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Research Article

Experimental Study on Nano-SiO_2 Improving Concrete Durability of Bridge Deck Pavement in Cold Regions

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In order to reduce early damage of bridge deck pavement concrete in cold regions, a certain content of nano-SiO_2 is added into the concrete to enhance its durability. Through tests on four durability indexes, strength, frost resistance, resistance to Cl^- ion permeability, and abrasion resistance of concrete with 1% nano-SiO_2 content and concrete without nano-SiO_2, the ability of nano-SiO_2 to improve the concrete durability of bridge deck pavement is evaluated. The results of tests and analysis show that the incorporation of nano-SiO_2 greatly improves the four durability indexes. Nano-SiO_2 effectively absorbs the calcium hydroxide released early by the hydration of cement, increases the calcium silicate hydrate content, and elevates the interface between the paste and aggregate of the hardened cement, which improves the durability of the concrete.

1. Introduction

Cement concrete bridge deck pavement has been very widely used in the construction of highway bridges in China; however, the early damage of bridge deck pavement is becoming increasingly more serious with the continuous increase in traffic volume and traffic load, and early damage of bridge deck pavement has become one of the major problems for bridges [1]. The phenomenon of early damage of concrete bridge deck pavement is more obvious in the cold regions of North China [2].

Compared with ordinary concrete pavement, damage of concrete of bridge deck pavement is more likely to occur. Bridge deck pavement, which is exposed to the natural environment for extended periods of time, is an important part of a bridge's crane system [3], and durability of the concrete that composes bridge deck pavement is affected by vehicle load and adverse natural conditions. The durability of concrete bridge deck pavement is a key component in providing effective services, and thus the lack of concrete durability will cause early damage of concrete bridge deck pavement and greatly reduce the service life of the pavement.

There are many factors that affect the durability of concrete. In order of importance, the factors causing the destruction of concrete structures include reinforcement corrosion, freezing and thawing damage, and chemical erosion [4].

Winter is long and cold in the vast northern regions in China, and cold weather conditions have a great impact on the durability of cement concrete. Freezing and thawing are the most representative indexes that affect concrete durability [5].

In winter, in order to remove ice and snow from roads in a timely manner following a snowfall, deicing salt is often applied to the road in many areas of northern China, especially in some key sections of cities, such as bridge approach roads and bridge deck pavement. A large number of the Cl^- ions contained in deicing salt can penetrate the concrete and diffuse to the surface of steel-reinforcing bars. Cl^- ions induce corrosion of the reinforcing bars and then cause protective layer cracking, which exacerbates the spread of Cl^- and steel corrosion. When the Cl^- ion concentration reaches a certain level, the destruction of concrete structures will occur [6]. Therefore, the resistance of concrete to corrosion merits attention.

Bridge deck pavements experience daily wear from a large number of vehicle tires. In addition, more frequent vehicle braking occurs on bridges because of speed bumps at bridge approaches or lower speed limits on bridges, so over time, the concrete surface of bridge deck pavement will wear away if the abrasion resistance of the bridge deck pavement is poor. As time passes, mortar will be worn away, aggregate will be exposed, loose aggregate will be taken under vehicle wheels, and larger cracks will form in bridge deck pavements. Water and other corrosive liquids (especially Cl^- contained in the water from melted snow) will penetrate the concrete and accelerate the destruction of the pavement.

Therefore, to improve the frost resistance (both from water and salt freezing), the Cl^- permeability resistance and abrasion resistance of concrete is the key to improving the concrete durability of bridge deck pavement in cold regions.

Nanomaterials are a type of nano-sized (1–100 nm) superfine materials, the size of which occurs in the transition region between atomic clusters and macroscopic objects and is greater than that of a group cluster and smaller than the usual powder [7]. Because the particle size of nano-SiO_2 is very small, highly active nano-SiO_2 particles mixed into concrete can improve its microstructure [8] and in turn, mechanical properties and durability of bridge deck pavement in cold regions of North China.

Mastali and Dalvand [9] conducted an extensive study, including an experimental and analytical approach that describes the effects of 1% nano-SiO_2 and 7% silica fume on the key mechanical properties of concrete. Their experimental results indicated that using both silica fume and nano-SiO_2 instead of cement in plain self-compacting concrete leads to improvements in the impact resistance and mechanical properties of the concrete. Givi et al. [10] investigated the water permeability and setting time of Portland cement mortar with nano-SiO_2 admixed at 0.5%, 1%, 1.5%, and 2% of cement through an experimental study. Their results revealed that the admixing of nano-SiO_2 particles not only led to denser cement mortar but also changed the morphology of the cement hydration products. Zhang et al. [11] conducted a parametric experiment to investigate the effect of nano-SiO_2 particles on the fracture properties of concrete composite containing fly ash. Their results revealed that the addition of lower-SiO_2 content (<5%) nanoparticles could help improve the fracture properties of such concrete composite.

Wang et al. [12, 13] explored and made use of nano-SiO_2 to improve the durability of high-performance concrete and researched its mechanism. His result revealed that at each cycle time point before the max of freezing thaw cycle, the coefficients of antifreezing durability of concrete with nano-SiO_2 were all higher than that without nano-SiO_2; adding nano-SiO_2 could effectively improve resistance to Cl^- permeability of high-performance concrete; at the same time, the electric flux obviously decreased with the increasing of nano-SiO_2 dosage.

Quercia Bianchi [14] conducted a study that two different types of nano-SiO_2 were applied in self-compacting concrete, both having similar particle size distributions but produced in two different processes (pyrogenic and colloidal precipitation). His result revealed that the addition of 3.8% by weight of cement of nano-SiO_2 improves the self-compacting concrete durability (chloride intrusion and freeze-thaw resistance) due to the refinement of the microstructure and the reduction in the connectivity of the pores.

Zhao et al. [15] conducted a test to investigate the relationships among nano-SiO_2 content of nano-SiO_2 concrete, air content, water-cement ratio, and frost resistance property. Their results show that the ability of freezing-thawing resistance and compression strength of the concrete mixed with some nano-SiO_2 will have an improvement, with the increase of impervious holes in hardened cement paste.

In the paper, the experimental study of concrete mixed with nano-SiO_2 was carried out with local cement and aggregate in Harbin as raw materials. The test results shew that nano-SiO_2 could improve the durability of concrete, especially the frost resistance and resistance to the Cl^- ion permeability. SiO_2 concrete is suitable for bridge deck pavement and bridge head approach in the cold regions of North China.

2. Testing Conditions

2.1. Raw Materials. Experimental raw materials include Harbin Yatai (China) cement of grade P.O. 42.5, fine aggregate (medium-sized sand) produced by Yunhe Sandpit (China), coarse aggregate (1-2 cm and 2-3 cm gravel) produced by Tianlongshan Quarry (China), and a concrete admixture (Y-1E air-entraining water-reducing agent), and three phosphoric acid tincture ester cement concrete mixture ratios are shown in Table 1.

In all the tests, the nano-SiO_2 is highly dispersible nano-SiO_2 produced by Nanjing EPRI Composite Materials Co., China. The main technical parameters of the dispersible nano-SiO_2 are shown in Table 2.

The method of adding nano-SiO_2 is to mix nano-powder and cement well in dry state before an experiment and then mixing them with other components to make concrete. The blending process of SiO_2 is shown in Figure 1. The mixing ratio is the mass percentage of nano-SiO_2 in the cementitious materials.

2.2. Durability Indexes. Frost resistance (both water and salt freezing), resistance to Cl^- ion permeability, and abrasion resistance of concrete are key factors that affect the durability of concrete bridge deck pavement in cold regions; furthermore, strength is the most basic performance parameter of concrete and is obtained by analyzing and consulting available information. Therefore, for this study, we selected strength, frost resistance, resistance to Cl^- ion permeability, and abrasion resistance of concrete (with 1% content of nano-SiO_2 and without nano-SiO_2) as the indexes by which to evaluate the durability of concrete bridge deck pavement in cold regions.

Through tests on the abovementioned four durability indexes, we evaluated the ability of nano-SiO_2 to improve the durability of concrete bridge deck pavement.

Table 1: Cement concrete mixture ratios.

Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Water reducer (kg/m^3)	Defoaming agent (kg/m^3)	Water cement ratio
370	752	1178	147	3.145	0.374	0.40

Table 2: Major technical parameters of nano-SiO_2.

Project	Average grain diameter (nm)	Purity (%)	Crystal form	Specific surface area (m^2/g)	Apparent density (g/cm^3)	Color
Technical index	15	99.5	Globospherite	300	0.05	White

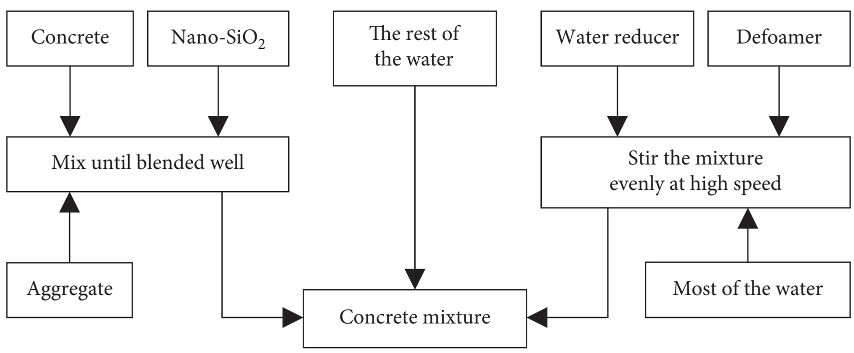


Figure 1: The blending process of SiO_2.

2.2.1. Concrete Strength. Strength is the most basic performance parameter of concrete and directly determines the durability of concrete bridge deck pavement. Therefore, the optimum content of nano-SiO_2 was determined through the experiments on the flexural and compressive strength of concrete using different amounts of nano-SiO_2.

According to T0558-2005 and T0555-2005 in *Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005)*, the flexural strength test and compressive strength test of concrete were carried out, respectively.

2.2.2. Frost Resistance. According to T0565-2005 in *Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005)*, the concrete frost resistance was carried out using the fast freezing method.

The concrete specimens were $100 \times 100 \times 400\,mm^3$ prisms. After 28 d of curing, the specimens (with and without nano-SiO_2) were frozen and thawed. In the first 4 d of freezing and thawing tests, the specimens (with and without nano-SiO_2) were divided into two groups and placed in the two separate solutions. One solution was ordinary water at a temperature between 15 and 20°C, which was used to simulate the ordinary nonfrost tests under a chloride salt environment. The other solution was a 5% sodium chloride solution at a temperature between 15 and 20°C, which was used to simulate freeze-thaw tests under a chloride salt environment.

2.2.3. Resistance to Cl^- Ion Permeability. Referring to *Standard for constructional quality acceptance of railway concrete and masonry engineering* (*TB10424-2003*), the test of resistance to Cl^- ion permeability was conducted using the electric flux method. The concrete specimens were made into cylinders 100 mm in diameter and 50 mm high. After 28 d of curing, the specimens were tested.

2.2.4. Abrasion Resistance. According to T0567-2005 in *Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005)*, the concrete abrasion resistance test was carried out.

The concrete specimens for abrasion testing were $150 \times 150 \times 150\text{-}mm^3$ cubes. After 27 d of curing, the specimens were wiped dry of surface moisture. After air drying for 12 h indoors, the specimens were placed in an oven with a temperature of 60°C for 12 h until they reached a constant weight.

3. Test Results Analysis

3.1. Strength Tests. In order to determine the optimum content of nano-SiO_2, tests of concrete flexural and compressive strength (for durations of 7 and 28 d) with 0, 0.2%, 0.5%, 0.8%, 1%, 2%, and 3% nano-SiO_2 content were performed.

Nano-SiO_2 was added to replace cement, that is, the amount of SiO_2 is added as much as the amount of cement is reduced.

The flexural strength test results are shown in Figure 2, which shows that the concrete flexural strength at 7 d increased by 7.7%, 12.5%, 13.1%, 15.4%, 15.8%, and 11.6%, respectively and at 28 d, increased by 3.9%, 6.0%, 7.1%, 9.7%,

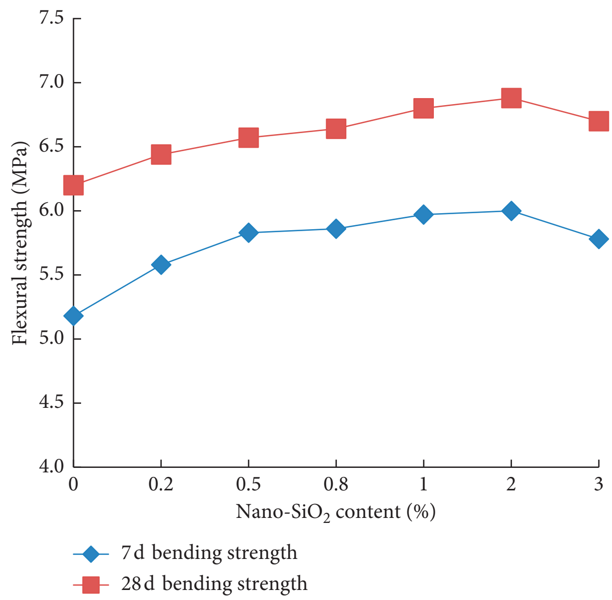


Figure 2: Flexural strength test results.

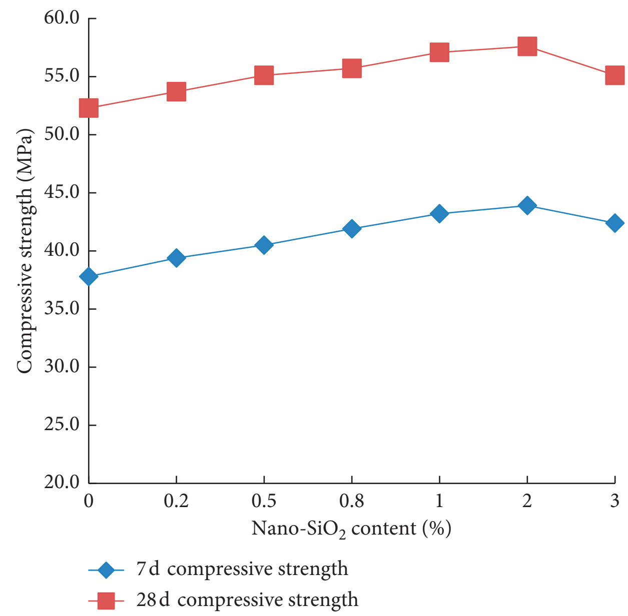


Figure 3: Compressive strength test results.

11.0%, and 8.1%, respectively, when the nano-SiO_2 content was increased from 0 to 0.2%, 0.5%, 0.8%, 1%, 2%, and 3%.

Compressive strength test results are shown in Figure 3, which shows that the concrete compressive strength at 7 d increased by 4.2%, 7.1%, 10.8%, 14.3%, 16.1%, and 12.2%, respectively and at 28 d, increased by 2.7%, 5.4%, 6.5%, 9.2%, 10.1%, and 5.4%, respectively, when the nano-SiO_2 content was increased from 0 to 0.2%, 0.5%, 0.8%, 1%, 2%, and 3%. Both 7- and 28-day concrete compressive strengths increased faster when the nano-SiO_2 content was increased from 0 to 1%.

It can be seen from Figures 2 and 3 that both 7- and 28-day flexural strengths and compressive strength concrete increased faster when the nano-SiO_2 content was increased from 0 to 1%. Improvements in concrete flexural strengths and compressive strength for the same duration are not obvious when the nano-SiO_2 content was increased from 1% to 2%. Both 7- and 28-day compressive strength and flexural strengths of concrete are reduced when the nano-SiO_2 content was increased from 2% to 3%.

From analysis of the results of Figures 2 and 3, when the nano-SiO_2 content was increased from 0 to 1%, both the flexural strength and compressive strength of concrete were significantly improved. When the nano-SiO_2 content was increased by more than 1%, the improvement of the concrete's flexural and compressive strength was not obvious. When the nano-SiO_2 content was close to 3%, both the flexural strength and compressive strength decreased. Therefore, we recommend 1% as the optimum amount of nano-SiO_2 in concrete bridge deck pavement, which was verified by follow-up testing.

3.2. Frost Resistance Tests

3.2.1. Common Frost Resistance Tests. Different numbers of freeze-thaw cycle tests of concrete with and without nano-SiO_2 were carried out under a nonchloride salt environment. Changes in concrete mass loss rate and relative dynamic elastic modulus with increasing number of freeze-thaw cycles are shown in Figures 4 and 5.

It can be seen from Figures 4 and 5 that under the condition of 50, 100, 150, 200, 250, and 300 freeze-thaw cycles, the mass loss rate of concrete with nano-SiO_2 is 0.24%, 0.4%, 0.63%, 0.74%, and 0.87% lower than that of concrete without nano-SiO_2, respectively, and the relative dynamic elastic modulus of concrete with nano-SiO_2 is 3.1%, 6.4%, 8.9%, 12.1%, 14.8%, and 18.2% higher than that of concrete without nano-SiO_2, respectively.

From analysis of the results of Figures 4 and 5, under the nonchloride salt environment, the frost resistance of concrete with nano-SiO_2 is better than that of concrete without nano-SiO_2. In particular, with an increasing number of freeze-thaw cycles, the effect of nano-SiO_2 in improving the frost resistance of concrete is more obvious.

3.2.2. Frost Resistance Tests under Chloride Salt Environment. The use of deicing salt causes serious salt damage to bridge deck pavement concrete in cold regions. In order to simulate the freezing and thawing conditions in a chloride salt environment in cold regions, the previously used solution was replaced with a 5% NaCl solution as a soaking solution for freeze-thaw cycle tests.

With an increasing number of freeze-thaw cycles, the changes in mass loss rate and the relative elastic modulus of concrete mixed with nano-SiO_2 and nondoped nano-SiO_2 in a chloride salt environment are shown in Figures 6 and 7, respectively.

From Figures 4 and 6, it can be seen that the mass loss rate of ordinary concrete (not doped with nano-SiO_2) in a chloride salt environment is 0.26%, 0.57%, 0.59%, 0.7%, 0.62%, and 0.92% higher than that in a nonchloride salt

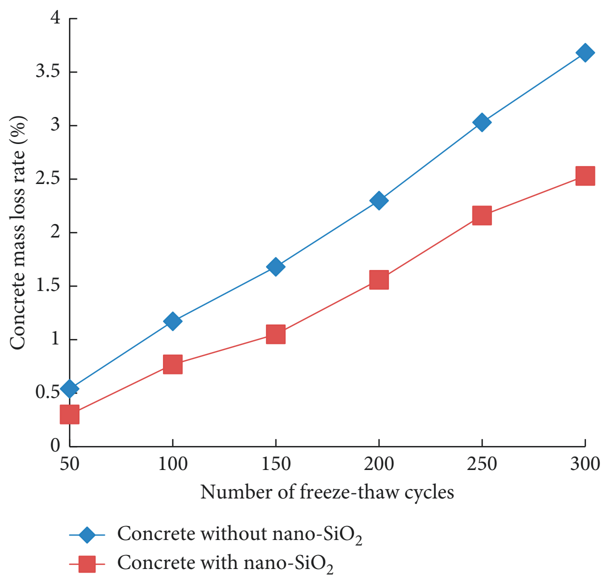


FIGURE 4: Change of mass loss rate with number of freeze-thaw cycles.

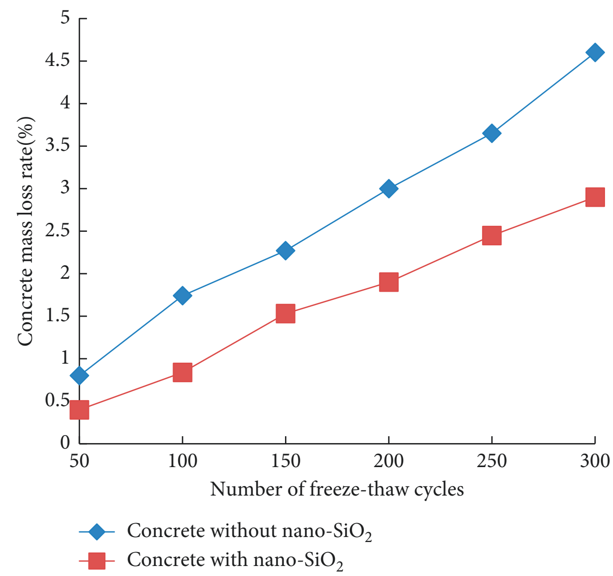


FIGURE 6: Variation of mass loss rate with freeze-thaw cycles in chloride salt environment.

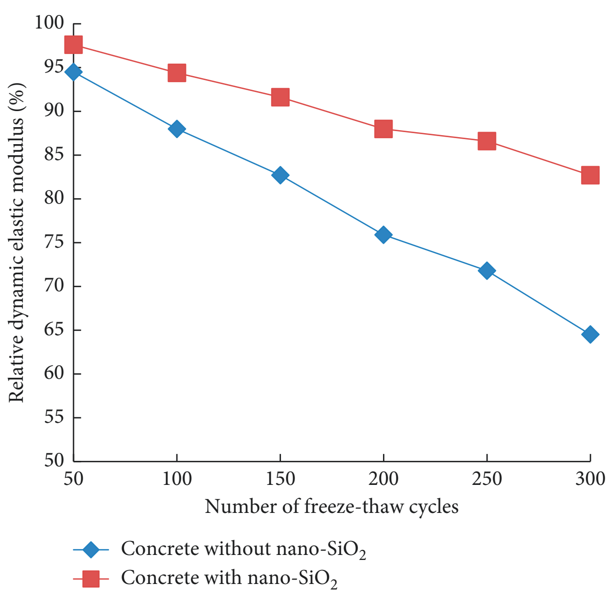


FIGURE 5: Change of relative dynamic elastic modulus with number of freeze-thaw cycles.

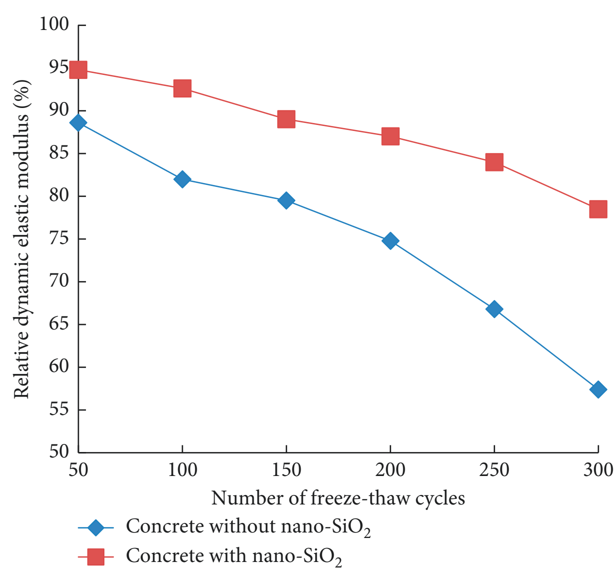


FIGURE 7: Change of relative dynamic elastic modulus with number of freeze-thaw cycles in chloride salt environment.

environment, respectively, under 50, 100, 150, 200, 250, and 300 freeze-thaw cycles. From Figures 5 and 7, it can be seen that the relative elastic modulus of ordinary concrete in a chloride salt environment is 5.9%, 6%, 3.2%, 1.1%, 5.0%, and 7.1% lower than that in a nonchloride salt environment, respectively, under 50, 100, 150, 200, 250, and 300 freeze-thaw cycles. The test results show that with the increase of freeze-thaw cycles, the destruction of chloride to concrete is accelerated.

It can be seen from Figures 6 and 7 that in a chloride salt environment, the mass loss rate of concrete doped with nano-SiO_2 is 0.4%, 0.9%, 0.74%, 1.1%, 1.2%, and 1.7% lower than that of concrete that was not doped with nano-SiO_2, respectively, and the relative elastic modulus of concrete doped with nano-SiO_2 is 6.2%, 10.6%, 9.5%, 12.2%, 17.2%, and 21.1% higher than that of concrete not doped with nano-SiO_2 respectively, under 50, 100, 150, 200, 250, and 300 freeze-thaw cycles.

These results show that the frost resistance of concrete doped with nano-SiO_2 is better than that of concrete not doped with nano-SiO_2 under a chloride salt environment, especially with increasing number of freeze-thaw cycles. Therefore, the effect of nano-SiO_2 in improving the frost resistance of concrete is more obvious in a chloride salt environment.

3.3. Resistance to Cl^- Ion Permeability Tests. Because concrete is a porous material, harmful ions such as Cl^- ions easily pass through pores into its interior and are able to change the pH of the concrete pore solution and cause damage from steel corrosion, alkali aggregate reaction, and electrochemical corrosion. Therefore, the resistance to Cl^- ion permeability is an important indicator in evaluating concrete durability [16]. Currently, there is no standard for evaluation and testing of resistance to Cl^- ion permeability for concrete in China.

The electric flux method was to evaluate the Cl^- ion permeability of concrete as specified in China National Standards No. JTJ275-2000 ("Corrosion prevention specifications for concrete structures of marine harbor engineering"), No. TB10424-2003 ("Standard for constructional quality acceptance of railway concrete and masonry engineering"), and SL 352-2006 ("Test code for hydraulic concrete").

In this paper, with reference to the aforementioned standards, electric flux tests of concrete with and without nano-SiO_2 were carried out to verify the ability that nano-SiO_2 improves the Cl^- ion permeability of concrete after curing for 7 and 28 d. The electric flux test results are shown in Figure 8.

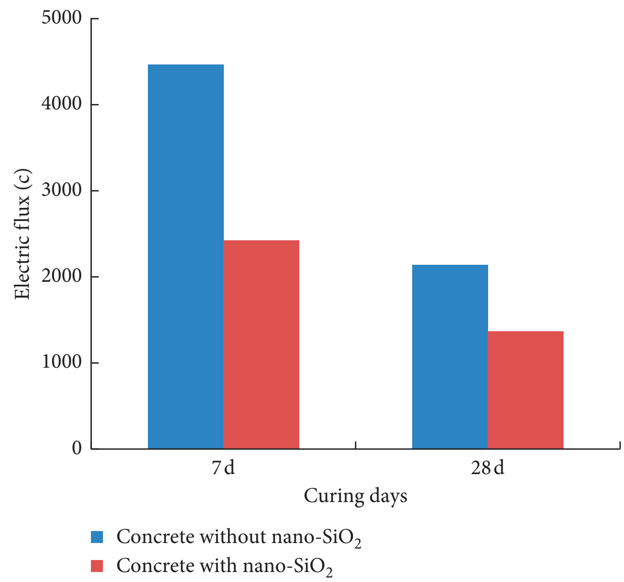


Figure 8: Electric flux test results.

From Figure 8, it can be seen that whether concrete is doped with or without nano-SiO_2, its electric flux after 28 d of curing is significantly lower than that after 7 d of curing. This indicates that concrete's resistance to Cl^- ion permeability is significantly improved with the growth of concrete and the increase of its strength. At the same time, it can also be seen from Figure 7 that after curing for 7 d, the electric flux of concrete with nano-SiO_2 is 2045 lower than that of concrete without nano-SiO_2, a decrease of 45.8%. After 28 d of curing, the electric flux of concrete with nano-SiO_2 is 770 lower than that of concrete without nano-SiO_2, a decrease of 36.0%. This indicates that the incorporation of nano-SiO_2 can obviously improve the resistance to Cl^- ion permeability of concrete, especially in the early period of concrete curing.

3.4. Abrasion Resistance Tests. Abrasion resistance tests of concrete mixed with and without nano-SiO_2 were carried out after curing for 28, 56, and 84 d.

We first weighed the concrete specimen after it was ground 30 times under a load of 200 N; this mass was denoted as m_1. We then weighed it after it was ground 60 times under a load of 200 N; this mass was denoted as m_2. Finally, the abrasion loss owing to specimen wear was calculated using the following formula:

$$G_C = \frac{m_1 - m_2}{0.0125}, \tag{1}$$

where G_C is the abrasion loss of unit area (in kg/m^2), m_1 the initial mass of the specimen (kg), m_2 the mass of the specimen after grinding (kg), and 0.0125 the wear area of the specimen (m^2).

The results of abrasion resistance tests of concrete mixed with and without nano-SiO_2 are shown in Figure 9. It can be seen from the figure that the abrasion resistance of concrete mixed with and without nano-SiO_2 increased gradually with increasing concrete age. At the same time, it can be seen from Figure 9 that after curing for 7 d, the abrasion loss rate of concrete with nano-SiO_2 is 1.2 lower than that of the concrete without nano-SiO_2, a decrease of 36.4%. After 28 d of curing, the abrasion loss rate of concrete with nano-SiO_2 is 0.9 lower than that of the concrete without nano-SiO_2, a decrease of 39.1%. After 84 d of curing, the abrasion loss rate of concrete with nano-SiO_2 is 0.8 lower than that of the concrete without nano-SiO_2, a decrease of 44.4%. These results show that the abrasion resistance of concrete is greatly improved by the incorporation of nano-SiO_2; in addition, the effect of nano-SiO_2 in improving the abrasion resistance of concrete is more obvious with increasing concrete age.

4. Analysis of Improvement Mechanism

By referring to the relevant literature, it can be seen that the density of cement concrete is related to the durability of the concrete [17]. The higher the density and uniformity of concrete, the better its durability [18].

In this study, scanning electron microscopy (SEM) (Quanta 200, Thermo Fisher Scientific, Inc., USA) was used to observe the microstructure of ordinary concrete with and without nano-SiO_2 after curing for 28 d.

Figure 10 shows a comparison of the microstructures of concrete core with and without nano-SiO_2. It can be seen from the figure that the pore size of ordinary concrete structure without nano-SiO_2 is larger and the pore structure of concrete with nano-SiO_2 is smaller. The structure of concrete with nano-SiO_2 is uniform and neat, close-grained, and closely combined, which indicates that nano-SiO_2 improves the micropore structure of cement concrete and enhances its density.

It has been shown in [19] that in the hydration process of concrete without nano-SiO_2, the interface between the coarse aggregate and the cement stone will accumulate a

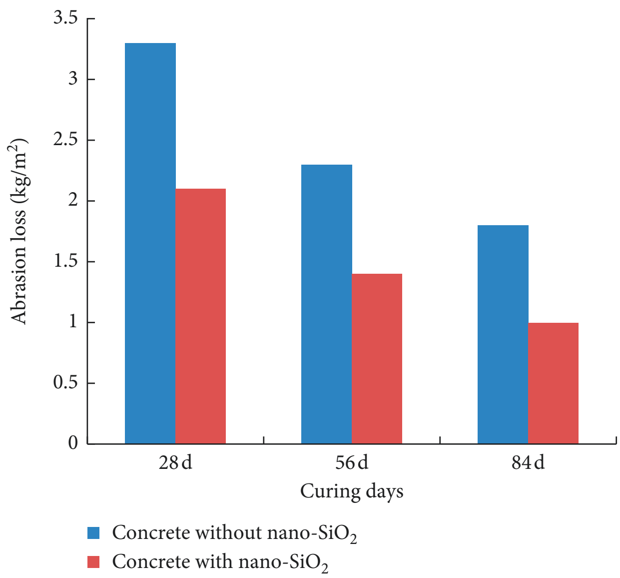


Figure 9: Abrasion resistance test results.

large amount of $Ca(OH)_2$. The crystallization and orientation of $Ca(OH)_2$ at the interface reduces the strength and durability of the concrete.

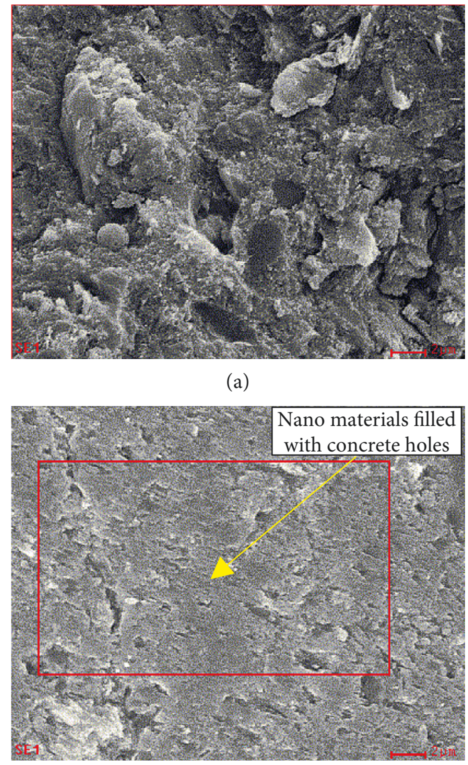
Figure 11 shows a comparative analysis of the distribution of elements in the microscopic regions of concrete with and without nano-SiO_2 using energy-dispersive X-ray spectroscopy. It can be seen from Figure 11 that the amount of free calcium ions in concrete decreased obviously after adding silica. It shows that nano-SiO_2 significantly reduces the peak value of $Ca(OH)_2$ in concrete. The following reaction occurred in cement concrete after the incorporation of nano-SiO_2 [20]:

$$n\mathrm{Ca(OH)_2} + \mathrm{SiO_2} + m\mathrm{H_2O} \longrightarrow m\mathrm{CaO} \cdot \mathrm{SiO_2} \cdot (m+n)\mathrm{H_2O} \quad (2)$$

The average particle size of nano-SiO_2 is only 15 nm, which makes it a kind of superfine material that can fill in the microscopic voids of cement concrete well [21]. The nano-sized particles promote the hydration reaction of concrete. A large number of nano-SiO_2 superfine particles on the surface of which the hydrated products gather, grow, spread into spaces, and overlap with each other are used as the "core." The hydrated products with nano-SiO_2 as their cores become small units that are connected to each other to form a uniform and compact whole [16, 17]. The nano-SiO_2 effectively absorbs the $Ca(OH)_2$, which was released in the early stage of hydration of cement and increases the content of hydrated calcium silicate, which improved the interface between the hardened cement paste and aggregate. This improves the strength of concrete and enhances its durability.

5. Conclusions

The addition of nano-SiO_2 in bridge deck pavement concrete can improve the durability of the concrete effectively, prolong the service life of the bridge deck pavement, reduce the early onset of damage to bridge deck pavement, and



(a)

(b)

Figure 10: Comparison of concrete microstructures for concrete without and with nano-SiO_2: (a) microstructure of concrete without nano-SiO_2; (b) microstructure of concrete with nano-SiO_2.

reduce repair and maintenance costs; consequently, it has significant social and economic value. The following conclusions are obtained from the experimental studies and theoretical analysis in this paper:

(1) In cold regions of China, bridge deck pavement concrete is prone to serious damage exacerbated by adverse weather conditions. The low durability of ordinary concrete is an important cause of damage to concrete bridge deck pavement. Therefore, it is necessary to enhance the durability of concrete used in bridge deck pavement in cold regions of China.

(2) Frost resistance, resistance to Cl^- ion permeability, and abrasion resistance of concrete are important indexes in the evaluation of the durability of bridge deck concrete in cold regions of China. Based on the results of tests described in this paper, when concrete is mixed with nano-SiO_2, the three aforementioned indexes are greatly improved. Thus, we conclude that the addition of nano-SiO_2 can improve the durability of bridge deck concrete in cold regions of China.

(3) Nano-SiO_2 incorporated into concrete can effectively absorb $Ca(OH)_2$, which is released in the early stage of hydration of cement and increases the content of hydrated calcium silicate, which improves the interface between the hardened cement paste and aggregate. In addition, it improves the strength of concrete and enhances its durability.

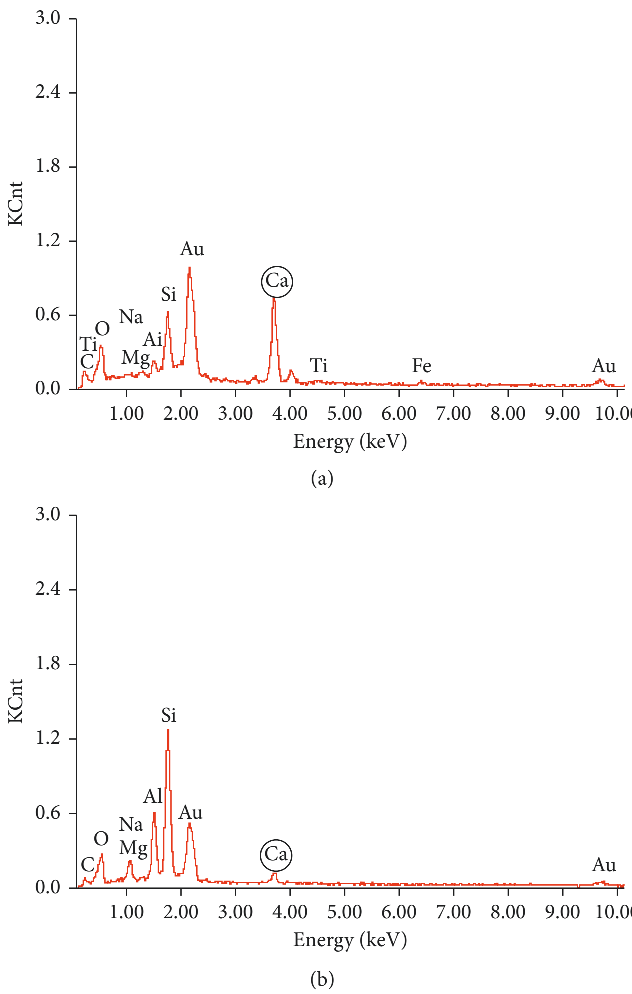


Figure 11: Comparison of distribution of elements in microscopic regions of concrete without and with nano-SiO_2: (a) distribution of elements in the microscopic region of concrete without nano-SiO_2; (b) distribution of elements in the microscopic region of concrete with nano-SiO_2.

(4) From a technical point of view, the addition of nano-SiO_2 will enhance the durability of concrete in cold regions of China, so it is suitable for most concrete road projects. However, from the economic perspective, nano-SiO_2 increases the costs of such projects, and its application is obviously uneconomical in ordinary road concrete projects. Therefore, addition of nano-SiO_2 is only suitable for the key parts of vehicle-bearing surfaces, such as bridge deck pavements and bridge head guidance roadways. It is especially suitable for the concrete layer of bridge deck pavement in cold regions of China because it is more prone to damage.

Data Availability

The experimental data used to support the findings of this study are included within the article. Requests for future data, 6 months after publication of this article, will be considered by the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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