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Mechanisms of Early Cracking in Concrete Structures in Cold Regions and On-Site Construction Control Techniques

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Abstract

Early-age cracking in concrete structures during winter construction has become increasingly prominent, seriously affecting structural durability and engineering safety. This study focuses on concrete structures in cold regions and systematically investigates the mechanisms of early-age cracking and on-site construction control techniques through theoretical analysis, construction technology research, and engineering applications. The research methodology includes the design of casting temperature and thermal insulation construction techniques, the establishment of a temperature control index system, dynamic evaluation of crack risk coefficients, and validation through projects in high-cold regions. Results indicate that concrete cracking in cold areas primarily results from the combined effects of thermal stress, shrinkage deformation, frost heave, and construction factors. Key control indicators include casting temperature, internal peak temperature, internal-external temperature differential, and cooling rate. The integrated application of heat storage insulation, electric heating, moisture-maintaining curing, and intelligent temperature control effectively reduces the number of cracks. By combining temperature monitoring with crack risk coefficients, dynamic closed-loop control during construction can significantly reduce early-age cracking. The proposed temperature control index system and dynamic crack management method systematically reveal the laws governing early-age cracking in concrete in cold regions and provide practical technical guidance for concrete construction in high-cold areas, offering important theoretical and engineering significance.

Keywords

Cold Regions; Concrete Cracking; Temperature Control; Dynamic Crack Monitoring; Construction Technology

1. Introduction

Extensive research has been conducted internationally on early-age cracking of concrete. Foreign scholars, including Bazant, Neville, and Mehta, have mainly analyzed the causes of cracking from the perspectives of thermal stress, heat of hydration, and shrinkage deformation, indicating that excessive internal-external temperature differentials are a critical factor in early-age cracking [(1)]. ACI 306 *Cold Weather Concreting* specifies temperature control and insulation requirements for concrete construction in cold weather and has been widely applied in North American and Northern European cold-region projects [(2)]. In addition, international research has employed finite element methods to establish coupled temperature-stress models to analyze crack development patterns of concrete under low-temperature conditions [(3)].

Domestic research in China has focused primarily on thermal stress theory, construction temperature control techniques, and crack monitoring. Some researchers have proposed systematic concrete crack control theories, emphasizing that both structural restraint and temperature-induced deformation jointly determine crack development [(4)]. Others have used numerical simulations to study the evolution of concrete temperature fields in cold environments, identifying cooling rates and environmental temperature differentials as important parameters affecting crack formation [(5)]. In recent years, with the development of high-speed railways and large cold-region bridges, research has gradually shifted from single-factor temperature control to multi-field coupling analyses of temperature, humidity, and stress. In terms of construction techniques, methods such as heat storage, electric heating, and insulation coverage have been widely applied, while IoT-based intelligent temperature control and real-time monitoring technologies have also gradually developed [(6)]. However, overall, a systematic understanding of the mechanisms of cold-region concrete cracking remains incomplete, and effective coordination among on-site temperature control, monitoring, and dynamic feedback is lacking.

Based on this context, this study focuses on the construction process of concrete structures in cold regions, following the main research framework of “crack formation mechanism-temperature-controlled construction techniques-temperature control indices-dynamic monitoring and control.” Firstly, the formation mechanisms of early-age cracking in cold-region concrete structures are analyzed. Secondly, on-site temperature control and insulation construction techniques suitable for cold-region projects are investigated. Thirdly, a construction temperature control index system is established. Finally, a dynamic crack control method is proposed based on on-site monitoring, and its effectiveness is verified through engineering case studies. The findings of this study provide theoretical support and technical references for quality control and durability improvement in cold-region concrete construction.

2. Mechanisms of Early-Age Cracking in Concrete Structures in Cold Regions

Under winter construction conditions in cold regions, concrete structures are subjected not only to the effects of heat of hydration and shrinkage deformation but also to low ambient temperatures, frost heave, and construction-related factors. These combined effects make early-age cracking more likely.

2.1. Mechanism of Thermal Stress

After concrete is cast, the hydration of cement releases a large amount of heat, raising the internal temperature, while the ambient temperature remains low. This creates a significant temperature differential between the interior and exterior of the structure. When the temperature differential is excessive, deformation between the interior and surface becomes incompatible, generating thermal stress. When thermal stress exceeds the tensile strength of concrete at the same age, cracking occurs. In cold regions, large diurnal temperature variations and rapid surface cooling make surface tensile cracks more likely to develop.

2.2. Shrinkage Deformation and Restraint Effects

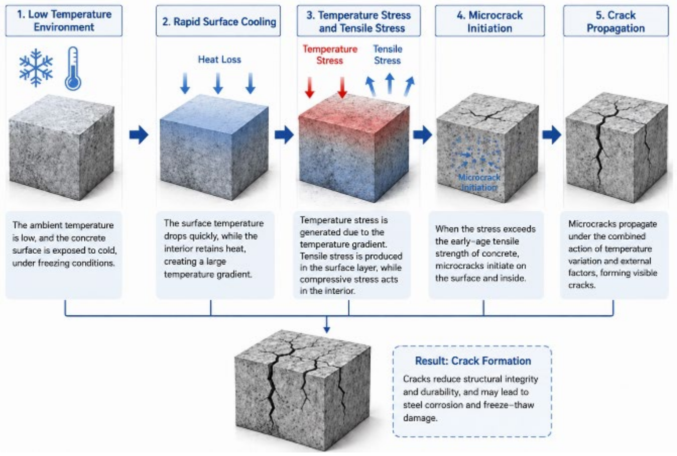
During hardening, concrete undergoes plastic shrinkage, drying shrinkage, and autogenous shrinkage. The dry air and high wind speeds typical of cold regions accelerate surface water loss, increasing the likelihood of shrinkage cracks. If concrete is restrained by foundations, reinforcement, or adjacent structural elements, shrinkage deformation cannot be freely released, generating restrained tensile stress. Table 1 shows that low-humidity environments in cold regions amplify shrinkage effects, thereby increasing the probability of cracking.

Table 1. Characteristics of Different Shrinkage Types.

Shrinkage Type	Formation Stage	Crack Characteris-tics
Plastic Shrinkage	Before initial set	Surface crazing
Drying Shrinkage	Hardening stage	Through cracks
Autogenous Shrinkage	Hydration stage	Internal microcracks

2.3. Mechanism of Frost Heave

When the ambient temperature falls below 0° C, free water in concrete freezes, expanding approximately 9% in volume, generating frost heave pressure. Early-age concrete has low strength, and its pore structure is easily damaged. Under low-temperature conditions, frost heave acts together with thermal stress, promoting the continuous propagation of microcracks. The formation process of concrete cracks in cold regions is illustrated in Fig. 1.



The ambient temperature is low, and the concrete surface is exposed to cold, under freezing conditions.

The surface temperature drops quickly, while the interior retains heat, creating a large temperature gradient.

Temperature stress is generated due to the temperature gradient. Tensile stress is produced in the surface layer, while compressive stress acts in the interior.

When the stress exceeds the early-age tensile strength of concrete, microcracks initiate on the surface and inside.

Microcracks propagate under the combined action of temperature variation and external factors, forming visible cracks.

Cracks reduce structural integrity and durability, and may lead to steel corrosion and freeze–thaw damage.

Figure 1. Formation Process of Concrete Cracks in Cold Regions.

2.4. Influence of Construction Factors

On-site construction practices also significantly affect crack formation. Low casting temperatures, insufficient insulation, or early formwork removal can accelerate heat loss from the concrete surface, exacerbating thermal cracking. In addition, inadequate compaction and curing increase porosity, reducing concrete's crack resistance. Engineering experience shows that corners and edges of mass concrete structures, due to faster heat dissipation, are prone to crack concentration.

2.5. Comprehensive Analysis

In summary, early-age cracking in concrete in cold regions results from the combined effects of thermal stress, shrinkage deformation, frost heave, and construction factors. Essentially, it is a multi-field coupling problem involving temperature, humidity, and stress. Therefore, crack control in cold-region concrete should encompass material design, temperature-controlled construction, and insulated curing throughout the construction process.

3. On-Site Temperature Control and Insulation Techniques for Concrete in Cold Regions

3.1. Casting Temperature Control Techniques

The casting temperature of concrete directly affects early hydration reactions and the distribution of internal temperature fields. If the temperature is too low, strength development is slow; if it is too high, subsequent temperature differentials may increase. Therefore, it is essential to control heat loss during material heating and transportation. In practice, heated mixing water and aggregates are commonly used to raise the casting temperature, and insulated transport vehicles help reduce heat loss. For mass concrete structures, the casting temperature should generally be controlled between 10 ° C and 15 ° C.

3.2. Heat Storage and Insulation Techniques

The heat storage method is the most commonly used insulation measure in cold-region construction. Its principle is to utilize the heat released by cement hydration and reduce heat loss through insulation layers. Increasing the thickness of the insulation layer or reducing the thermal conductivity can decrease heat loss. Commonly used insulation materials are listed in Table 2. Construction should focus on thorough coverage of corners and edges and avoid early formwork removal to prevent surface temperature drops that may cause cracking.

Table 2. Properties of Common Insulation Materials.

Insulation Material	Thermal Conductivity W/(m•K)	Applicable Locations
Straw mat	0.12	Small components
Cotton quilt	0.05	Beam and slab structures
Rock wool board	0.04	Mass concrete structures
Polyurethane board	0.03	Extremely cold regions

3.3. Electric Heating and Steam Insulation Techniques

In extremely cold regions, heat storage alone may not meet temperature control requirements, so active insulation techniques such as electric heating or steam heating are often used. Electric heating provides stable temperature control and high adaptability, suitable for bridge piers and local weak areas, while steam heating offers rapid temperature rise, suitable for enclosed spaces and precast components. However, heating and cooling rates should not be too rapid to avoid generating additional thermal stress.

3.4. Moisture Curing and Intelligent Temperature Control

Low ambient humidity in cold regions can accelerate surface water loss and shrinkage. Therefore, in addition to insulation, moisture curing should be reinforced. Common practices include covering with plastic films, spraying curing agents, and using windbreaks to reduce water evaporation. Simultaneously, embedding temperature sensors within the structure enables real-time monitoring. Generally, the internal-external temperature differential should be controlled within 25° C. When the differential approaches the warning threshold, dynamic adjustments can be made by increasing insulation coverage or adjusting heating power.

4. Temperature Control Index System and Dynamic Crack Control Methods for Cold-Region Concrete Construction

4.1. Key Temperature Control Indicators

4.1.1. Casting Temperature

Casting temperature is the primary control parameter for winter construction in cold regions. If the casting temperature is too low, cement hydration is slow, and early-age strength is insufficient; if it is too high, subsequent cooling-phase temperature differentials may increase. Based on practical experience, the casting temperature should generally be maintained between 10 ° C and 15 ° C, with a minimum of 5 ° C. Recommended casting temperatures for different structural types are shown in Table 3.

Table 3. Recommended Casting Temperatures for Different Structures.

Structure Type	Recommended Casting Temperature (°C)	Control Requirements
Beam and slab	10–12	Prevent rapid surface cooling
Pier and column	12–15	Ensure early strength development
Mass foundation	8–12	Reduce internal peak temperature
Precast components	~15	Improve demolding strength

4.1.2. Internal-External Temperature Differential

Temperature differential is a key factor determining thermal stress. Excessive differences between the internal and surface temperatures may induce surface tensile cracks. Monitoring data from numerous cold-region projects indicate that cracking probability increases significantly when the differential exceeds 25 ° C. Therefore, during construction, the differential should be maintained below 25 ° C. For mass concrete or extremely cold projects, a more conservative limit of 20 ° C is recommended to provide additional safety margin.

4.1.3. Cooling Rate

The cooling phase is the period most susceptible to thermal cracking. Rapid surface cooling can create significant internal-external deformation differences. Therefore, cooling rates must be controlled. Typically, the average daily cooling rate should be ≤2 ° C/day; for mass concrete structures, it should not exceed 1.5 ° C/day. Cooling can be slowed by extending insulation duration, staged formwork removal, or increasing insulation layer thickness.

4.2. Crack Risk Assessment Method

To achieve dynamic crack control during construction, a temperature crack risk coefficient K_r can be introduced:

$$K_r = \frac{\sigma_t}{f_t} \tag{1}$$

where σ_t is the concrete tensile stress at the same age and f_t is the corresponding tensile strength. Based on the magnitude of K_r, crack risk can be classified into three levels as shown in Table 4. Real-time calculation of the risk coefficient allows early identification of potential cracking zones and enables dynamic adjustment during construction.

Table 4. Temperature Crack Risk Levels.

Risk Coefficient K_r	Risk Level	Control Measures
$K_r < 0.7$	Low	Normal curing
$0.7 \leqslant K_r < 1.0$	Medium	Strengthen insulation and monitoring

$K_r \geqslant 1.0$	High	Immediate cooling or supplemental heating

4.3. Dynamic Temperature Field Monitoring

To ensure the effective implementation of temperature control indices, a real-time on-site monitoring system should be established. Typically, a three-layer monitoring model is used: "sensors → data acquisition → early warning analysis," as shown in Figure 2. Temperature sensors are generally installed at structural centers, surfaces, and corners. For mass concrete, sensor spacing should be 3–5 m. Wireless transmission allows real-time data upload and remote analysis. For enhanced accuracy, 3D temperature field models can be established using BIM and IoT technologies to visualize temperature variations across different structural regions, improving crack prediction capability.

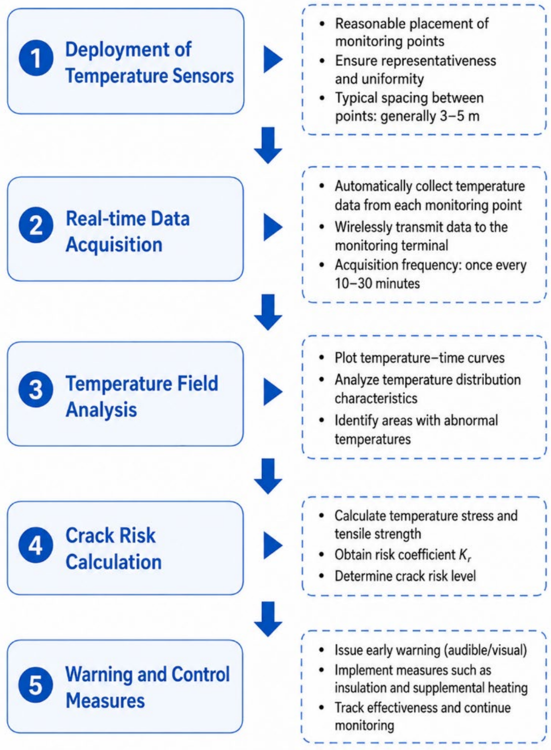


Figure 2. Dynamic Temperature Monitoring Workflow.

4.4. Dynamic Crack Control Methods

Based on real-time monitoring results, dynamic adjustments can be applied during construction:

(1) If internal temperature rises too rapidly, reduce cement content or use low-heat cement to lower peak temperature.

(2) If the internal-external temperature differential approaches the warning threshold, increase insulation thickness or delay formwork removal.

(3) If the surface cools too quickly, apply electric heating or hot air circulation for supplementary heating.

(4) If ambient humidity is low, strengthen spray curing and moisture coverage to reduce drying shrinkage risk.

5. Engineering Application

The temperature control index system for cold-region concrete construction and the crack dynamic control method based on real-time monitoring were applied to a practical project in Lhasa, Tibet, to verify the feasibility and effectiveness of the proposed theories and techniques.

5.1. Project Overview

A construction project in the high-cold region of Lhasa was selected as the case study. During winter, the ambient temperature often drops below -10°C, with diurnal temperature variations exceeding 30°C and relative humidity around 30-40%. The structural characteristics and construction environment represent typical scenarios for early-age cracking in cold-region concrete. Based on the proposed temperature control index system, the following construction control measures were implemented:

(1) Casting Temperature Control: Concrete casting temperatures for beam-slab structures were maintained at 12°C, and for column structures at 14°C, achieved via heated mixing water and aggregates.

(2) Internal Peak Temperature Control: The peak temperature of mass foundation concrete was kept below 60°C to reduce internal-external temperature differentials and associated thermal stress.

(3) Internal-External Differential and Cooling Rate: Temperature differential was limited to ≤25°C, and the average daily cooling rate was controlled within 1.5°C/day.

(4) Insulation and Heating Measures: Heat storage insulation was combined with electric heating and moisture coverage, with intensified insulation for corners and edges.

(5) Dynamic Monitoring and Risk Control: Temperature sensors were installed at the core, surface, and corners of the structure. Real-time monitoring was conducted via a wireless data acquisition system, and the crack risk coefficient K_{r} was calculated.

Insulation layer thickness and material selection followed Table 2. Beam-slab structures were covered with 50 mm cotton quilt; columns and mass foundations used 100 mm polyurethane boards. For corners and weak sections, localized electric heating was applied with a controlled heating rate ≤0.5°C/h to minimize thermal stress.

During construction, 120 temperature monitoring points were installed across the core, surface, and edges. Real-time temperature data were collected wirelessly, and K_{r} was calculated continuously.

5.2. Crack Control Evaluation

After construction, crack formation was assessed through visual inspection and non-destructive testing. Results indicated that beam-slab surfaces had no through-cracks, only microcracks <0.1 mm concentrated at beam ends and corners. Columns and mass foundation cores showed no significant cracks. Temperature monitoring data closely matched actual crack distribution. The temperature control measures significantly reduced early-age thermal cracking: compared with uncontrolled sections, the number of cracks decreased by ~80%, and crack widths decreased by ~60%.

5.3. Comprehensive Analysis

Engineering practice demonstrated the following characteristics of cold-region concrete temperature control and dynamic management:

(1) Practicality of the Temperature Control Index System: Casting temperature, internal-external differential, and cooling rate effectively guide construction planning and quantify crack risk.

(2) Effectiveness of Dynamic Monitoring and Closed-Loop Control: Real-time temperature monitoring combined with risk coefficient calculation enables dynamic intervention during construction, significantly reducing early-age cracking.

(3) Superiority of Multi-Technology Coordination: The integrated application of heat storage insulation, electric heating, moisture curing, and intelligent monitoring outperforms single measures.

(4) High Applicability: The temperature control and dynamic crack management techniques can be adapted to different structural types and climatic conditions, suitable for cold-region bridges, foundations, and large-scale building concrete construction.

6. Conclusions

A systematic study was conducted on early-age cracking in cold-region concrete structures, and temperature-controlled construction and dynamic crack control methods were proposed and validated through practical high-cold engineering projects. The main conclusions are as follows:

(1) Early-age cracking in cold-region concrete is the result of thermal stress, shrinkage deformation, frost heave, and construction factors. Excessive temperature differentials are the main cause, particularly at structural surfaces under diurnal temperature variation, wind, and low ambient temperature. Shrinkage is more pronounced in low-humidity environments, and frost heave can induce internal microcracks in early-age concrete with undeveloped pore structure. Construction factors, such as low casting temperature, insufficient insulation, or premature formwork removal, also significantly exacerbate cracking.

(2) Casting temperature and temperature field control are critical for reducing

early-age cracking risk. Concrete casting temperature should be controlled between 8–15° C depending on structure type; internal peak temperature should remain below 60° C to reduce internal differential stress; internal-external differential should be ≤25° C (or ≤20° C for mass concrete/high-cold regions), with daily average cooling rates of 1.5-2° C/day. These parameters effectively slow surface shrinkage and reduce peak thermal stress, significantly lowering crack probability.

(3) Heat storage insulation slows heat loss; electric heating and steam heating provide localized temperature compensation; moisture curing and intelligent monitoring maintain surface humidity, reducing drying shrinkage risk.

(4) The temperature control index system combined with real-time monitoring and crack risk coefficient enables comprehensive risk management throughout construction. The system provides early warning for low-, medium-, and high-risk levels, guiding dynamic adjustment of insulation thickness, heating power, and formwork removal timing to form a closed-loop control mechanism. Application results confirm that this approach effectively identifies potential cracking zones, directs on-site interventions, and ensures construction quality.

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