaining in the sample led to more water-occupied pore spaces, and the damage was more intensive during the freeze-thaw cycles. However, the degree of difference of the freeze-thaw cycle damage between AASC-4 (water-to-slag ratio was 0.37) and AASC-5 (water-to-slag ratio was 0.35) was not evident. By increasing the number of the freeze-thaw cycles, a similar damage law in the dynamic elastic modulus loss rate and mass loss rate after the freeze-thaw cycle was presented; i.e., the higher 28d compressive strength had a lower loss rate. For example, AASC-4 had the highest 28d compressive strength, which was the least dynamic elastic modulus loss rate after 300 freeze-thaw cycles (13.42%). This was mainly because the properties of the gel material had a denser gel structure and a stronger bonding ability, which were able to resist more freeze-thaw cycle damage.

The dynamic modulus loss rate of the AASC (13.42–24.63%) was much lower than that of the OCC (36.91%) because the gel materials Ca(OH)\(_2\) and C–S–H in OCC had a lower resistance to the freeze-thaw damage than the gel materials C–S–H (I) and C–(A)–S–H in the AASC [22]. Additionally, the dynamic elastic modulus changed significantly during the entire freeze-thaw cycle, and the AASC-6 dynamic elastic modulus loss rate was 24.63%. The significant change in the dynamic elastic modulus was meaningful to the study of evaluating the entire law and damage degree of the AASC during the freeze-thaw cycles. Therefore, the change in the dynamic elastic modulus loss rate could reflect the failure process and damage degree of the AASC under the freeze-thaw cycle.

4.4. Analysis of the Freeze-Thaw Damage Mechanism. The performance of the gel material in the AASC directly affects the frost resistance of the AASC. At the onset of the freeze-thaw cycle, the pore water on the surface of the AASC and

### Table 5: Mass of the prism samples after different freeze-thaw cycles.

| Times code | 0  | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 | 250 | 275 | 300 |
|------------|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| AASC-1     | 9.678 | 9.668 | 9.658 | 9.642 | 9.625 | 9.611 | 9.593 | 9.579 | 9.571 | 9.562 | 9.555 | 9.541 | 9.529 |
| AASC-2     | 9.736 | 9.728 | 9.720 | 9.711 | 9.699 | 9.681 | 9.666 | 9.658 | 9.647 | 9.636 | 9.621 | 9.611 | 9.590 |
| AASC-3     | 9.765 | 9.759 | 9.751 | 9.745 | 9.731 | 9.715 | 9.708 | 9.697 | 9.686 | 9.678 | 9.672 | 9.666 | 9.653 |
| AASC-4     | 9.667 | 9.660 | 9.651 | 9.636 | 9.629 | 9.621 | 9.615 | 9.608 | 9.601 | 9.591 | 9.582 | 9.571 | 9.568 |
| AASC-5     | 9.701 | 9.696 | 9.689 | 9.682 | 9.677 | 9.661 | 9.649 | 9.635 | 9.629 | 9.623 | 9.615 | 9.615 | 9.600 |
| AASC-6     | 9.634 | 9.621 | 9.603 | 9.591 | 9.586 | 9.576 | 9.567 | 9.558 | 9.551 | 9.543 | 9.531 | 9.521 | 9.510 |
| OCC-1      | 9.996 | 9.980 | 9.934 | 9.881 | 9.837 | 9.803 | 9.773 | 9.745 | 9.719 | 9.691 | 9.658 | 9.619 | 9.558 |

![Figure 8: Relation between the mass loss rate and freeze-thaw cycle.](image)
the coarse aggregate were saturated, and as the temperature gradually decreased, these pores undertook the “pumping effect.” Meanwhile, the gel material in the AASC had fewer pores and cracks than that of the OCC, which maintained a lower water absorption rate, and the pumping effect was weaker. The pumping effects indirectly caused more intense movement of water from the surface to the inside. During this process, partial water began to freeze and expand, and the internal water generated a temperature difference wherein lower temperature water migrated. Consequently, the osmotic and hydrostatic pressures are formed through the alternating positive and negative water temperatures. Frost heave damage occurred when the osmotic and hydrostatic pressures exceeded the AASC-bearable stress, and the total water movement channel during the freeze-thaw cycle was reduced, while the damage rate was retarded owing to the denser gel structure of the AASC, thereby resulting in only a small number of microcracks inside the AASC. The pore water in the AASC thawed as the temperature increased, while the small pores and newly generated microcracks were saturated with water owing to the capillary phenomenon. The connected pores would also absorb some water, and the porosity at this time becomes higher than before. With increasing freeze-thaw cycle, reticulated or flocculent gel materials began to increase, and the cracks generated expanded and connected with each other due to the alkali-activated gel hydration. The frost heave damage was intensified by continually absorbing water and became saturated, while the gel material wrapped on the surface began to fall off, the surface became rough, and several densely packed small holes appeared. Subsequently, the AASC had different degrees of tearing and breaking damage due to the uneven local force, a certain amount of concrete began to peel off, and the coarse aggregates were exposed and eventually caused the mortar to split. This indicated that the freeze-thaw damage in the sample was a fatigue failure process; the more the freeze-thaw cycles, the more serious the damage. In the freeze-thaw cycle process, the AASC exhibited better freeze-thaw resistance performance than the OCC.

### 5. Freeze-Thaw Damage Mechanics Models

The damage model was established on the basis of damage mechanics, mainly focusing on the impact of damage on the macroscopic properties of materials, the process, and the law of damage evolution, which differed from traditional damage theories that solely focused on the instantaneous state and situation of material damage. The damage theory was used to analyze the response of the material micro-structural changes to macroscopic properties and to understand the properties of materials more deeply and reasonably. According to Powers’ hydrostatic pressure theory [26] and osmotic pressure hypothesis [27], the external macroscopic property deterioration of the concrete after the freeze-thaw cycle was mainly due to the frost heave pressure generated, which led to the continuous expansion of internal defects and accumulated damage. Many indicators can be used to evaluate concrete damage variables and the corresponding freeze-thaw damage models, and the internal cumulative damage is considered to be a macroscopic variable, while the mass loss, compressive strength loss, and dynamic elastic modulus loss are macroscopic variables according to damage mechanics.

Based on previous research, although the mass loss could duly reflect the sample damage, the mass loss was only caused by the external surface shedding of the sample but could not reflect the overall sample damage; however, the mass loss was only slightly changed during the entire freeze-thaw cycle compared with the change in quality. Hence, a

| Code  | Compressive strength of cube samples after different freeze-thaw cycles (MPa) |
|-------|-----------------------------------------------------------------------------|
|       | 0 times | 50 times | 100 times | 150 times | 200 times | 250 times | 300 times |
| AASC-1| 51.5    | 50.2     | 47.6      | 42.3      | 37.6      | 35.2      | 32.1      |
| AASC-2| 54.0    | 51.3     | 46.8      | 41.1      | 38.1      | 34.9      | 33.2      |
| AASC-3| 55.1    | 51.9     | 46.6      | 42.6      | 40.2      | 38.1      | 35.8      |
| AASC-4| 56.7    | 53.6     | 49.4      | 44.3      | 41.1      | 38.6      | 36.1      |
| AASC-5| 55.5    | 52.4     | 48.6      | 43.2      | 37.2      | 35.1      | 33.6      |
| AASC-6| 51.3    | 49.6     | 45.2      | 41.3      | 36.1      | 33.1      | 27.3      |
| OCC-1 | 46.6    | 42.5     | 38.9      | 30.8      | 23.4      | 15.6      | 9.5       |

Table 6: Compressive strength of cube samples after different freeze-thaw cycles.

![Figure 9: Relation between the compressive strength loss rate and freeze-thaw cycle.](image)
| Freeze-thaw cycle (n) | AASC-1 | AASC-2 | AASC-3 | AASC-4 | AASC-5 | AASC-6 | OCC-1 |
|----------------------|--------|--------|--------|--------|--------|--------|-------|
|                      | Transverse fundamental frequency (Hz) | Dynamic elastic modulus (GPa) | Transverse fundamental frequency (Hz) | Dynamic elastic modulus (GPa) | Transverse fundamental frequency (Hz) | Dynamic elastic modulus (GPa) | Transverse fundamental frequency (Hz) | Dynamic elastic modulus (GPa) |
| 0                    | 2213   | 40.17  | 2202   | 40.01  | 2185   | 39.52  | 2303   | 43.46  | 2264   | 42.15  | 2210   | 39.88  | 2349   | 46.75  |
| 25                   | 2196   | 39.52  | 2182   | 39.26  | 2174   | 39.10  | 2297   | 43.20  | 2250   | 41.61  | 2193   | 39.22  | 2307   | 45.02  |
| 50                   | 2179   | 38.87  | 2170   | 38.80  | 2159   | 38.53  | 2291   | 42.94  | 2236   | 41.06  | 2173   | 38.43  | 2265   | 43.20  |
| 75                   | 2162   | 38.20  | 2153   | 38.15  | 2147   | 38.08  | 2280   | 42.46  | 2219   | 40.41  | 2153   | 37.68  | 2235   | 41.84  |
| 100                  | 2148   | 37.64  | 2141   | 37.68  | 2133   | 37.53  | 2262   | 41.76  | 2204   | 39.84  | 2132   | 36.93  | 2190   | 39.99  |
| 125                  | 2140   | 37.31  | 2124   | 37.02  | 2116   | 36.87  | 2247   | 41.17  | 2192   | 39.35  | 2112   | 36.21  | 2151   | 38.44  |
| 150                  | 2122   | 36.61  | 2104   | 36.27  | 2102   | 36.36  | 2230   | 40.53  | 2180   | 38.87  | 2088   | 35.35  | 2097   | 36.43  |
| 175                  | 2114   | 36.29  | 2086   | 35.62  | 2088   | 35.83  | 2213   | 39.88  | 2166   | 38.31  | 2070   | 34.71  | 2049   | 34.68  |
| 200                  | 2097   | 35.67  | 2071   | 35.07  | 2074   | 35.32  | 2195   | 39.21  | 2158   | 38.01  | 2050   | 34.02  | 2010   | 33.28  |
| 225                  | 2085   | 35.23  | 2062   | 34.73  | 2060   | 34.81  | 2180   | 38.63  | 2147   | 37.60  | 2026   | 33.20  | 1986   | 32.40  |
| 250                  | 2068   | 34.64  | 2050   | 34.27  | 2048   | 34.39  | 2168   | 38.17  | 2133   | 37.08  | 1999   | 32.28  | 1956   | 31.32  |
| 275                  | 2041   | 33.69  | 2039   | 33.87  | 2036   | 33.96  | 2159   | 37.81  | 2121   | 36.61  | 1975   | 31.48  | 1932   | 30.43  |
| 300                  | 2017   | 32.86  | 2028   | 33.43  | 2024   | 33.52  | 2154   | 37.63  | 2106   | 36.05  | 1931   | 30.06  | 1908   | 29.49  |
large error would occur if a damage model or attenuation model based on mass damage was established. The compressive strength of concrete is an important index for concrete property measurement, which could reflect the sample property directly and could be used for evaluating the degree of freeze-thaw damage, and although more samples would be required, they are relatively easy to obtain. Moreover, the relative dynamic elastic modulus of concrete could better reflect the concrete damage degree, wherein the required samples were fewer and the data were relatively easy to measure. The establishment of attenuation models or accumulative damage models based on compressive strength and relative dynamic elastic modulus has been well recognized in OCC research. Therefore, in this study, damage attenuation models and accumulative damage models were established using the compressive strength and relative dynamic elastic modulus of the AASC as damage variables, which could be used to effectively characterize the damage degree of the AASC according to the freeze-thaw cycles.

5.1. Compressive Strength Attenuation Model. Research on the decay of OCC compressive strength under freeze-thaw cycles showed that the decay curve of compressive strength conformed to the exponential function distribution law. Considering that the influence of different compressive strengths and AASC damage during freeze-thaw cycles were less than those of OCC, combined with the test results in this study, the freeze-thaw damage power function model was obtained according to (4). The compressive strength attenuation power function model is shown in Figure 11 and its properties are listed in Table 8.

\[ D = \frac{f_{c,ni}}{f_{c,0i}} \times 100\% = aN^b. \]  

The test results were fitted according to the exponential function of (5) to obtain the freeze-thaw damage model, which was the compressive strength exponential function model of the AASC freeze-thaw damage shown in Figure 12 and Table 9.

\[ D = \frac{f_{c,ni}}{f_{c,0i}} \times 100\% = ae^{bN}. \]  

Based on the results of this study, the analyses of compressive strength attenuation power function models from Figures 11 and 12 and Tables 8 and 9 show that the accuracy of the compressive strength attenuation power function model is low and the prediction deviation is large, although the compressive strength attenuation exponential function model has a high degree of accuracy. The compressive strength attenuation exponential function model could accurately reflect the attenuation law of the AASC after the freeze-thaw cycle.

5.2. Compressive Strength Accumulative Damage Model. As the number of the freeze-thaw cycles increased, the compressive strength loss was elevated, which indicated a more severe damage degree. Based on damage mechanics research, the compressive strength loss rate was defined as the damage degree \( D \) shown in (6), while the test results were fitted and established in the freeze-thaw damage models in accordance with (7) and (8), respectively. The compressive strength accumulative damage power function model and exponential function model of the AASC freeze-thaw damage are shown in Figures 13 and 14 and Tables 10 and 11.

\[ D = \frac{\Delta f_{c,ni}}{f_{c,0i}} \times 100\% = aN^b, \]  

\[ D = e^{a+bN}. \]  

The results obtained in this study revealed that the analyses of the compressive strength accumulative model from Figures 10, 13 and Tables 10, 11 indicated that the compressive strength accumulative exponential function model had low accuracy and large prediction deviation, but the compressive strength accumulative power function model had a high accuracy. Meanwhile, both the compressive strength attenuation exponential function model and the accumulative damage power function model had high fitted accuracy.

5.3. Relative Dynamic Elastic Modulus Attenuation Model. According to previous studies, the relative dynamic elastic decay loss rate was proportional to the number of freeze-thaw cycles in the entire process. The relative dynamic elastic modulus was used as the damage variable and combined with the test results, and the freeze-thaw damage power
Figure 11: Compressive strength attenuation power function model.

Table 8: Compressive strength attenuation power function and pertinence coefficient.

| Code   | Fitting coefficient, $a$   | Fitting coefficient, $b$ | Correlation coefficient, $R^2$ |
|--------|--------------------------|--------------------------|---------------------------------|
| AASC-1 | 255.327                  | $-0.2355$                | 0.8849                          |
| AASC-2 | 249.100                  | $-0.2398$                | 0.9534                          |
| AASC-3 | 207.866                  | $-0.1993$                | 0.9835                          |
| AASC-4 | 222.888                  | $-0.2130$                | 0.9510                          |
| AASC-5 | 261.481                  | $-0.2514$                | 0.9145                          |
| AASC-6 | 299.279                  | $-0.2776$                | 0.8550                          |

Figure 12: Compressive strength attenuation exponential function model.
A function model was established according to (9). The relative dynamic elastic modulus attenuation power function model of the AASC freeze-thaw damage is shown in Figure 15 and Table 12.

\[ D = \frac{P_n}{P_0} \times 100% = aN^b. \]  

The relative dynamic elastic modulus is used to establish an exponential function freeze-thaw damage model according to (10), and the relative dynamic elastic modulus exponential function attenuation model of the AASC freeze-thaw damage is shown in Figure 16 and Table 13.

\[ D = \frac{P_n}{P_0} \times 100% = ae^{bN}. \]  

The results of this study revealed that the analyses of the relative dynamic elastic attenuation model presented in Figures 15 and 16 and Tables 12 and 13 indicated that the accuracy of the relative dynamic elastic attenuation power function model was low and the prediction deviation was large; however, the relative dynamic elastic attenuation exponential function model had a high degree of accuracy. This was similar to the OCC freeze-thaw damage model studied by scholars with the submission that the relative dynamic elastic modulus attenuation exponential function model was more accurate than the relative dynamic elastic modulus attenuation power function model.

### 5.4. Relative Dynamic Elastic Modulus Accumulative Damage Model

According to Section 5.3, it was established that the damage degree of concrete could be measured by the changes in the relative dynamic elastic modulus. However, as the number of freeze-thaw cycles increased, the relative dynamic elastic modulus loss and damage degree intensified. Based on damage mechanics, the relative dynamic elastic modulus loss rate \( (\Delta P_n) \) was defined as the damage degree \( (D) \) shown in (11) and combined with the test results to establish the freeze-thaw damage model according to (12) and (13), respectively. The relative dynamic elastic modulus accumulative damage power function model and the exponential function model of the AASC were obtained by fitting, as shown in Figures 17 and 18 and Tables 14 and 15.

| Code | Fitting coefficient, \( a \) | Fitting coefficient, \( b \) | Correlation coefficient, \( R^2 \) |
|------|----------------|----------------|----------------|
| AASC-1 | 108.431 | -0.0019 | 0.9861 |
| AASC-2 | 103.206 | -0.0018 | 0.9830 |
| AASC-3 | 99.259 | -0.0015 | 0.9725 |
| AASC-4 | 101.801 | -0.0016 | 0.9890 |
| AASC-5 | 104.355 | -0.0020 | 0.9705 |
| AASC-6 | 109.769 | -0.0022 | 0.9825 |

**Figure 13:** Compressive strength accumulative damage power function model.

**Figure 14:** Compressive strength accumulative damage exponential function model.
Table 10: Compressive strength accumulative damage power function and pertinence coefficient.

| Code   | Fitting coefficient, $a$ | Fitting coefficient, $b$ | Correlation coefficient, $R^2$ |
|--------|--------------------------|--------------------------|---------------------------------|
| AASC-1 | 0.0357                   | 1.2278                   | 0.9690                          |
| AASC-2 | 0.2062                   | 0.9265                   | 0.9652                          |
| AASC-3 | 0.3790                   | 0.7987                   | 0.9696                          |
| AASC-4 | 0.2130                   | 0.9070                   | 0.9784                          |
| AASC-5 | 0.1744                   | 0.9632                   | 0.9507                          |
| AASC-6 | 0.0349                   | 1.2614                   | 0.9924                          |

Table 11: Compressive strength accumulative damage exponential function and pertinence coefficient.

| Code   | Fitting coefficient, $a$ | Fitting coefficient, $b$ | Correlation coefficient, $R^2$ |
|--------|--------------------------|--------------------------|---------------------------------|
| AASC-1 | 1.7861                   | 0.0064                   | 0.8750                          |
| AASC-2 | 2.2238                   | 0.0051                   | 0.8442                          |
| AASC-3 | 2.2765                   | 0.0045                   | 0.8476                          |
| AASC-4 | 2.1676                   | 0.0050                   | 0.8711                          |
| AASC-5 | 2.2255                   | 0.0052                   | 0.8300                          |
| AASC-6 | 1.8947                   | 0.0066                   | 0.9379                          |

Figure 15: Relative dynamic elastic modulus attenuation power function model.

Table 12: Relative dynamic elastic modulus attenuation power function and pertinence coefficient.

| Code   | Fitting coefficient, $a$ | Fitting coefficient, $b$ | Correlation coefficient, $R^2$ |
|--------|--------------------------|--------------------------|---------------------------------|
| AASC-1 | 123.007                  | −0.0612                  | 0.8327                          |
| AASC-2 | 122.829                  | −0.0614                  | 0.8936                          |
| AASC-3 | 122.259                  | −0.0581                  | 0.8878                          |
| AASC-4 | 122.840                  | −0.0567                  | 0.8607                          |
| AASC-5 | 117.060                  | −0.0520                  | 0.9064                          |
| AASC-6 | 137.593                  | −0.0912                  | 0.8267                          |
Figure 16: Relative dynamic elastic modulus attenuation exponential function model.

Table 13: Relative dynamic elastic modulus attenuation exponential function and pertinence coefficient.

| Code  | Fitting coefficient, $a$ | Fitting coefficient, $b$ | Correlation coefficient, $R^2$ |
|-------|--------------------------|--------------------------|-------------------------------|
| AASC-1| 100.031                  | -0.0006                  | 0.9823                        |
| AASC-2| 99.581                   | -0.0006                  | 0.9928                        |
| AASC-3| 100.287                  | -0.0005                  | 0.9990                        |
| AASC-4| 101.340                  | -0.0005                  | 0.9891                        |
| AASC-5| 99.610                   | -0.0001                  | 0.9966                        |
| AASC-6| 101.344                  | -0.0009                  | 0.9882                        |

Figure 17: Relative dynamic elastic modulus accumulative damage power function model.
\[ D = \Delta P_{ni} = \frac{P_{0i} - P_{ni}}{P_{0i}} \times 100\%, \]  

\[ D = aN^b, \]  

\[ D = e^{ax + byN}. \]

Results of this study revealed that the analyses of the relative dynamic elastic modulus accumulative models presented in Figures 17 and 18 and Tables 14 and 15 indicated that the accuracy of the relative dynamic elastic modulus accumulative exponential function model was low and the prediction deviation was large, although the relative dynamic elastic modulus accumulative power function model had a high degree of accuracy. Meanwhile, both the relative dynamic elastic modulus attenuation exponential function model and the accumulative damage power function model had a highly fitted accuracy.

6. Conclusions

(1) AASC, which was prepared and cured at room temperature using solid sodium aluminate and sodium silicate as composite alkaline activators, had an excellent freeze-thaw resistance and exceeded the F300 level freeze-thaw resistance verified by experiments.

(2) The AASC slag content volume had a significant impact on the mass under freeze-thaw damage: the higher the content, the less the mass damage. The
AASC water-to-slag ratio and compressive strength had a significant impact on the mechanical properties under freeze-thaw damage: the higher the water-to-slag ratio, the more severe the damage to the mechanical properties; on the other hand, the higher the compressive strength, the less the damage.

(3) The AASC mass loss was too small under freeze-thaw damage, which was unsuitable as an evaluation index for freeze-thaw damage, while the compressive strength and relative dynamic elastic modulus could be used to evaluate the damage degree of the AASC under freeze-thaw damage.

(4) Microscopic studies showed that AASC mainly generated crack pores and microcracks with small space and large surface area under freeze-thaw damage, and when the freeze-thaw damage was aggravated, the structural porosity gradually increased, which led to mechanical property damage, but the dense hydration structure and C–S–H(I) gel maintained a better freeze-thaw resistance.

(5) The attenuation and accumulative damage models were established using the compressive strength and relative dynamic elastic modulus as variable bases. Both the compressive strength and relative dynamic elastic modulus had similar damage laws, the exponential function model for the attenuation model had better accuracy, and the power function model for the accumulative damage model had a higher accuracy than the exponential function model. The established damage model could better reflect the law and degree of AASC freeze-thaw damage and could be used to evaluate and predict the AASC freeze-thaw cycle life. Meanwhile, it provided a scientific study reference for further research on the microscopic and macroscopic analyses of the AASC freeze-thaw damage.

Data Availability

All data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was funded by Heilongjiang Traffic and Transportation Department (JTZD-20181826) and Fundamental Research Funds for the Central Universities (2572019CT01).

References

[1] J. L. Provis and S. A. Bernal, “Geopolymers and related alkali-activated materials,” Annual Review of Materials Research, vol. 44, no. 1, pp. 299–327, 2014.
[2] K. L. Scrivener and R. J. Kirkpatrick, “Innovation in use and research on cementitious material,” Cement and Concrete Research, vol. 38, no. 2, pp. 128–136, 2008.
[3] J. L. Provis, G. C. Lukey, and J. S. J. Van Deventer, “Do geopolymers actually contain nanocrystalline zeolites? a reexamination of existing results,” Chemistry of Materials, vol. 17, no. 12, pp. 3075–3085, 2005.
[4] P. Duxson, G. C. Lukey, F. Separovic, and J. S. J. Van Deventer, “Effect of alkali cations on aluminum incorporation in geopolymeric gels,” Industrial & Engineering Chemistry Research, vol. 44, no. 4, pp. 832–839, 2005.
[5] K. L. Scrivener and A. Nonat, “Hydration of cementitious materials, present and future,” Cement and Concrete Research, vol. 41, no. 7, pp. 651–665, 2011.
[6] K.-H. Yang, J.-K. Song, A. F. Ashour, and E.-T. Lee, “Properties of cementless mortars activated by sodium silicate,” Construction and Building Materials, vol. 22, no. 9, pp. 1981–1989, 2008.
[7] P. Shoaei, F. Ameri, H. Reza Musaei, T. Ghasemi, and C. B. Cheah, “Glass powder as a partial precursor in Portland cement and alkali-activated slag mortar: a comprehensive comparative study,” Construction and Building Materials, vol. 251, 2020.
[8] F. Ameri, P. Shoaei, H. Reza Musaei, S. Alireza Zareei, and C. B. Cheah, “Partial replacement of copper slag with treated crumb rubber aggregates in alkali-activated slag mortar,” Construction and Building Materials, vol. 256, 2020.
[9] Z. Jiao, Y. Wang, W. Zheng, and W. Huang, “Effect of dosage of sodium carbonate on the strength and drying shrinkage of sodium hydroxide based alkali-activated slag paste,” Construction and Building Materials, vol. 179, pp. 11–24, 2018.
[10] Z. Jiao, Y. Wang, W. Zheng, and W. Huang, “Effect of the activator on the performance of alkali-activated slag mortars with pottery sand as fine aggregate,” Construction and Building Materials, vol. 197, pp. 83–90, 2019.
[11] P. Zhang, Z. Gao, J. Wang, J. Guo, S. Hu, and Y. Ling, “Properties of fresh and hardened fly ash/slag based geopolymer concrete: a review,” Journal of Cleaner Production, vol. 270, Article ID 122389, 2020.
[12] W. Ferdous, A. Manalo, A. Khennane, and O. Kayali, “Geopolymer concrete-filled pultruded composite beams - concrete mix design and application,” Cement and Concrete Composites, vol. 58, pp. 1–13, 2015.
[13] Krivenko, “Alkaline cements: structure, properties, aspects of durability,” in Proceedings of the Second Int. Conf. Alkaline Cem. Concr., Kiev, Ukraine, 1999.
[14] L. Cai, H. Wang, and Y. Fu, “Freeze-thaw resistance of alkali-slag concrete based on response surface methodology,” Construction and Building Materials, vol. 49, pp. 70–76, 2013.
[15] Y. Fu, L. Cai, and W. Yonggen, “Freeze-thaw cycle test and damage mechanics models of alkali-activated slag concrete,” Construction and Building Materials, vol. 25, no. 7, pp. 3144–3148, 2011.
[16] H. Bilek and V. Sklborzova, “Freezing and thawing resistance of alkali-activated concretes for the production of building elements,” in Proceedings of the 10th CANMET/ACI Conf. Recent Adv. Concr. Technol., Suplementary Pap., Seville, Spain, 2009.
[17] Standardization Administration of the People’s Republic of China, GB/T 18046-2017: Ground Granulated Blast Furnace Slag Used for Cement, Mortar and concrete, China Standards Press, Beijing, China, 2017.
[18] Ministry of Housing and Urban-Rural Development of People’s Republic of China, GB/T 50081-2019: Standard for
Test Methods of concrete Physical and Mechanical Properties, China Building Materials Industry Press, Beijing, China, 2019.

[19] Beijing: China Building Materials Industry Press of the People's Republic of China, GB/T 50082-2009: Standard for Test Methods of Long-Term Performance and Durability of Ordinary concrete, Advances in Materials Science and Engineering, Beijing, China, 2009.

[20] B. Chen, J. Wang, and J. Zhao, “Effect of sodium aluminate dosage as a solid alkaline activator on the properties of alkali-activated slag paste,” *Annals of Materials Science & Engineering*, vol. 2021, Article ID 6658588, 13 pages, 2021.

[21] B. Chen, J. Wang, and J. Zhao, "Mitigating the drying shrinkage and autogenous shrinkage of alkali-activated slag by NaAlO2," *Materials*, vol. 13, 2020.

[22] R. D. C. Shi and P. V. Krivenko, *Alkali-Activated Cements and Concrete*, Taylor & Francis, London, UK, 2006.

[23] M. Cyr and R. Pouhet, "The frost resistance of alkali-activated cement-based binders," in *Handbook of Alkali-Activated Cements, Mortars and Concretes*, pp. 293–318, Elsevier Inc., Universite de Toulouse, Toulouse, France, 2015.

[24] P. M. Gifford and J. E. Gillott, "Freeze-thaw durability of activated blast furnace slag cement concrete," *ACI Materials Journal*, vol. 93, pp. 242–245, 1996.

[25] K. Byfors and G. Klingstedt, "Durability of concrete made with alkali-activated slag," in *Third International Conference Proceedings. Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete. ACI SP-114*, pp. 1429–1466, Trondheim, Norway, June 1989.

[26] T. C. A. Powers, "A working hypothesis for further studies of frost resistance of concrete," *Journal ACIIO*, vol. 16, pp. 245–272, 1945.

[27] T. C. Powers and R. A. Helmuth, “Theory of volume changes in hardened cement paste during freezing,” in *Proceedings of the Highway Research Board*, Washington, DC, USA, January 1953.