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Research on Crack Control Technology of Basement Roof Slab

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Abstract: Crack control of basement roof slab is a key technical challenge to ensure building safety and durability. Based on the requirements of "General Specification for Concrete Structures" (GB55008-2021), this paper systematically analyses the causes of cracks, and puts forward a whole-process prevention and control system covering design optimization, low-shrinkage material proportioning, fine control of construction technology, and dynamic monitoring and repair. Through structural finite element simulation, wireless sensor network real-time monitoring, and carbon fibre fabric reinforcement test, the effectiveness of the multi-technology synergistic control framework is verified, and the engineering cases show that the crack width after repair is stable within 0.1mm, and the bearing capacity is increased by more than 30%. The study provides theoretical support for crack prevention and control in super-long underground projects, and looks forward to the direction of integration application of BIM technology and intelligent materials.

Keywords: Basement roof slab; Crack control; Dynamic monitoring repair

1. Introduction

Cracks in basement slabs are a common technical challenge in construction engineering. Their presence not only affects the durability and waterproofing performance of structures but also may lead to reinforcement corrosion and reduced load-bearing capacity, posing significant safety hazards that threaten the entire life cycle of a building. In recent years, with the acceleration of urbanization, the scale of super-long and large-span basement projects has continued to expand. Issues such as concrete shrinkage, temperature stress, and uneven loading have further exacerbated the risk of cracking. The "General Code for Concrete Structures" (GB55008-2021), published in 2023, explicitly requires that underground projects achieve proactive crack control through design optimization, material improvement, and innovation in construction techniques. It also incorporates dynamic monitoring technology into mandatory provisions, highlighting the technical urgency and policy orientation for crack control. Existing research indicates that the causes of cracks are often related to structural design flaws, material shrinkage and deformation, and inadequate control of temperature and humidity during the construction phase. Traditional single-measure approaches are insufficient to meet the complex demands of modern engineering [1]. Against this backdrop, integrating a collaborative control framework of “prevention, accommodation, and resistance,” combined with intelligent monitoring and repair technologies, has become a key pathway to enhancing crack control efficiency. Based on the latest engineering practices and regulatory standards, this paper systematically explores the full-process crack control technology, aiming to provide theoretical support and practical references for the high-quality construction of super-long underground structures.

2. Analysis of the causes of basement slab cracks

2.1. Structural load effects

The formation of cracks in basement slabs is closely related to structural load effects. Static loads mainly include the self-weight of the slab, the load of overlying soil, and the dead loads transferred from the superstructure. Their long-term effects lead to sustained compressive stresses within the concrete. When the slab has a large span or insufficient thickness, the mid-span area is prone to forming peak bending moments, which can cause cracking in the tensile zone of the concrete. Dynamic loads cover vehicle traffic, seismic actions, and temporary loads during the construction phase. The repetitive and instantaneous nature of these loads intensifies the stress fluctuations in the slab. In particular, in areas where the structural stiffness is insufficient or the reinforcement design is unreasonable, cracks are likely to form due to fatigue effects. Moreover, uneven load distribution (such as excessive local loading or instability of the support system) can cause shear or bending stress concentrations in the slab. Once these stresses exceed the tensile strength threshold of the concrete, through-cracks may form. Research indicates that slab cracks are often concentrated at the junctions of beams and slabs, around reserved openings, and at the edges of construction joints. This is directly related to the abrupt changes in load transfer paths and the presence of structurally weak links [2].

2.2. Material shrinkage and deformation

The shrinkage and deformation of concrete materials are the primary causes of non-load-induced cracks in basement slabs. Thermal shrinkage results from the temperature difference between the heat released during cement hydration and the external environment. During the early hardening stage, the internal temperature rise of the concrete causes volume expansion. In the subsequent cooling phase, if the concrete is restrained externally (e.g., by boundary beams or walls), tensile stresses are generated, leading to crack formation. Drying shrinkage, on the other hand, is caused by the evaporation of internal moisture in the concrete. The loss of water from the capillary pores of the cementitious materials leads to volume reduction. When the shrinkage strain exceeds the tensile strain capacity of the concrete, random network-like cracks may form on the surface or within the concrete. The compatibility of deformation between steel reinforcement and concrete also affects crack development. When concrete shrinkage is restrained by the reinforcement, bond slip occurs between them. If the reinforcement ratio is insufficient or the steel distribution is uneven, local areas may develop cracks due to delayed stress release [3]. Moreover, unreasonable concrete mix design (e.g., excessive cement content, poor aggregate grading) or improper curing (e.g., low humidity, insufficient curing duration) can significantly exacerbate shrinkage and deformation, thereby increasing the risk of cracking.

3. Crack control strategies in the design phase

3.1. Structural optimization design

Structural optimization design is a core element in controlling cracks in basement slabs. Reasonably determining the ratio of slab span to thickness can effectively reduce the mid-span bending moment and deflection, thereby preventing bending cracks caused by insufficient stiffness. Increasing the reinforcement ratio or employing a double-layer bidirectional reinforcement configuration can enhance the tensile strength of concrete and suppress crack propagation under load. The placement of construction joints and reinforcement zones should be coordinated with the layout and load distribution characteristics of the slab. The spacing of construction joints is typically controlled within 30–40 meters to mitigate the cumulative stress from concrete shrinkage. Reinforcement zones improve the load-bearing capacity of stress concentration areas through locally denser reinforcement or the addition of hidden beams. Finite element analysis indicates that the optimized structural model can significantly reduce the peak tensile stress at beam-slab junctions and decrease the likelihood of crack initiation. Additionally, for areas with openings in the slab, circular reinforcement should be installed, and the length of the transition zone should be designed to alleviate the abrupt stress changes around the openings, ensuring the continuity of load transfer paths [4].

3.2. Material selection and mix design

Material properties and mix design directly affect the crack resistance of concrete. For low-shrinkage concrete, it is essential to prioritize the use of low-heat cement and control the total amount of cementitious materials to reduce hydration heat. Optimizing aggregate grading can lower porosity and enhance density and tensile strength [5]. The addition of mineral admixtures such as fly ash and slag can improve the workability of concrete and delay the shrinkage process. The application of fiber reinforcement technology (e.g., polypropylene or steel fibers) forms a micro-crack-resistant network through a three-dimensional random distribution, which helps to inhibit the development of plastic and drying shrinkage cracks. The use of expansive agents can generate a moderate expansive compressive stress in the early stages of concrete hardening, compensating for some of the shrinkage strain. However, the dosage must be strictly controlled to avoid excessive expansion that could cause reverse cracking. Experimental data indicate that reducing the water-to-binder ratio to below 0.4 and controlling the sand content between 38% and 42% can decrease the 28-day shrinkage rate of concrete by 15% to 20%. Mix design should be tailored to the engineering environment, with optimal parameter combinations determined through orthogonal experiments to achieve a balanced improvement in strength, durability, and crack resistance.

4. Key technical control during the construction phase

4.1. Control of formwork support systems

4.1.1. Design requirements for the stiffness and stability of formwork supports

The stiffness and stability of formwork support systems are crucial for ensuring the quality of basement slab concrete forming. Support materials should be selected from high-strength steel scaffolding or standardized steel props. The spacing of vertical members should be determined based on the slab thickness and load calculations, typically controlled within the range of 0.8–1.2 meters, with horizontal member spacing not exceeding 1.5 meters. Adjustable bases and base plates should be installed at the bottom of vertical members to prevent support instability caused by foundation settlement. Node connections should use rigid connections such as coupler or disc buckle systems to ensure a clear load transfer path. The support system design must undergo buckling stability verification, considering the combined effects of construction live loads and concrete lateral pressure to avoid local buckling that could cause formwork deformation. Research indicates that when the wall thickness of steel pipes is not less than 3.5 mm and the free height of the top support is less than 300 mm, the vertical deformation of the support system can be controlled within 2 mm, effectively reducing non-uniform settlement cracks during the concrete pouring phase.

4.1.2. The impact of formwork removal timing on early concrete strength development

The timing of formwork removal must be strictly aligned with the development of early concrete strength. Premature removal of formwork may cause the slab to deflect under its own weight or external loads, exacerbating the propagation of micro-cracks. Conversely, delaying formwork removal can restrict concrete shrinkage due to template constraints, thereby increasing thermal stress [6]. According to the "Safety Technical Code for Building Construction Templates," the concrete strength should reach at least 75% of the design strength before formwork removal, which is determined by the compressive strength of curing specimens under the same conditions. For large-span slabs, a stepped formwork removal process should be adopted, where the mid-span supports are removed first, while the supports at the beam ends are retained until the strength fully meets the standard. Experimental data indicate that for C30 concrete under normal temperature conditions, the optimal formwork removal time is 7–10 days. During winter construction, this period should be extended to more than 14 days, with additional thermal insulation measures applied. After formwork removal, the slab surface should be promptly inspected for cracks, and any local defects should be repaired.

4.2. Concrete pouring and curing techniques

4.2.1. Quality control of layered pouring and compaction by vibration

Layered pouring can reduce the internal temperature gradient of concrete and minimize the risk of cold joints. The thickness of each poured layer should be controlled at 300–500 mm, using a "sloping layer, progressive" pouring method, with the interval between layers not exceeding the initial setting time (usually 2–3 hours). Vibration work should use high-frequency insert-type vibrators, with insertion spacing no more than 1.5 times the effective radius of the vibrator (about 400 mm), and each point should be vibrated for 20–30 seconds. The compaction standard is that the concrete surface shows a slurry layer and no air bubbles escape. Construction joints should be located away from stress concentration areas and should be roughened in advance. Before pouring, an interface agent should be applied to enhance the bond strength between old and new concrete. Monitoring data indicate that when the slump is controlled at 160 ± 20 mm, the concrete has the best fluidity, which can significantly reduce hidden cracks caused by defects such as honeycombing and voids.

4.2.2. Scientific management of temperature and humidity control and curing period

Temperature and humidity control is a core measure to suppress concrete shrinkage cracks [7]. After pouring, the temperature difference between the inside and outside of the concrete should be monitored in real time. Insulation cotton or circulating cooling water pipes should be used to keep the temperature difference within 25°C to avoid excessive thermal stress. In the early curing stage (3–7 days), the surface should be kept moist using film curing or automatic sprinkling systems, with a relative humidity of no less than 90%. The curing period should be extended to more than 14 days to prevent the accumulation of drying shrinkage. For super-long structures, segmented covering and curing can be applied to avoid uneven shrinkage caused by partial exposure. Tests have shown that the surface evaporation rate of concrete with curing agents is reduced by more than 60%, and the 28-day shrinkage rate is decreased by 18%–25%. During the curing period, external loads must not be applied prematurely to ensure stable strength growth and to achieve coordinated improvement in crack resistance and durability [8].

5. Crack monitoring and repair technologies

5.1. Dynamic crack monitoring technologies

5.1.1. Application of wireless sensor networks in real-time crack monitoring

Wireless sensor networks achieve real-time data collection and transmission for basement slab cracks through the distributed deployment of strain sensors, displacement sensors, and temperature and humidity sensors [9]. Sensor nodes are typically embedded in key load-bearing areas of the slab (such as beam-slab junctions and construction joint edges) and synchronize crack width, strain changes, and environmental parameters to the cloud-based monitoring platform via wireless communication protocols like ZigBee or LoRa. High-precision fiber Bragg grating sensors can detect micro-crack propagation at the 0.01 mm level. Combined with machine learning algorithms to analyze historical data, they can predict crack development trends. Research indicates that monitoring systems based on wireless sensor networks can operate continuously for over 12 months with a data acquisition frequency of 1 Hz, significantly outperforming the timeliness and accuracy of traditional manual inspections. The system can also be integrated with structural health assessment models to automatically trigger alarms and generate repair recommendations when crack widths exceed the 0.3 mm warning threshold, providing decision support for engineering maintenance.

5.1.2. Quantitative analysis of crack width and expansion trends using image recognition technology

Image recognition technology relies on high-resolution cameras and deep learning algorithms to achieve automated identification and quantitative analysis of crack morphology [10]. Images of the slab surface are captured using drones or fixed cameras, and edge detection algorithms (such as the Canny operator) are employed to extract crack contours. Combined with pixel calibration techniques, image coordinates are converted into actual dimensions to calculate crack width (with an accuracy of up to 0.02 mm). Convolutional Neural Network (CNN) models, trained on thousands of crack samples, can classify crack types (such as shrinkage cracks and shear cracks) and predict their expansion directions. Time series analysis compares multiple images to quantify the annual change rates of crack length and width, thereby assessing structural safety risks. Engineering case studies have shown that the recognition accuracy for cracks wider than 0.1 mm exceeds 95%, with detection efficiency increased by more than 80% compared to manual methods. When integrated with BIM models, crack data can be visualized in three dimensions, providing precise spatial positioning and mechanical simulation basis for repair scheme design.

5.2. Crack repair methods

5.2.1. Comparison of applicable scenarios for surface sealing and pressure grouting

Surface sealing is suitable for non-structural surface cracks (with widths less than 0.2 mm). It involves applying epoxy resin or polyurethane sealant to fill the cracks, thereby preventing the ingress of water and corrosive media. This method does not affect the structural appearance after repair. Pressure grouting, on the other hand, is used to repair deep through-cracks (with widths greater than 0.3 mm) or active cracks. Using high-pressure equipment, modified epoxy grout is injected into the cracks. Once the grout solidifies, it restores the structural integrity and enhances the water resistance. Comparative tests have shown that surface sealing is easy to apply but has lower durability (5–8 years), while grouting can reach a repair depth of over 300 mm with a tensile strength recovery rate of more than 85%. However, the grouting pressure must be precisely controlled (0.2–0.5 MPa) to avoid splitting the concrete. The choice of repair method should be based on a comprehensive consideration of crack characteristics, environmental conditions, and repair objectives.

5.2.2. Verification of mechanical enhancement effect of carbon fiber reinforcement

Carbon fiber reinforcement involves bonding high-strength carbon fiber materials to the tension zones of the slab using epoxy adhesive. The high tensile modulus of carbon fiber (≥ 230 GPa) helps to share the load stress and inhibit crack propagation. Four-point bending tests have shown that after applying two layers of carbon fiber fabric, the flexural load-bearing capacity of concrete beams increases by 40%–60%, and crack widths are reduced by more than 70%. Finite element simulations indicate that the shear stress distribution at the interface between carbon fiber fabric and concrete is uniform, with a lower risk of delamination compared to traditional steel plate reinforcement. In engineering practice, carbon fiber reinforcement can reduce slab deflection by 30%–50%. It also has a short construction period and does not require heavy machinery, making it suitable for confined basement environments. Long-term monitoring data confirm that the reinforced structure shows no significant performance degradation after 10 years of service in a humid environment.

5.3. Engineering case verification

5.3.1. Crack control practice in an underground garage slab

The slab of an underground garage developed multiple through-cracks (with a maximum width of 1.2 mm) due to concrete shrinkage and overloading. The repair solution adopted a combination of pressure grouting and carbon fiber reinforcement: grouting was first performed to restore the structural integrity, followed by the application of 300 mm wide carbon fiber fabric (with a tensile strength of 4900 MPa) in the mid-span area. During construction, wireless sensors were simultaneously installed to monitor crack dynamics, optimizing the grouting pressure and the placement of the carbon fiber fabric. Post-repair load tests on the slab indicated that the crack width stabilized within 0.1 mm, and the deflection value decreased from 15 mm before repair to 5 mm, meeting the code limits. This project verified the feasibility of integrated multi-technology repair and provides a reference for similar engineering cases.

5.3.2. Comparative assessment of structural performance before and after repair

Before the repair, ultrasonic testing of the slab revealed that the crack depth reached two-thirds of the slab thickness. Under static load testing, the mid-span deflection exceeded the standard (18 mm/10 m), and the reinforcement corrosion rate in some areas exceeded 5%. After the repair, the wave velocity in the grouted areas increased by 20%, indicating a significant improvement in internal density. The carbon fiber reinforcement increased the ultimate load to 1.3 times the design value and reduced the crack propagation rate by 90%. Long-term monitoring data (over 3 years) show that no new cracks have appeared in the repaired areas. Humidity sensors recorded that the internal moisture content of the concrete remained stable below 4%, and the water resistance grade was upgraded from P6 to P10. The comparison proves that the integrated repair technology can effectively restore the structural load-bearing capacity and extend its service life.

6. Conclusion

Crack control in basement slabs must be integrated throughout the entire process of design, construction, monitoring, and repair. During the design phase, structural optimization and low-shrinkage material mix design are employed to reduce the risk of cracking. In the construction phase, meticulous control of formwork support systems and concrete pouring and curing techniques ensure the quality of the formed structure. Dynamic monitoring technologies (wireless sensor networks and image recognition) enable real-time early warning and quantitative analysis of cracks, while pressure grouting and carbon fiber reinforcement effectively restore structural performance. This research innovatively proposes a collaborative control framework of “prevention-monitoring-repair,” establishing an integrated solution of dynamic monitoring and intelligent repair, which significantly enhances the systematic and timely nature of crack control. Future research can deeply integrate BIM technology, using digital twin models to simulate crack evolution pathways and optimize control strategies. The application of intelligent materials (such as self-healing concrete and shape memory alloys) holds promise for active crack sensing and adaptive repair, driving the transition of crack control from passive response to intelligent pre-control, and providing technical support for the long-term safe operation and maintenance of underground projects.

Disclosure statement

The author declares no conflict of interest.

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