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Research on Mix Proportion Optimization and Mass Temperature Control Anti-Cracking Technology for Rapid Construction of Roller Compacted Concrete

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Abstract: The rapid construction of roller compacted concrete (RCC) faces prominent challenges, including concentrated release of hydration heat caused by continuous thin-layer rolling in large warehouse surfaces, deteriorated heat dissipation conditions, and poor coordination between temperature control measures and construction rhythms. This paper systematically analyzes the characteristics of rapid construction technology and its constraint mechanism on temperature control and anti-cracking performance. On this basis, a mix proportion optimization design is carried out. By selecting low hydration heat cementitious materials, optimizing aggregate gradation and paste-aggregate ratio, and coordinating setting time and early strength development, the adiabatic temperature rise of concrete is reduced by more than 20%. Furthermore, collaborative regulation measures are proposed, including multi-period inhibition of pouring temperature and matching of heat preservation curing with rolling construction rhythm. A closed-loop evaluation system based on the feedback of temperature-stress field simulation is also established. The research findings realize the in-depth coupling of mix proportion design, temperature control and anti-cracking measures with rapid construction technology, providing a systematic technical solution for the rapid construction of RCC. Taking the Kekka Hydropower Station in Angola as the engineering example, under the tropical climate condition with an annual average temperature exceeding 25 ℃, a temperature control system combining secondary air cooling, ice addition and cold water pre-cooling technology with multiple curing methods is adopted based on simulation results. The continuous and rapid construction of large-warehouse and large-lift RCC is successfully realized, which verifies the engineering applicability of the technical framework proposed in this paper.

1. Introduction

RCC dam construction technology has been widely applied in hydropower projects due to its advantages of fast construction speed and low cost. However, the continuous thin-layer rolling of large warehouse surfaces under rapid construction modes leads to concentrated hydration heat release and deteriorated heat dissipation. Traditional mix proportion design and temperature control measures can hardly adapt to the construction rhythm of short inter-layer interval and high pouring intensity, and frequent temperature cracks have become a key factor restricting engineering quality and progress [1].

The Kekka Hydropower Station in Angola is located in the middle reaches of the Kwanza River, featuring a tropical savanna climate with distinct rainy and dry seasons and an annual average temperature above 25℃. The high-temperature and high-evaporation environment poses severe challenges to the initial setting time, inter-layer bonding and crack control of RCC. It is an urgent technical bottleneck to reduce the adiabatic temperature rise, enhance crack resistance through mix proportion optimization, and establish a temperature control and anti-cracking system highly coordinated with the construction rhythm while ensuring rapid construction efficiency [2].

The main dam of the Kekka Hydropower Station is an RCC gravity dam with a maximum height of 116 m and a crest length of 533 m, consisting of 32 dam sections with a total concrete volume of approximately 1.56 million cubic meters. A continuous pouring process with a large lift height of 10–20 m is adopted after the concrete breaks away from the strong constraint zone, and the whole process from concrete discharge from the mixing plant to paving and finishing is controlled within 75 minutes. The extreme climatic conditions and stringent construction rhythm make temperature control and anti-cracking the core technical difficulty of the project, which also forms the practical engineering background of this study [3].

Combined with the technical characteristics of rapid RCC construction and its constraint mechanism on temperature control and anti-cracking, this paper conducts mix proportion optimization from the perspectives of low hydration heat material selection, aggregate system regulation, and coordination of setting time and strength development. Corresponding collaborative regulation measures including pouring temperature control, zoned cooling, heat preservation curing and simulation feedback are proposed, aiming to form a systematic solution for temperature control and anti-cracking of mass concrete adapted to rapid construction [4].

2. Technical Characteristics and Temperature Control Difficulties of Rapid RCC Construction

2.1 Inter-layer Interval Time and Pouring Intensity under Rapid Construction

The core of rapid RCC construction lies in shortening the inter-layer interval time and increasing the daily pouring intensity. The inter-layer interval time of conventional RCC construction is generally controlled within 6–8 hours to ensure good inter-layer bonding, while it can be shortened to 2–4 hours under rapid construction modes. This high-intensity continuous operation significantly improves the single-compartment pouring capacity, with a daily rising height of 1.0–1.5 m.

For the Kekka Hydropower Station, a continuous rising construction method with a large lift height of 10–20 m is adopted after exiting the strong constraint zone. The whole process from concrete discharge to paving and rolling is completed within 2 hours, with a single-layer compaction thickness of 30±2 cm. Nevertheless, the excessively short inter-layer interval limits the early heat dissipation window of lower concrete layers, resulting in the superposition of hydration heat layer by layer in a short time. Meanwhile, high pouring intensity requires seamless connection of mixing, transportation, paving and rolling procedures; any delay in individual links will lead to overtime inter-layer intervals and degrade inter-layer bonding quality [5].

In this project, construction joints are classified into hot joints, warm joints and cold joints according to the interval time: less than initial setting time plus 1–3 hours, initial setting time plus 3–6 hours, and more than initial setting time plus 6 hours. Differentiated treatment processes including scum removal, roller brushing loosening and high-pressure water jet (≥30 MPa) scouring are adopted to guarantee inter-layer bonding quality. Therefore, the inter-layer interval and pouring intensity in rapid construction are not blindly pursued at a high level, but balanced between ensuring inter-layer bonding quality and controlling temperature rise rate, which constitutes the primary difficulty of temperature control and anti-cracking.

2.2 Early Hydration Heat Accumulation Law Caused by Continuous Construction of Large Warehouse Surfaces

The continuous construction of large warehouse surfaces leads to a significant spatial accumulation effect of hydration heat release in RCC. Different from the traditional columnar pouring method, RCC adopts continuous thin-layer pouring across the whole warehouse, with a single warehouse area ranging from thousands to tens of thousands of square meters. Under such conditions, the hydration heat released by each concrete layer cannot be effectively dissipated through lateral boundaries, and heat is mainly transferred upward along the thickness direction. The continuous coverage of new concrete layers forms a typical "thermal blanket effect".

Measured data show that under large-warehouse construction conditions, the peak internal temperature of concrete appears 12–24 hours earlier than that in conventional construction, and the peak temperature is 25–35 ℃ higher than the ambient temperature. The temperature process curve from the project temperature control simulation shows that without forced cooling measures, the internal and external temperature difference of concrete can reach 15–18 ℃, and the maximum internal temperature in the strong constraint zone exceeds the standard temperature difference control value. Theoretical analysis indicates that water pipe cooling is the most effective measure to meet the control standard. However, through the triple coordination of further mix proportion optimization, inlet temperature control and enhanced surface curing, effective crack control is realized without laying cooling pipes, verifying the feasibility of the technical route of "prioritizing mix proportion optimization and relying on comprehensive curing".

More importantly, since the warehouse size is far larger than the concrete thickness, heat can hardly dissipate along the horizontal direction, resulting in a highly uniform temperature field in a large range. This "infinitely large plane" thermal boundary condition makes upward heat conduction and slow later-stage cooling the only heat dissipation paths, thus exacerbating the accumulation of temperature stress.

2.3 Constraint Mechanism of Rapid Construction on Temperature Control and Anti-Cracking System

The rapid construction mode poses severe challenges to traditional temperature control and anti-cracking systems and forms multi-dimensional constraint mechanisms. Firstly, the time window is limited: conventional temperature control measures such as cooling pipe embedding and thermal insulation covering require construction intervals, while the non-stop feature of rapid construction compresses the operation window, making it difficult to implement conventional temperature control measures as scheduled. Secondly, the spatial layout is restricted: the continuous construction of large warehouse surfaces makes it hard to arrange dense cooling pipe networks, and the increased pipe spacing significantly reduces the cooling effect.

Thirdly, the regulation accuracy is affected: the inlet temperature of concrete under rapid construction is more sensitive to external environmental fluctuations, and the huge daily pouring volume sharply increases the load of temperature reduction measures such as aggregate pre-cooling and ice mixing. Finally, the response mechanism is lagging: when abnormal temperature monitoring data is fed back, the accumulated heat of multiple constructed layers under rapid construction cannot be remedied by local adjustments. Accordingly, temperature control measures must shift from passive remediation to active prediction. These constraints determine that the temperature control and anti-cracking of mass RCC in rapid construction must be deeply coupled with the construction rhythm.

3. Mix Proportion Optimization Design and Adaptability to Rapid Construction

3.1 Optimization and Compounding of Low Hydration Heat Cementitious Material System

To solve the problem of concentrated early hydration heat release in rapid RCC construction, the optimization of cementitious material systems focuses on reducing the total unit-volume hydration heat. Low-heat Portland cement is selected as the basic cementitious material, whose 3-day hydration heat is 25%–30% lower than that of ordinary Portland cement. On this basis, the addition of large-volume mineral admixtures is the key to further reducing adiabatic temperature rise.

Fly ash can effectively delay the heat release rate due to its spherical particle effect and slow hydration activity; when the fly ash content accounts for 40%–60% of the total cementitious materials, the adiabatic temperature rise can be reduced by 5–8 ℃. The compound application of slag powder and phosphorus slag powder can compensate for the later strength development without significantly prolonging the setting time. Considering the large differences in activity index and specific surface area of different admixtures, orthogonal tests are required to determine the optimal compound ratio, balancing the early workability and middle-late crack resistance to form a heat release curve with low initial heat release, slow heat release process and stable final state.

The RCC mix proportion adopted by the Kekka Hydropower Station adopts an ultra-lean cementitious material system with a total cementitious material dosage of 153 kg/m^3 and a water-binder ratio of 0.59. The adiabatic temperature rise of this mix proportion is at a low level (the measured adiabatic temperature rise formula of RCC is $T=21.41t/(1.44+t)$), which fundamentally reduces the total hydration heat, creates basic conditions for canceling cooling pipes, and serves as a key foundation for simplifying subsequent temperature control measures.

3.2 Influence of Aggregate Gradation and Paste-Aggregate Ratio on Workability and Adiabatic Temperature Rise

The design of the aggregate system directly affects the compactness and filling effect of RCC, unit cement dosage and thermal performance. The ideal aggregate gradation aims to maximize the stacking density and minimize the void ratio, so as to reduce the paste volume required for void filling. The research shows that when the mass ratio of 20–40 mm coarse aggregate to 5–20 mm coarse aggregate is controlled at 6:4, and appropriate manufactured sand is added to optimize fine aggregate gradation, the aggregate stacking void ratio can be reduced to below 22%.

As a key control parameter for mix proportion design, every 0.01 reduction of the paste-aggregate ratio reduces the cementitious material dosage per unit volume by 15–20 kg, corresponding to a 1.0–1.5 ℃ decrease in adiabatic temperature rise. However, an excessively low paste-aggregate ratio will weaken the lubrication effect of the mixture, resulting in an excessive VB value and insufficient rolling compactness. For rapid construction conditions, the VB value of RCC is controlled within 10–15 seconds, which ensures effective compaction by vibratory rollers and avoids dry shrinkage cracks and increased hydration heat caused by excessive paste content.

3.3 Coordination of Setting Time and Strength Based on Rapid Construction Window Period

Rapid construction puts forward a unique requirement of "early strength development without early setting, delayed setting without retarded strength growth" for RCC, which requires precise coordination between setting time and strength development. The initial setting time must be longer than the total time from concrete discharge to rolling finishing, generally no less than 6–8 hours, to avoid inter-layer cold joints. Nevertheless, excessive initial setting time will delay formwork removal and subsequent covering procedures, so it needs to be precisely matched with the construction window period.

The combined application of naphthalene-based retarding superplasticizer and retarders (such as sodium gluconate) can flexibly regulate the initial setting time, with every 0.05% increase in dosage prolonging the initial setting time by about 2 hours. Meanwhile, to meet the bearing and covering requirements within the short interval of rapid construction, concrete needs sufficient early strength: the 24-hour compressive strength is required to be no less than 3.0 MPa to support construction equipment passage, and the 7-day strength should reach more than 50% of the design value. Adjusting cement fineness, admixture activity and micro-dosing of early strength components (such as sodium sulfate) can improve early strength without significantly shortening the initial setting time.

3.4 Verification of Adiabatic Temperature Rise and Crack Resistance of Optimized Mix Proportion

The final determination of the optimized mix proportion requires systematic tests on adiabatic temperature rise and crack resistance evaluation. An adiabatic calorimeter is adopted to test the temperature rise curve of concrete under approximate adiabatic conditions, focusing on three characteristic parameters: peak temperature, maximum temperature rise rate and peak occurrence time. The adiabatic temperature rise of the optimized scheme is reduced by more than 20% compared with the reference mix proportion, and the peak temperature rise rate is delayed to 40–60 hours after pouring, avoiding the intensive inter-layer covering stage of rapid construction.

The crack resistance is evaluated by temperature-stress testing machine (TSTM) or circular constraint shrinkage test to determine the first constrained cracking temperature and ultimate tensile strain of concrete. The ideal mix proportion should ensure the constrained cracking temperature is more than 5 ℃ lower than the predicted minimum ambient temperature, with the ultimate tensile strain no less than 100 με. In addition, large-plate simulation tests are carried out to verify the actual temperature field distribution under large-warehouse conditions, ensuring the reliable crack resistance of the optimized mix proportion in real construction environments.

4. Collaborative Regulation of Mass Temperature Control Anti-Cracking Measures and Rapid Construction

Rapid RCC construction is characterized by continuous thin-layer pouring in large warehouses, with single-batch operation lasting for tens of hours to several days and nights, and the construction process cannot be interrupted due to diurnal changes or temperature control requirements. Therefore, temperature control and anti-cracking measures must be deeply embedded into the continuous construction rhythm, forming an integrated regulation system of pouring, temperature inhibition, curing and feedback.

4.1 Pouring Temperature Control and Multi-Period Inlet Temperature Rise Inhibition Strategy

Under rapid construction modes, the huge daily pouring volume brings practical difficulties including insufficient aggregate pre-cooling capacity and significant temperature rise during transportation. A phased and link-based temperature rise inhibition strategy is established. In the aggregate stage, coarse aggregates are cooled to below 5 ℃ through air cooling or water cooling, and sunshade sheds are equipped to reduce temperature rise caused by solar radiation. In the mixing stage, flake ice is used to replace part of the mixing water, and each ton of flake ice can reduce the concrete discharge temperature by 0.5–0.8 ℃. In the transportation stage, truck hoppers are covered with thermal insulation tarpaulins, and transportation routes and waiting time are adjusted according to ambient temperature.

For construction areas with large diurnal temperature differences, pouring operations are preferably arranged during low-temperature periods at night and early morning, and the single-layer paving thickness is controlled within 35 cm to shorten heat accumulation time. For the exposure period of concrete from discharge to rolling finishing (0.5–2 hours), warehouse temperature inhibition measures linked to diurnal rhythms are adopted for unrolled or under-construction paving layers to control the concrete temperature before rolling.

During high-temperature daytime periods, mobile spray devices are continuously operated at discharge outlets, paver fronts and rolling operation areas to form a local humid microclimate, inhibiting temperature rise through water mist evaporation and reducing single-layer paving thickness to shorten heat accumulation time. During low-temperature nighttime periods, spraying is stopped and temporary covering is adopted to control temperature rise by natural low-temperature conditions. During high-humidity early morning periods with low spray cooling efficiency, the construction pace is accelerated to prioritize rapid paving.

The mixing system of the Kekka Hydropower Station adopts a combined pre-cooling process of secondary air cooling, ice addition and cold water addition, with a designed total production capacity of 400 m^3/h (353 m^3/h for RCC). An intelligent control system is equipped to realize automatic recording and real-time monitoring of the whole process to ensure the discharge temperature meets design requirements. Verified by field RCC production tests and simulation analysis, the scheme of 18 ℃ pouring temperature combined with surface spray curing is feasible, providing a technical basis for canceling cooling pipes.

4.2 Surface Thermal and Moisture Curing Technology Matching with Rapid Covering Rhythm

The thin-layer continuous covering feature of rapid RCC construction requires surface thermal and moisture curing to be precisely matched with the paving rhythm without interrupting construction. The curing measures in this section target finished rolled concrete layers, which are temporally connected and functionally differentiated from the pre-rolling temperature control measures in the previous section, focusing on post-rolling thermal and moisture preservation to prevent surface cracks and drying shrinkage deformation.

The "immediate covering after rolling" process is adopted for thermal curing: geotextiles or thermal insulation quilts are laid within 30 minutes after vibration rolling, with the thickness adjusted seasonally (2–3 mm in summer and 10–15 mm in winter). Intermittent spraying or water curtain systems are applied for moisture curing; slow-release curing agents or atomized water are sprayed 10–15 minutes before covering new layers to maintain the surface humidity above 90%. Humidity sensors embedded in concrete are used to adjust the spraying frequency during inter-layer curing to avoid ponding that affects subsequent rolling quality.

Under rapid construction conditions, a single cycle of layer curing covering and rolling equipment alternating operation is controlled within 1.5–2 hours, ensuring no construction delay and inhibiting surface water evaporation to prevent plastic shrinkage cracks and drying shrinkage cracks. The Kekka Hydropower Station adopts a composite curing system integrating manual water spraying, self-flowing water supply through perforated plastic pipes, mechanical spraying, atomization curing and geotextile/thermal insulation quilt covering. Self-flowing water films are formed on upstream and downstream dam surfaces using φ25 plastic pipes with 100 mm spacing holes, and fixed and mobile sprayers are deployed on horizontal warehouse surfaces to form a local humid microclimate. The zoned combination of multiple curing methods effectively reduces warehouse evaporation rate and internal and external temperature difference, realizing effective surface crack control without cooling pipes.

4.3 Temperature-Stress Field Simulation Feedback and Crack Resistance Evaluation Method

The implementation effect of temperature control measures is evaluated through closed-loop feedback of temperature-stress field simulation and on-site monitoring. A three-dimensional finite element model is established, with real-time meteorological data, concrete thermal parameters, construction schedule and measured boundary conditions input to dynamically simulate the evolution of temperature and stress fields from pouring and cooling to curing.

Key evaluation indicators include the stress ratio (ratio of maximum tensile stress to concrete tensile strength) with an early warning threshold of 0.7, maximum temperature gradient controlled within 0.3 ℃/cm, and the matching degree between peak temperature occurrence time and cooling peak reduction period. A distributed optical fiber temperature measurement system and embedded strain gauges are adopted for on-site monitoring, feeding measured data back to the simulation model every 4 hours. Kalman filtering and data assimilation algorithms are used to correct model parameters, realizing the dynamic closed-loop regulation of temperature-stress prediction, monitoring and correction.

Crack resistance is quantitatively evaluated by final crack length density (total crack length/pouring volume, unit: m/m^3) and maximum crack width, with target control values of 0.02 m/m^3 and 0.2 mm respectively. The selection of temperature control schemes relies on the mutual verification of theoretical simulation and field tests. For the Kekka Hydropower Station, theoretical simulation shows that water pipe cooling is the most effective measure for temperature control in strong constraint zones, which can reduce the maximum temperature by 4–6.4 ℃. However, considering construction cost, construction period and field test results, the project finally adopts a simplified scheme of low-heat mix proportion, inlet temperature control and comprehensive curing. Engineering practice proves that when the adiabatic temperature rise of concrete is controlled at a low level, refined inlet temperature control and curing management can fully meet crack control requirements, reflecting the dynamic coordination between simulation feedback and actual construction conditions.

5. Conclusions

Aiming at the mix proportion optimization and mass temperature control anti-cracking problems of RCC rapid construction, this paper systematically reveals the temperature control difficulties caused by early hydration heat accumulation under the rapid construction characteristics of short inter-layer intervals and large-warehouse continuous pouring, and clarifies the time, space and response constraints imposed on traditional crack resistance systems.

An optimized mix proportion scheme adapted to rapid construction rhythm is formed by selecting low hydration heat cementitious materials, optimizing aggregate gradation and paste-aggregate ratio, and coordinating setting time and early strength development. Test results show that the adiabatic temperature rise is reduced by more than 20% with significantly improved crack resistance. Collaborative regulation measures including multi-period pouring temperature inhibition and construction-rhythm-matched thermal curing are proposed, and a closed-loop evaluation system is established based on temperature-stress field simulation feedback, forming a systematic solution for temperature control and anti-cracking of rapid RCC construction.

The engineering practice of the Kekka Hydropower Station verifies that in high-temperature and rainy regions, the technical route of "prioritizing mix proportion optimization, coordinating inlet temperature control and comprehensive curing" based on the ultra-lean cementitious material mix proportion (total cementitious material dosage of 153 kg/m^3) can effectively control the temperature crack risk of large-warehouse and large-lift rapid construction without water cooling. It provides an economical and convenient technical paradigm for similar overseas hydropower projects.

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