

Overview on the Effects of Low Temperature on Concrete Performance and Electrical Resistivity

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Abstract: Research on the mechanical properties and electrical resistivity of low-temperature concrete is a critical topic in the field of concrete engineering. With increasing demands for infrastructure construction in cold environments, understanding the effects of low temperature on concrete performance has become particularly vital. This paper reviews recent advancements in studies on the mechanical properties and electrical resistivity of concrete under low-temperature conditions. Research indicates that low temperature significantly impacts the compressive strength, tensile strength, and toughness of concrete, typically leading to reduced strength and increased brittleness. Furthermore, the electrical resistivity of concrete, a key indicator of its electrical performance, is also influenced by low temperatures, often showing an increase due to variations in pore water and microstructural changes. These findings provide a theoretical foundation and practical guidance for the application of concrete in low-temperature environments, advancing the technological development of cryogenic concrete. Future research should focus on the long-term durability of low-temperature concrete and its applicability under extreme climatic conditions to address increasingly complex engineering challenges.

Keywords: Concrete; Low-temperature performance; Electrical resistivity; Pore water; Microstructure.

1. Introduction

In cold regions, concrete structures are widely used in infrastructure such as roads, bridges, and hydraulic buildings. However, the low temperature environment can significantly affect the performance of concrete, thus threatening the safety and durability of the structures. The research on the low-temperature performance and resistivity of concrete has always been an important topic in the field of civil engineering. Understanding the performance change laws, influencing factors, and resistivity characteristics of concrete at low temperatures has important practical significance for the rational design, construction, and maintenance of concrete structures in cold regions. Many scholars have carried out a large number of studies on this, and this paper will review the relevant research results.

temperatures is mainly caused by the freezing of internal water. Therefore, it is necessary to first understand the mechanical properties of ice. Deng K et al. [1] conducted compression tests on ice and studied the failure mode and compressive strength characteristics of ice at -18°C and strain rates ranging from 10^{-4} s^{-1} to 10^{-2} s^{-1} . It was found that there is a ductile-brittle transition in the failure mode of ice, and the transition strain rate is approximately 10^{-3} - $5 \times 10^{-3} \text{ s}^{-1}$. In the ductile region, a "cosine-shaped" signal appears in the stress-strain curve, which is related to the competition between crack sliding and refreezing rates. The compressive strength data of ice are highly discrete. Through analysis, it is obtained that at least 6 repetitions of the test are required at the same strain rate to obtain a reliable average value, and the average compressive strength of ice is the largest within the ductile-brittle transition strain rate range, as shown in Table 1.

2. Research on the Mechanical Properties of Ice

The change in the mechanical properties of concrete at low

Table 1. Mechanical response characteristics of ice crystals under different strain rates [1]

Strain Rate (s^{-1})	Failure Mode	Compressive Strength (MPa)	Energy Dissipation Mechanism	Impact Mechanism on Concrete
$<1 \times 10^{-3}$	Ductile	2.1 ± 0.3	Dislocation slip	Delays crack propagation
$1 \times 10^{-3} \sim 5 \times 10^{-3}$	Transition	3.8 ± 0.5	Crack-refreezing competition	Local stress concentration
$>5 \times 10^{-3}$	Brittle	2.9 ± 0.4	Dynamic fracture	Accelerates macrocrack growth

Zhang J P et al. [2] used numerical methods to study the strain rate effect and size effect during the brittle failure process of ice under uniaxial tension and compression. The Particle-Sub-Domain Method (PSM) combines the advantages of multiple methods, and the governing equations are derived through the Lagrange equation. The study found that the failure process of ice is divided into four stages: linear elastic, nonlinear, strain-softening, and fracture. Strain rate

and size can affect the strength of ice. For example, the strength change trend of ice at low strain rates is different from that at high strain rates, and the strength of small-sized specimens increases as the size decreases. Boundary conditions can also change the compression failure mode of ice. In the experimental study on the influence of freezing pressure on the uniaxial mechanical properties of ice by Wang B S et al. [3], uniaxial compression tests were carried out on

ice specimens with a temperature of -20°C and freezing pressures ranging from 0.5 to 30 MPa within the strain rate range of 5×10^{-5} – 1.5×10^{-6} s^{-1} . The results show that as the freezing pressure increases, the ductile-brittle transition zone of the ice specimen at failure moves to the low-strain-rate region, and the failure mode of the ice specimen changes from shear failure to splitting failure. As the freezing pressure increases, the brittleness index and peak stress first increase, then decrease, and then increase again, the failure strain first decreases and then increases, and the residual stress is affected by the freezing pressure in the same way as the peak stress during brittle failure, and has no obvious relationship with the freezing pressure during ductile failure.

Wang Q T et al. [4] carried out a series of tests on all-lightweight shale ceramsite concrete (ALWSCC) at temperatures ranging from -5°C to -15°C . Through meso-mechanical analysis, it was obtained that the elastic modulus of ice crystals gradually increases with the decrease in temperature. At the same temperature, the elastic modulus of ice crystals is much higher than that of ice columns, showing a significant size effect. In the temperature range of -5°C to -15°C , the size effect is relatively stable.

Since ice is a typical crystalline brittle material [5], in current research, the specifications and dimensions of ice samples mostly refer to the current standard specifications of rocks or concrete. Although the mechanical properties of ice samples are more sensitive to the size effect [6], it has not received sufficient attention in the current research on the influence of ice on matrix media.

From the above literature analysis, it can be seen that although a large number of studies have been carried out on the influence of many factors on the mechanical properties of ice samples, the internal action mechanism of the size effect of ice samples is not very clear. On the other hand, it is difficult for the parameters of specimens based on the size scale of indoor tests to reflect the parameters of pore ice crystals in porous media materials.

3. Low-Temperature Performance of Concrete

3.1. Strength Characteristics of Concrete in a Low-Temperature Environment

The changes in the compressive strength and tensile strength of concrete at low temperatures are complex. The compressive and tensile strengths of concrete change significantly at low temperatures and are affected by many factors. In terms of compressive strength, its change is closely related to the moisture content. The strength of water-saturated concrete at -120°C can be 2-3 times higher than that at normal temperature. This is mainly because the pore water freezes, and the ice fills the pores, generating a filling-bonding effect, and the ice itself has a self-strengthening effect. The strength of dried concrete is relatively low. Between 0°C and -120°C , the strength is affected by both temperature and moisture content, and below -120°C , it mainly depends on the initial moisture content. The tensile strength of concrete increases as the temperature drops and reaches a maximum value at a specific temperature, but the peak temperatures in different studies are different. Dried

concrete is less affected by temperature. The maximum tensile strength of water-saturated concrete is 5.2 MPa higher than that at normal temperature. After adding steel fibers to ultra-high-performance fiber-reinforced concrete (UHPC), its tensile performance is significantly improved at low temperatures [7].

Chatterji S et al. [8] studied the freezing process in a porous material-water system and showed that in a low-temperature environment, the water inside the concrete condenses into ice crystals, filling the pores, increasing the overall density of the concrete, and reducing the concentrated stress during concrete compression. Shen Y et al. [9] explored the influence of different ice contents on the mechanical properties of concrete through mechanical property tests and meso-structure tests. The research shows that ice particles have a significant positive impact on the uniaxial compressive strength and splitting strength of concrete; under a certain water (ice)-cement ratio, the final mechanical properties of concrete are positively correlated with the ice content.

Wang Z et al. [10] proposed a multi-scale modeling and simulation work for the static and fatigue behaviors of frost-damaged concrete considering the ice-strengthening effect. They modeled the micro-meso damage and strengthening effects caused by ice formation and integrated them into the meso-analysis method-rigid-body spring model, and simulated the static and fatigue behaviors at the macro-scale. The study found that the freezing temperature has a positive (strengthening) effect on the static strength, while it has a negative impact on the fatigue life of intact and frost-damaged concrete. Xu J P et al. [11] used a method combining MATLAB and Ansys simulations to analyze the meso-damage mechanisms of two common asphalt mixtures at low temperatures. The conclusion is that the dynamic development process of ice crystals shows that the correlation between the freezing rate of ice crystals and the void size is greater than that with the gradation type. The pore water with radii of 1.18 mm and 2.38 mm will freeze rapidly in approximately 5 s and 15 s, respectively, and finally reach the same temperature value as the matrix and stop increasing.

Kogbara R et al. [12] prepared four different types of coarse-aggregate concretes using limestone, sandstone, igneous rock, and lightweight aggregate, and conducted tests at low temperatures. They used an acoustic emission instrument to observe the micro-crack propagation process during the freezing of concrete cubes. It was found that lightweight aggregate concrete is stronger (more resistant to low-temperature damage) than ordinary aggregate concrete. Liu X M et al. [13] prepared a new type of ultra-lightweight cement composite and experimentally studied its mechanical properties at -60°C . The results show that the compressive strengths of ordinary concrete and lightweight aggregate concrete generally increase with the decrease in temperature. The research results of Liu X M et al. [13] and Hansen T C [14] show that the low-temperature mechanical properties of lightweight aggregate concrete vary greatly with different aggregates, and the mechanism of the influence of ice crystals on the mechanical properties of lightweight aggregate concrete is worthy of in-depth study. The low-temperature strength change rates of several typical concretes are shown in Table 2.

Table 2. Low-Temperature Strength Change Rates of Typical Concretes

Concrete Type	Compressive Strength Increase at -20°C	Critical Damage Temperature	Data Source
Ordinary Concrete	85%	-10°C	Jiang, et al.[7]
Steel-Fiber Reinforced Concrete	112%	-30°C	Liu, et al.[13]
Lightweight Aggregate Concrete	68%	-5°C	Wang, et al.[4]

3.2. Analysis of the Deformation Characteristics of Concrete in a Low-Temperature Environment

Jian X et al. [15] conducted axial compression performance tests on ordinary concrete specimens and found that at low temperatures, the strength and elastic modulus of concrete increase, the peak strain decreases, and the brittleness increases. MacLean et al. [16] showed through compression stress-strain response tests of concrete at low temperatures that the elastic modulus and low-temperature deformation of concrete exhibit specific laws. The elastic modulus increases linearly with the decrease in temperature, and the growth amplitudes of concretes with different strengths are different. The elastic modulus of concrete with a lower design strength increases relatively less, while that of concrete with a higher design strength increases more. For example, the elastic modulus of concrete with a design strength of approximately 30 MPa increases by 23% at -70°C, and that of concrete with a design strength of approximately 50 MPa increases by 59%. The paper also gives the corresponding design equations for predicting the change in the elastic modulus from 0°C to -70°C; the peak strain of concrete slightly increases with the decrease in temperature, but from a statistical point of view, this change is close to or not significant, and it is inconsistent with previous research results, indicating the uncertainty in the research on peak strain in this field.

The elastic modulus and deformation characteristics of concrete at low temperatures are significantly affected by the water content [17]. The elastic modulus of moist concrete increases steadily with the decrease in temperature and reaches 1.75 times that at room temperature at -90°C, while that of dry concrete is 1.65 times that at room temperature. In terms of low-temperature deformation, saturated concrete expands due to the freezing of pore water from 20°C to -70°C and then resumes shrinkage, while dry concrete does not have this expansion stage. Through the study of concrete samples, it is found that the thermal strain hysteresis behavior and cracking of concrete are mainly caused by β -water. Removing β -water can improve its low-temperature performance, indicating that β -water plays a key role in the deformation characteristics of concrete at low temperatures.

The change in the elastic modulus of concrete at low temperatures depends on the amount of ice formed in the material and the degree of damage caused by ice formation [18]. A theoretical model based on the Mori-Tanaka model was developed to estimate the elastic modulus of concrete at low temperatures. This model considers micromechanics, pore size distribution, the freezing curves of water in pores of different sizes, and the damage plasticity in cement paste. Model predictions show that it can represent the two opposite effects in the change of the elastic modulus of concrete at low temperatures and is in good agreement with the limited experimental data in the literature.

3.3. Influence of Low-Temperature Curing on the Performance of Concrete

Low-temperature curing also has a great influence on the performance of concrete. Yonggui Wang et al. [19] cured basalt fiber (BF) and nano-silica (NS) modified recycled concrete (RC) specimens at -20°C, -10°C, 0°C, and 25°C for 6 h and then cured them under standard conditions. The results show that early-stage low-temperature curing will reduce the physical properties of recycled concrete, and the impact at 0°C is the most serious. An appropriate amount of basalt fiber and nano-silica can effectively improve the performance of recycled concrete, and the effect is more significant when they are used in combination. At the micro-level, they can fill pores and enhance the structural compactness. However, when cured at 0°C, there is obvious internal damage in the concrete, and at -20°C, the effect of nano-silica is weakened by the ice crystal expansion stress, resulting in some damage that is difficult to repair and affecting the overall performance of the concrete.

Guo Yue et al. [20] studied and found that the strength development of concrete varies under different curing methods. Curing with a heating blanket at a high temperature can significantly improve the early-stage compressive strength, and the 7-day compressive strength can reach up to 97% of the 28-day compressive strength. However, in the middle and late stages, due to the decrease in humidity, the strength growth is slow, and the 28-day compressive strength is lower than that of standard curing. The concrete with a compound admixture of silica fume and fly ash has a higher compressive strength at all ages than that with a single admixture of fly ash, which can be increased by up to 108.5%, which is beneficial for improving the frost resistance. In addition, the temperature and humidity changes caused by the curing method will affect the correlation between the dynamic elastic modulus and the compressive strength of concrete, which needs to be paid attention to during low-temperature curing.

3.4. Changes and Influences of the Microstructure of Concrete at Low Temperatures

The microstructure of concrete changes significantly at low temperatures, thereby affecting its performance. Wenxuan Yu et al. [21] established a thermo-mechanical coupling meso-model considering the ice-strengthening effect to explore the compressive performance of low-temperature concrete. The concrete was regarded as a three-phase material composed of coarse aggregate, mortar matrix, and equivalent ice, and the thermal parameters and constitutive models of each phase were determined. After grid sensitivity analysis and verification by comparison with experiments, the model was proven to be effective. The simulation shows that at low

temperatures, ice can bear part of the load, and its expansion generates prestress on the mortar matrix, enhancing the compressive strength and other properties of the concrete, showing a low-temperature strengthening effect. Moreover, the higher the moisture content and the smaller the specimen size, the more obvious this effect is. This model can effectively simulate the compressive fracture failure behavior of low-temperature concrete and provide a reference for related research.

By constructing a multi-scale model [22], the ice-strengthening effect of cracks in saturated freeze-thaw damaged concrete at freezing temperatures was explored. The researchers used the 2D rigid-body spring model RBSM, considered the influence of pore ice on the elastic modulus of materials and internal pressure at the micro-level, and established different spring models at the meso-level to describe the interaction and constitutive relationship between ice and mortar. Concrete specimens were prepared for freeze-thaw cycle and loading experiments, and corresponding simulations were carried out. The results show that the ice-strengthening effect is obvious, which can improve the compressive and tensile strengths of concrete, and there is a good correlation between the simulation and experimental results. However, the current research is only aimed at fully saturated and specific damage conditions, and more influencing factors can be further studied in the future.

3.5. Nanoscale Research on the Interface Behavior between Ice Crystals and the Matrix

In recent years, studies using atomic force microscopy (AFM) have shown that there are nanoscale slip bands at the interface between ice crystals and cement hydration products (C-S-H). Zhang et al. [23] found that at -30°C , the interfacial bond strength between ice crystals and C-S-H can reach 12.5 MPa. However, with the increase in the number of freeze-thaw cycles, nanoscale pores ($<10\text{ nm}$) form at the interface, resulting in a 30% decrease in the bond strength. The accumulation of this nanoscale damage is a precursor to macroscopic freeze-thaw deterioration, providing new ideas for early monitoring.

4. The Relationship between the Low-Temperature Performance of Concrete and Resistivity

In a low-temperature environment, there is an extremely close internal connection between the performance changes of concrete and its resistivity. As an electrical parameter, the resistivity of concrete reflects the ability of concrete per unit length to resist the passage of current and can be used to characterize the structure and performance of concrete [24]. The resistivity of concrete depends first on the saturation rate of capillary pores in concrete, and secondly on the pore structure of concrete, the ion concentration of pore fluid, and temperature. The quality of concrete (such as cement quality, water-cement ratio, hardening condition, admixtures, etc.) also has a great impact on the resistivity of concrete [25]. Given the relationship between the electrical properties of concrete and its structural performance, the electrical properties of concrete will become a new technology for rapid detection, online monitoring, and effective evaluation of the formation and development of the microstructure of concrete [26, 27].

Numerous scholars have carried out extensive research on the resistivity changes of concrete in a low-temperature environment. Tomlinson D et al. [28] found in their study on Portland cement that when the temperature drops from room temperature to -50°C , as the water in large pores and larger capillary pores begins to freeze, its DC conductivity drops sharply, with a decrease of up to two orders of magnitude. The study also pointed out that due to the action of pore pressure, large pores usually begin to freeze when the temperature drops to -8°C . Cai H and Liu X et al. from Tsinghua University [29] studied the ice formation process in the pores of concrete under freeze-thaw conditions using the resistivity method. The research shows that concrete frost damage mainly occurs between 0°C and -10°C . Wang Y et al. [30] conducted freeze-thaw cycles on concrete and studied the relationship between ice content and conductivity under factors such as temperature and water saturation, and established a theoretical model for conductivity and ice content. However, it is necessary to further explore whether this model is applicable when concrete with a high initial water content is frozen. In the range of -30°C to -70°C , the conductivity and activation energy satisfy the Arrhenius relationship. Mccarter W J et al. [31] used the conductivity of concrete to calculate the changes in activation energy of concrete with different mineral admixtures during the freeze-thaw cycle, and proved that due to the existence of ink-bottle-shaped pores, compared with the freezing process, there is more ice in the pores of concrete during the melting process. When the water-binder ratio of cement-based materials containing supplementary cementitious materials is lower than 0.35, the temperature and conductivity are linearly related, and the water in the pores does not freeze.

Wang Y et al. [32] proposed a model to estimate the ice content by applying electrical measurements. During the freeze-thaw process of concrete, the resistivity first increases and then decreases. In the initial freezing stage, the formation of ice crystals increases the ion concentration in the pore solution, hindering the migration of ions and resulting in an increase in resistivity. As the number of freeze-thaw cycles increases, microcracks in the concrete expand, water migration intensifies, and the channels formed after some ice crystals melt increase the ion migration paths, causing the resistivity to gradually decrease. Based on the relationship between ice content and resistivity, the electrical response is finally used as an effective index for the quantitative evaluation of frost damage of the elastic modulus and flexural strength of mortar [33]. In the experimental study on the low-temperature electrical response of cementitious materials, Wang Y et al. [34] also found that since the conductivity of cementitious materials mainly depends on the condition of the pore solution and the internal mobile ions, the freezing of the pore solution will significantly reduce its conductivity. According to the thermodynamics principle, as the temperature decreases, more pore water (pore water with a smaller pore radius) will freeze into ice, resulting in an increase in resistivity. In the initial freezing stage, that is, from 0°C to -20°C , the resistivity increases slowly, but in the later freezing stage when the temperature is between -20°C and -40°C , the growth rate of resistivity suddenly speeds up. This indicates that small-sized pores with a very low freezing point play an important role in determining the resistivity.

The durability of concrete is of great significance for hydraulic structures in cold regions. Cai H et al. [35] studied its freeze-thaw durability. By monitoring the changes in the

conductivity of concrete during the freeze-thaw cycle, they studied the ice formation process in the pores to evaluate the freeze-thaw damage of concrete. The research found that there is a hysteresis in the ice formation process, and the ice content during the melting process is not suitable for evaluating frost damage. The freezing rate of the pore solution in concrete above -10°C is higher than that below -10°C . The frost damage of ordinary concrete below -10°C can be ignored, but the frost damage of high-strength concrete in this temperature range still needs further study. In addition, air entrainment mainly affects the mechanical properties of concrete and has little obvious effect on the behavior of the pore solution. This research is helpful for considering freeze-thaw durability in the design and maintenance of concrete structures.

In the Norddalsfjorden Bridge project in Norway in 2023, a distributed fiber optic sensing system (DFOS) was used to monitor the resistivity of concrete in real time. The monitoring data showed that the abnormal fluctuation of the resistivity of the bridge pier at -25°C (coefficient of variation $>18\%$) successfully warned of local freeze-thaw damage, reducing the maintenance cost by 42% [36]. This case verifies the engineering practicability of the resistivity technology.

In summary, in a low-temperature environment, there is a close connection between the performance changes of concrete and its resistivity. When concrete is at a low temperature, the freezing of pore water leads to changes in the internal structure of concrete, which not only affects its mechanical properties but also causes changes in resistivity. During the freeze-thaw cycle, as the internal damage of concrete intensifies, the pore structure deteriorates continuously, and the resistivity changes accordingly. Studying the relationship between the low-temperature performance of concrete and its resistivity helps to monitor the performance changes of concrete in a low-temperature environment in real time by measuring the resistivity, providing an effective means for the health monitoring of concrete structures in cold regions. For example, in bridge engineering in cold regions, the resistivity of concrete can be measured regularly to evaluate the damage degree of the internal structure of concrete, detect potential problems in time, and take corresponding maintenance measures.

5. Conclusions and Outlook

Scholars at home and abroad have achieved rich results in the research field of the coupling effect between pore ice crystals and matrix concrete, covering aspects such as the mechanical properties of ice, the changes in the low-temperature performance of concrete, and the force-electric correlation effect, laying a solid foundation for subsequent research. However, there are still some deficiencies in current research. In terms of research content, most studies focus on single factors or specific working conditions, and there are few studies on the evolution laws of concrete performance under the complex coupling action of multiple factors. In actual engineering in cold regions, concrete structures are jointly affected by multiple factors such as temperature, humidity, mechanical load, and chemical erosion, and the existing research has insufficient discussion on this coupling effect. In terms of research methods, due to the large differences in raw materials, experimental methods, and test standards in experimental research, the comparability and universality of the results are limited; numerical simulation

faces the problem of difficult accurate acquisition of mesoscopic mechanical parameters of pore ice crystals. There are deviations between theoretical models and reality, and simulations are mostly limited to small-sized specimens, making it difficult to directly apply to the analysis of large-scale engineering structures.

Future research can be carried out from the following aspects: First, strengthen the research on the performance of concrete under the coupling action of multiple factors, design experiments that are more in line with actual working conditions, and use advanced testing technologies to comprehensively reveal the coupling mechanism between pore ice crystals and matrix concrete; second, unify the experimental standards and methods, improve the reliability and comparability of research results, and strengthen the integrated analysis of different research results; third, with the help of new micro-testing technologies, deeply explore the micro-mechanism of the interaction between pore ice crystals and concrete, providing a more solid theoretical basis for macroscopic performance research; fourth, improve and perfect the numerical simulation method, improve the accuracy of obtaining mesoscopic parameters of pore ice crystals, and develop efficient numerical models suitable for large-scale engineering structures to achieve accurate prediction and optimal design of the performance of actual engineering structures in a low-temperature environment. Through these studies, it is expected to improve the theoretical system of the coupling effect between low-temperature pore ice crystals and matrix concrete, provide more scientific and reliable theoretical and technical support for engineering construction in cold regions, and promote the sustainable development of infrastructure construction in cold regions.

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