

Effect of surface insulation on thermal stress of concrete

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Abstract. For concrete, the appearance of temperature load due to the hydration heat of cementitious materials is inevitable and important to the structural safety of dam. This paper investigates the effect of different surface insulation measures on the thermal stress of dam concrete by means of finite element simulation calculation. The calculation results show that surface insulation is important for lowering the surface thermal stress of concrete. When the equivalent surface coefficient of heat transfer was less than $3\text{kJ}/(\text{m}^2\cdot\text{h}\cdot^\circ\text{C})$, the surface tensile stress can be decreased by 80%–90% for concrete undergoing diurnal temperature variation and cold wave.

Keywords: Mass concrete; Cracking control; Temperature variation; Surface insulation.

1. Introduction

Different from the thin-walled structures/components (beams, columns and slabs) in the industrial and civil construction industry, the hydraulic concrete structures with cross sections larger than 1.0m are highly difficult to construct due to the large amount of cementitious materials and the vulnerability to external environment such as solar radiation and temperature, as well as the complex construction technology of high arch dams. Its construction measures are closely related to its own material characteristics and meteorological conditions in the dam site area [1-3]. Internal temperature can arise after concrete mixing caused by the hydration of cementitious materials such as cement and fly ash. Once the deformation is restraint by the foundation and/or adjacent parts, significant tensile stress inside the structure can be generated [4]. Cracking occurs once the tensile stress in the temperature drop stage reaches the strength of concrete. Therefore, how to effectively reduce the tensile stress of concrete is the most concerned problem in the engineering field.

Generally, for the concrete structure with a section size greater than 1.0m, the adverse factors of too thick section combined with the thermal inertia of concrete materials make it difficult for the internal hydration heat to dissipate through natural heat dissipation, so cooling water pipes are needed for water cooling [5-6]. On the other hand, in order to cope with the large temperature difference (temperature gradient) caused by the sudden change of

external temperature, thermal insulation measures should be taken on the surface of the dam body. First cooling by the embedded cooling pipes is carried out at the initial stage of casting to reduce the temperature peak, and later cooling is carried out before the arch grouting to make sure the concrete can reach the target grouting temperature [7]. Due to the low early-age strength of concrete (especially concrete mixed with fly ash), unreasonable first cooling may increase the cracking risk of early-age concrete.

Based on a three-dimensional numerical simulation calculation, this paper investigated the effects of surface insulation measures on the generation and development of concrete thermal stress, quantitatively analyzed the influence law of each factor on dam safety, and finally provided a strong theoretical and technical support for the realization of high quality mass concrete construction.

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2. Temperature field calculation method

The heat conduction equation of concrete is shown in Equation (1) [8,9]

$$\frac{\partial T}{\partial \tau} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q}{c\rho} \quad (1)$$

where, a is the coefficient of temperature conductivity, m^2/h ; T is actual temperature, $^{\circ}C$; τ is the age, h ; ρ is the density, kg/m^3 ; c is the specific heat, $kJ/(kg^{\circ}C)$; Q is the hydration heat of cementitious material, kJ/kg . The adiabatic temperature rise of cementitious material is θ , one can obtain [10]

$$\frac{\partial \theta}{\partial \tau} = \frac{Q}{c\rho} \quad (2)$$

Substituting Equation (2) into Equation (1), one can have

$$\frac{\partial T}{\partial \tau} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial \tau} \quad (3)$$

3. Project summary

3.1 Project and meteorological conditions

Two concrete mixtures for a high concrete arch dam construction is selected for simulation calculation. The arch dam normal water level is 2254.00m, the dam elevation is 2259.00m, the lowest elevation of the dam is 2059.00m, and the maximum height of the dam is 200m. The average annual temperature in the area where the dam site is located is $13.9^{\circ}C$ with the extreme maximum temperature being $35.9^{\circ}C$ and the minimum temperature being $-15.9^{\circ}C$.

3.2 Material performance of concrete

Tables 1 and 2 show the thermal parameters and elastic modulus of dam concrete, respectively.

Table 1. Thermal parameters of dam concrete

	coefficient of temperature conductivity (m^2/h)	coefficient of thermal conductivity ($kJ/m \cdot h \cdot ^{\circ}C$)	specific heat ($kJ/kg \cdot ^{\circ}C$)	thermal expansion coefficient ($10^{-6}/^{\circ}C$)	adiabatic temperature rise ($^{\circ}C$)
C ₁₈₀ 35	0.0031	6.01	0.78	9.0	28.0
C ₁₈₀ 30	0.0031	5.74	0.75	9.0	26.0

Table 2. Elastic modulus of dam concrete

	Grading	Elastic modulus (GPa)			
		7d	28 d	90 d	180 d
C ₁₈₀ 35	4	17.71	23.04	26.68	31.00
C ₁₈₀ 30	4	15.24	20.43	24.21	28.00

4. Research and analysis of surface insulation measures

4.1 Computational models and boundary conditions

In order to analyze the effect of cold wave and daily temperature difference on the concrete cracking risk of concrete under different surface insulation measures, a refinement model (40 m (length)×20 m (width)×10 m (height)) was prepared. Two different concrete temperature drops ($15^{\circ}C$ and $20^{\circ}C$), two diurnal temperature drops ($6^{\circ}C$ and $15^{\circ}C$) and five concrete age (3, 7, 14, 28 and 90d) were adopted. The model has 56320 units and 63068 nodes, as shown in Figure 1.

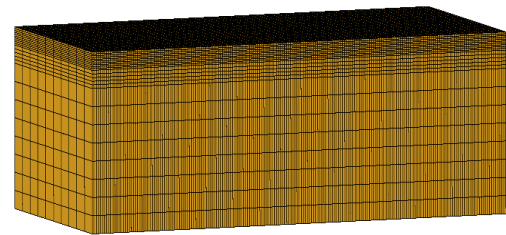


Figure 1. Refined model for surface protection analysis

4.2 Results and discussions

Table 3 and Table 4 show the maximum tensile stress of surface concrete at different ages under the influence of rapid temperature change process based on diurnal temperature difference, respectively. As can be seen from the tables, in the absence of surface protection measures, the maximum surface stress of C35 is 1.09MPa and 1.45MPa when the diurnal temperature drop is $15^{\circ}C$ and $20^{\circ}C$ respectively. The maximum stress of concrete decreases to 0.11~0.14MPa when the surface coefficient of heat transfer of insulation material $\beta \leq 3kJ/(m^2 \cdot h \cdot ^{\circ}C)$. In the absence of surface protection measures, the maximum surface stress of C30 is 1.03MPa and 1.37MPa when the diurnal temperature drop is $15^{\circ}C$ and $20^{\circ}C$, respectively. The maximum stress of concrete decreases to 0.10~0.14MPa when $\beta \leq 3kJ/(m^2 \cdot h \cdot ^{\circ}C)$. To sum up, the maximum reduction magnitude of concrete thermal stress is about 90% when strict surface insulation measures are taken.

Table 5 and Table 6 show the maximum tensile stress of surface concrete under different rapid temperature change processes ($6^{\circ}C$ and $15^{\circ}C$ temperature drop in 2 days). As can be seen from the tables, in the absence of surface protection measures, the maximum surface stress of C35 is 1.30MPa and 3.24MPa when the temperature drop is $6^{\circ}C$

and 15°C, respectively. After taking different surface insulation measures, the maximum surface stress level decreases dramatically. When $\beta \leq 3\text{kJ}/(\text{m}^2 \cdot \text{h} \cdot ^\circ\text{C})$, the maximum surface stress of concrete can be reduced to 0.26MPa and 0.66MPa when the temperature drop is 6°C and 15°C, respectively. In the absence of surface protection measures, the maximum surface stress of C30 is 1.23MPa and 3.07MPa when the temperature drop is 6°C and 15°C, respectively. When $\beta \leq 3\text{kJ}/(\text{m}^2 \cdot \text{h} \cdot ^\circ\text{C})$, the maximum surface stress of concrete can be reduced to 0.25MPa and 0.63MPa when the temperature drop is 6°C and 15°C, respectively. To sum up, the maximum reduction magnitude of concrete thermal stress is about 80% with strict surface insulation measures.

Table 3. Thermal stress of C35 under diurnal temperature variation (Unit: MPa)

Case	Surface insulation condition (β)	Age (day)				
		3	7	14	28	90
Diurnal temperature variation:15°C	/	0.5	0.64	0.77	0.9	1.09
	10kJ/(m ² ·h·°C)	0.16	0.2	0.24	0.28	0.34
	5kJ/(m ² ·h·°C)	0.08	0.1	0.12	0.14	0.17
	3kJ/(m ² ·h·°C)	0.05	0.06	0.08	0.09	0.11
Diurnal temperature variation:20°C	/	0.66	0.85	1.03	1.2	1.45
	10kJ/(m ² ·h·°C)	0.21	0.27	0.32	0.38	0.46
	5kJ/(m ² ·h·°C)	0.1	0.13	0.16	0.19	0.23
	3kJ/(m ² ·h·°C)	0.07	0.08	0.1	0.12	0.14

Table 4. Thermal stress of C30 under diurnal temperature variation (Unit: MPa)

Case	Surface insulation condition (β)	Age (day)				
		3	7	14	28	90
Diurnal temperature variation:15°C	/	0.47	0.60	0.72	0.85	1.03
	10kJ/(m ² ·h·°C)	0.15	0.19	0.23	0.27	0.32
	5kJ/(m ² ·h·°C)	0.07	0.10	0.11	0.13	0.16
	3kJ/(m ² ·h·°C)	0.05	0.06	0.07	0.08	0.10
Diurnal temperature variation:20°C	/	0.62	0.80	0.97	1.13	1.37
	10kJ/(m ² ·h·°C)	0.20	0.25	0.30	0.36	0.43
	5kJ/(m ² ·h·°C)	0.10	0.13	0.15	0.18	0.22
	3kJ/(m ² ·h·°C)	0.06	0.08	0.10	0.11	0.14

Table 5. Thermal stress of C35 under rapid temperature drop (Unit: MPa)

Case	Surface insulation condition (β)	Age (day)				
		3	7	14	28	90
Temperature drop in 2 days:6°C	/	0.64	0.79	0.93	1.08	1.30
	10kJ/(m ² ·h·°C)	0.34	0.42	0.49	0.57	0.68
	5kJ/(m ² ·h·°C)	0.20	0.24	0.29	0.33	0.40
	3kJ/(m ² ·h·°C)	0.13	0.16	0.19	0.22	0.26
Temperature drop in 2 days:15°C	/	1.59	1.97	2.33	2.69	3.24
	10kJ/(m ² ·h·°C)	0.86	1.05	1.23	1.42	1.71
	5kJ/(m ² ·h·°C)	0.50	0.61	0.71	0.83	0.99
	3kJ/(m ² ·h·°C)	0.33	0.41	0.48	0.55	0.66

Table 6. Thermal stress of C30 under rapid temperature drop (Unit: MPa)

Case	Surface insulation condition (β)	Age (day)				
		3	7	14	28	90
Temperature drop in 2 days:6°C	/	0.60	0.74	0.88	1.02	1.23
	10kJ/(m ² ·h·°C)	0.32	0.39	0.46	0.54	0.65
	5kJ/(m ² ·h·°C)	0.19	0.23	0.27	0.31	0.38
	3kJ/(m ² ·h·°C)	0.13	0.15	0.18	0.21	0.25
Temperature drop in 2 days:15°C	/	1.50	1.85	2.19	2.54	3.07
	10kJ/(m ² ·h·°C)	0.81	0.99	1.16	1.34	1.62
	5kJ/(m ² ·h·°C)	0.47	0.57	0.67	0.78	0.94
	3kJ/(m ² ·h·°C)	0.32	0.38	0.45	0.52	0.63

5. Conclusion

Surface insulation measures can effectively improve the cracking risk of surface concrete under the condition of rapid temperature change. When the equivalent surface coefficient of heat transfer is less than or equal to 3kJ/(m²·h·°C), the maximum thermal stress of concrete decreases by 80%~90% under the condition of rapid temperature variations.

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