

Research Progress on Hydration Heat of Mass Concrete

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Abstract

Mass concrete is widely used in bridge pile caps, hydraulic structures, foundations of high-rise buildings, nuclear power projects, and large underground structures. Due to the large structural dimensions, the hydration heat generated inside concrete is difficult to dissipate rapidly, which often leads to a high early-age temperature rise and significant temperature difference between the interior and surface. When thermal deformation is restrained, thermal stress develops inside the structure. If the tensile thermal stress exceeds the early-age tensile strength of concrete, temperature cracks may occur, thereby affecting structural integrity, durability, and service safety. Based on previous studies, this paper reviews the research progress on hydration heat of mass concrete from the aspects of hydration heat mechanism, material and mix proportion control, construction temperature-control measures, temperature monitoring, and numerical simulation. Existing studies show that reducing the hydration heat of cementitious materials, optimizing the proportion of mineral admixtures, controlling placing temperature, adopting layered and block construction, strengthening thermal insulation and moisture curing, and using cooling pipes can effectively reduce peak temperature and internal-surface temperature difference. With the development of monitoring technologies and numerical methods, temperature control of mass concrete is gradually moving toward refinement, intelligence, and whole-process control..

Keywords

Mass Concrete; Hydration Heat; Temperature Field; Thermal Cracking; Temperature-Control Measures; Numerical Simulation

1. Introduction

Mass concrete generally refers to concrete with large structural dimensions, or concrete that may develop harmful cracks due to temperature change and shrinkage caused by hydration heat. According to the Chinese standard Standard for Construction of Mass Concrete GB 50496—2018, concrete with a minimum structural dimension not less than 1 m, or concrete expected to develop harmful

cracks due to hydration heat and shrinkage, can be classified as mass concrete [3]. Such structures are commonly found in bridge pile caps, dams, thick foundation slabs, foundations of super high-rise buildings, and large equipment foundations [1,2].

Compared with ordinary concrete members, the main problem of mass concrete is not simply insufficient load-carrying capacity, but the risk of cracking caused by early-age temperature variation and restrained deformation. Cement and other cementitious materials release heat during hydration. The internal part of mass concrete heats up rapidly, while the surface cools relatively quickly due to environmental temperature, curing conditions, and heat dissipation boundaries, which easily results in a large internal-surface temperature difference [1,5]. If the temperature gradient and restraint are significant, early-age concrete may crack before its tensile strength fully develops, leading to surface cracks, deep cracks, or even through cracks [5,6].

Therefore, the core of hydration heat research on mass concrete is to reveal the relationship among hydration heat release, temperature field evolution, thermal stress formation, and crack development, and to achieve temperature control and crack prevention through material optimization, construction measures, monitoring, and numerical analysis [5,17]. ACI 207 also regards materials, mix proportioning, properties, construction methods, and temperature-control measures as major issues in mass concrete, which is commonly used in dams, bridge components, and building foundations with high temperature-control requirements [1,2].

2. Research Progress on Hydration Heat of Mass Concrete

2.1. Hydration Heat Mechanism and Thermal Cracking

The hydration heat of mass concrete mainly comes from the hydration reaction of cement clinker minerals, among which C_3S and C_3A release heat rapidly at early ages and have a significant influence on early temperature rise [8,19,20]. As hydration proceeds, the internal temperature of concrete generally experiences rapid heating, peak temperature, slow cooling, and gradual stabilization toward ambient temperature. Due to poor heat dissipation inside large-volume concrete, the peak temperature in the core region is usually much higher than that near the surface, resulting in internal-surface temperature difference and temperature gradients [1,5].

Early studies mainly focused on heat conduction theory and thermal stress analysis, aiming to establish calculation formulas for hydration temperature rise and evaluation methods for thermal cracking. With the accumulation of engineering practice, research has gradually expanded from simple temperature-rise calculation to comprehensive analysis of temperature field, stress field, creep, shrinkage, and restraint conditions [5,6,17]. Technical reports on thermal cracking of mass concrete also indicate that the prediction and control of thermal stress caused by

cement hydration remain key issues in the design and construction of mass concrete structures [5].

The formation of thermal cracks is closely related to temperature gradient, cooling rate, external restraint, internal restraint, and the development of early-age tensile strength [6,10]. In engineering practice, cracking risk is usually reduced by controlling temperature rise, internal-surface temperature difference, and cooling rate. GB 50496—2018 specifies requirements for temperature rise after placement, internal-surface temperature difference, and cooling rate during mass concrete construction, among which internal-surface temperature difference and cooling rate are important indices for temperature control and crack prevention [3,4].

2.2. Material and Mix Proportion Control

Materials and mix proportion are fundamental factors affecting hydration heat of mass concrete. Cement type, cement content, water-binder ratio, type and dosage of mineral admixtures, chemical admixtures, and aggregate properties all influence the heat release rate and temperature rise of concrete [1,2,19,20]. In general, reducing cement content, using low-heat or moderate-heat cement, and adding mineral admixtures such as fly ash and slag can reduce the early hydration heat release rate and peak temperature [1,7,14].

Existing studies show that mineral admixtures can not only reduce the amount of cement clinker, but also improve later-age strength and durability [7,18,20]. Fly ash has relatively low early activity and is generally beneficial for reducing early heat release. Slag has higher activity, and its influence on early temperature rise depends on dosage and fineness [7]. A reasonable combination of fly ash and slag can improve temperature-control performance while maintaining workability and mechanical properties [7,14].

Chemical admixtures mainly influence hydration heat by regulating the hydration process and improving workability. Retarders can delay hydration and reduce the early heat release rate. High-range water reducers can improve concrete flowability while reducing water demand, thereby creating conditions for reducing cementitious material content [19,20]. However, the influence of chemical admixtures on total heat release is usually less significant than that of cement content and mineral admixtures. Therefore, admixture selection should be determined comprehensively according to strength, setting time, workability, and temperature-control requirements [1,2].

2.3. Construction Temperature Control and Field Monitoring

Construction temperature control is a key part of hydration heat control in mass concrete. Common measures include reducing raw material temperature, controlling placing temperature, layered and block pouring, optimizing pouring intervals, installing cooling pipes, strengthening surface thermal insulation and

moisture curing, and controlling formwork removal time [1-4]. For thick foundations, bridge pile caps, and hydraulic structures, cooling pipes are often used to actively remove internal hydration heat and reduce core temperature and internal-surface temperature difference [13,16].

The temperature-control effect of cooling pipes is affected by pipe diameter, pipe spacing, cooling duration, inlet water temperature, flow rate, and water circulation mode [13]. In recent years, some projects have adopted automatic cooling systems, which adjust cooling water flow and direction according to measured temperature data to achieve more refined temperature control [16].

Field temperature monitoring is an important means to verify the effectiveness of temperature-control schemes. GB/T 51028—2015 Technical Code for Temperature Measurement and Control of Mass Concrete applies to temperature monitoring and control of mass concrete in industrial and civil buildings as well as other concrete with special requirements [4]. It covers temperature-time curve testing, temperature monitoring, temperature control, and water-cooling systems [4]. By arranging temperature sensors in the core region, surface layer, corners, and surrounding environment, engineers can track peak temperature, internal-surface temperature difference, and cooling rate in time, providing a basis for adjusting insulation and cooling measures [4,16].

2.4. Numerical Simulation and Intelligent Control

With the development of computational technology, numerical simulation has become an important method for studying hydration heat of mass concrete. Common methods include the finite difference method, finite element method, and thermo-mechanical coupling analysis [8,11,12]. By treating hydration heat as an internal heat source and considering boundary heat dissipation, thermal parameters of materials, construction layers, environmental temperature, and curing conditions, the temperature field and thermal stress development of concrete can be predicted [8,12].

Early numerical simulations mainly focused on temperature field calculation. Later studies gradually introduced the development of elastic modulus, tensile strength, creep, shrinkage, and damage evolution to evaluate early-age cracking risk [10-12]. In recent years, some studies have further adopted hydration kinetics models to predict hydration heat release and coupled them with temperature field, stress field, and damage models for temperature control and crack prevention analysis of mass concrete [7,11,15].

Meanwhile, the combination of monitoring technology and numerical simulation has promoted the development of intelligent temperature control for mass concrete [12,16]. By arranging temperature sensors, real-time internal temperature data can be obtained and compared with predicted results, so that temperature-control parameters can be dynamically corrected. In the future, temperature-control

systems based on the Internet of Things, digital twins, and intelligent algorithms are expected to realize a transition from “ post-monitoring ” to “ real-time prediction and active control ” [16].

3. Existing Problems and Development Trends

Overall, a relatively complete technical system has been formed for the study of hydration heat in mass concrete, but several problems still remain [1,2,5].

First, there are still differences between hydration heat parameters obtained from tests and those in actual engineering projects. Laboratory calorimetry tests and adiabatic temperature-rise tests differ from field mass concrete structures in boundary conditions, and direct use of test parameters may lead to deviations in predicting peak temperature and cooling process [5,12,15].

Second, materials, structural dimensions, environmental conditions, and construction technology are strongly coupled. Cement type, admixture ratio, pouring thickness, restraint conditions, and climate conditions vary greatly among projects, making it difficult to apply a unified temperature-control scheme directly [1,2,14].

Third, coupling analysis of temperature field and stress field still needs further improvement. Controlling temperature difference alone cannot fully reflect cracking risk. Restraint degree, elastic modulus development, creep relaxation, shrinkage deformation, and tensile strength growth should also be considered [5,6,10].

Future studies may be carried out in the following aspects. First, testing and back-analysis methods for hydration heat parameters that better reflect field conditions should be established. Second, calculation models considering hydration, temperature, humidity, stress, and damage coupling should be developed [8,11,15]. Third, the effects of fly ash, slag, low-heat cement, and new low-carbon cementitious materials on hydration heat should be further studied [7,14,18]. Fourth, engineering application of temperature monitoring, intelligent cooling, and digital construction control should be promoted [4,16]. Fifth, temperature-control and crack-prevention design methods suitable for different structural types and climatic conditions should be established [1,2,5].

4. Conclusions

(1) The hydration heat problem of mass concrete is mainly characterized by high early-age temperature rise, large internal-surface temperature difference, and increased restrained tensile stress during the cooling stage. It is essentially the result of the combined effects of hydration heat release, heat dissipation conditions, and restrained deformation [1,5].

(2) Material and mix proportion control is the basic measure for reducing hydration heat. The use of low-heat cement, reduced cementitious material content, appropriate addition of fly ash and slag, optimized water-binder ratio, and proper chemical admixtures can effectively slow down the heat release rate [1,7,14].

(3) Construction temperature-control measures play an important role in preventing thermal cracks. Controlling placing temperature, layered and block construction, cooling pipe systems, thermal insulation and moisture curing, and reasonable formwork removal are commonly used measures in engineering practice [1-4,13].

(4) Field temperature monitoring can reflect internal temperature changes in concrete in time and provide a basis for adjusting insulation and cooling measures. The combination of temperature monitoring and construction control is an important way to ensure the quality of mass concrete construction [4,16].

(5) Numerical simulation has developed from simple temperature field analysis to thermo-mechanical-damage coupling analysis. In the future, measured data, intelligent algorithms, and digital construction technologies should be further integrated to realize refined and intelligent temperature control and crack prevention for mass concrete [11,12,15,16].

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