Evaluation of thermal cracks in mass concrete structures during construction

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Abstract. During construction, the problem of temperature crack formation in mass concrete structures is really an important issue that needs attention and research. This paper provides an overview of the current criteria for evaluating the possibility of forming thermal cracks. At the same time, the concrete block under certain construction conditions was considered to predict the temperature field and thermal stress. Besides that, the numerical method has been implemented with the help of Midas software for structural analysis. The results obtained allow us to assess the risk of thermal cracking and compare it with the criteria used in actual construction practices.

1. Introduction

During the construction of hydraulic and power structures, bridges, foundations, etc are often large in size and are known as mass concrete [1]. As we know that one of the significant impacts on mass concrete structures is the temperature factor. The temperature changes during cement hydration will change the state of stress-strain in the structure during both construction and operation stages [2, 3].

The temperature regime in a mass concrete is formed under the influence of many factors. External temperature effects may include as air temperature, ground temperature, solar radiation, the presence of wind and its direction. The main factor in the construction period is cement exotherm. The composition of the concrete mix affects the magnitude of exothermic heating such as cement consumption and its heat release. In addition, many technological factors influence the formation of the temperature field in mass concrete: the concreting scheme, the temperature of concrete to be laid, the thickness of concrete layers to be laid, concreting intensity, use of cooling pipe system, etc. During construction, the amount of heat due to cement hydration has increased significantly inside of concrete blocks. As a result of this, the temperature difference between the center and the surface of concrete blocks occurs significantly. That difference in temperature causes the formation of thermal cracks [4, 5].

Currently, many requirements are made to regulate and control the formation of thermal cracks in concrete blocks [6, 7]. However, the problem of thermal cracks in concrete blocks is still a large concern for scientists and researchers. The ability to form thermal cracking is usually estimated by the temperature difference between the center and the surface of the concrete block [8] and does not take into account its size. However, these general parameters do not assess the possibility of local cracking at any location in concrete blocks.

This paper presents the research results on the possibility of thermal cracking of concrete structures during construction based on the common parameter of the temperature difference between the center
and the surface of concrete blocks. Besides, the thermal stress state is also calculated in locations on the concrete block. The studies were performed by finite element method with the help of Midas software. The proposed approach and the results obtained can be used in the practice design and construction process of mass concrete structures.

2. Materials and methods

2.1. Criteria for evaluating the crack formation of a concrete mass during the construction phase

Currently, in Russia and other countries of the world, there are many standards for controlling the cracks formed during the construction of massive concrete structures. Each standard presents criteria appropriate to the climatic conditions and construction technology in each country.

As a rule for pouring concrete, the temperature difference between the center and the surface of the concrete block should be controlled. The temperature difference at any point in the concrete block is assumed not to exceed ~ 20 °C [9].

In Russia, many of the documents [10, 11] describe the required temperature differences in mass concrete, which depending on the concrete technology and construction area. According to SP 357.1325800.2017 [12] standard in the area of contact with the ground, the temperature difference ΔT does not exceed (16-18) °C when placing concrete long-strip and the temperature difference ΔT does not exceed (20-27) °C when placing concrete cutting columns. The contact zone is understood to be the zone constructed at the construction site with a height equal to 0.2 of the largest block size in the plan. In the contact zone, the cooling of concrete is not allowed below the calculated temperature. For concrete in the free zone (above the contact zone from the base surface), the temperature difference between the core and the surface ΔT in the mass concrete is allowed no more than (20-25) °C.

The thermal regime in mass concrete blocks during construction is also required in international construction practice. Therefore, according to the standards of Vietnam TCVN:305.2004 «Mass Concrete - code of practice of construction and acceptance » two factors are used to control its influence on the formation of thermal cracks in mass concrete structures. The first factor is the temperature difference between the center and the surface of the concrete ΔT. To prevent the formation of cracks, the following condition is necessary ΔT < 20 °C. The second factor is the temperature gradient, the value of which should be MT ≤ 50 °C/m [13].

According to the design standards for gravity and arch dams in China [14], the maximum permissible temperature difference between the center and the surface of concrete blocks depends on its size and is presented in Table 1.

Table 1. Permissible temperature gradients ΔT (°C) according to the design codes of China

| Concrete block height | Concrete block length L, m |
|-----------------------|---------------------------|
|                       | < 16          | 17 – 20        | 21 – 30        | 31 – 40        | > 40         |
| (0 – 0.1)L            | 26 -25       | 24 - 22        | 22 - 19        | 19 - 16        | 16 - 14      |
| (0.1 – 0.4) L         | 33 - 31      | 31 - 28        | 28 - 26        | 24 -20         | 20 - 18      |

In accordance with the criterion for evaluation of the process of crack formation according to the CIRIA C600 standard (Great Britain), the maximum temperature difference between the center and the surface of concrete blocks ΔTmax is determined by the formula (1) [15]:

$$ΔT_{max} = \frac{3.7\varepsilon}{\alpha},$$

where: ε - ultimate elongation of concrete at the age of τ days; α - the coefficient of thermal expansion of concrete.

After substituting the known values α = 13.10^{-6} and ε = 70.10^{-6} into the above equation (1), we obtain the maximum allowable difference ΔTmax = 19.9 °C ≈ 20 °C. Thus, the requirement of temperature regime in concrete blocks during construction (1) has decreased compared to the previous
general requirements and restrictions. The temperature difference between the center and the surface of the concrete mass should not exceed 20 °C.

A simple method for preliminary evaluation of the formation of thermal cracks has been proposed by V.I. Teleshev [16]. In this case, the value of the permissible temperature in the mass concrete depends on the size of the concrete block and the ratio of the elastic modulus of concrete and the foundation. The maximum allowable temperature in the mass concrete is determined by the formula (2) [16]:

$$T_{c}^{\text{max}} = T_{c,\text{oper}}^{\text{ave}} + \left[ T_{c}^{\text{ave}} \right] k_{1},$$

where: $T_{c,\text{oper}}^{\text{ave}}$ - the average temperature in concrete blocks during operation; $\left[ T_{c}^{\text{ave}} \right]$ - the permissible temperature difference in the block during construction defined as (3) [16].

$$\left[ T_{c}^{\text{ave}} \right] = \left[ T_{c}^{\text{ave}} \right] k_{1}, \quad \left[ T_{c}^{\text{ave}} \right] = \frac{\varepsilon}{\alpha k_{2} k_{3} k_{4}},$$

where: $k_{1}$ - transition coefficient from the average temperature in the unit during heat evolution period to the maximum one ($k_{1} \approx 1.3-1.5$); $\varepsilon$ - the limit compliance concrete (depends on the concrete grade, its composition and age.); $\alpha$ - linear concrete expansion coefficient ($\alpha \approx 1.10^{-5}$); $k_{2}$ - crushing factor average ($k_{2} \in (H/L, E/E_{b})$); $k_{3}$ - relaxation factor (average), $k_{3} \in f(t_{\text{co}}, t_{\text{k}}, \Delta t)$; $t_{\text{co}}$ - concrete age at the start of cooling concrete masonry; $t_{\text{k}}$ - concrete age by the time of cooling concrete masonry to the temperature of joint grouting of construction joints; $\Delta t$ - time of cooling [16].

Foreign and Russian scientists have proposed a number of criteria in order to assess the formation of thermal cracking. Therefore, according to the document [18], to prevent thermal cracking, maximum tensile stress values $\sigma$ should not exceed the permissible value:

$$\sigma(\tau) \leq \frac{\varepsilon'}{E(\tau)},$$

where: $\sigma$ - thermal stress at time $\tau$; $E(\tau)$ - modulus of elasticity of concrete without creep (obtained from conventional tensile tests); $K$ - safety factor.

When placing large concrete, the value of $\varepsilon_{\text{ap}}'$ depends on many factors such as concrete composition, age of concrete, uniformity, stress state, loading time, loading speed, etc [17]. In a first approximation, we can take $\varepsilon' = (7-10) \times 10^{-4}$.

Criteria for evaluating the ability to prevent thermal cracking are built into the SP41.13330.2012 standard (proposed by P.I. Vasilieva) [18].

$$\sigma(\tau) \leq \gamma_{b3} \gamma_{b6} E_{\text{lim}} \phi(\tau) E(\tau),$$

where: $\gamma_{b3}$ - coefficient of working conditions for massive structures; $\gamma_{b6}$ - coefficient of the working condition of a structure takes into account the influence of tensile strength of deformation gradient on a cross-section; $E_{\text{lim}}$ - ultimate tensile strength of concrete, taken according to [18]; $\phi(\tau)$ - coefficient taking into account the dependence of $E_{\text{lim}}$ on the age of concrete, determined according to [18]; $E(\tau)$ - modulus of elasticity of concrete at the age of $\tau$.

In fact, in foreign countries, the design of mass concrete structures also performed the same criteria in order to assess the occurrence of thermal cracking. Therefore, according to the document [18], to approximate the possibility of cracks in the concrete structure then formula (6) similar to formula (5) was used. However, formula (6) is not written using the ultimate tensile strength of concrete but using the temperature difference $\Delta T$. To prevent thermal cracking, maximum tensile stress values $\sigma$ should not exceed the permissible value:

$$\sigma(\tau) = RK \frac{E(\tau) \alpha \Delta T}{K} \leq \frac{R}{K},$$

(6)
where: R - constraint coefficient; \( K_p \) - relaxation coefficient; \( E(\tau) \) - modulus of elasticity of concrete at time \( \tau \); \( \alpha \) - coefficient of linear expansion of concrete \( (\alpha \approx 1.10^{-5}) \); \( \Delta T \) - temperature difference in concrete mass; \( R_t \) - the allowable tensile stress of concrete; \( K \) - safety factor.

In Japan, to assess the occurrence of cracks in a mass concrete structure, the crack index is used and is defined as follows [19, 20]:

\[
I_{ct} = \frac{f_{sp}(\tau)}{f_t(\tau)},
\]

(7)

where: \( I_{ct} \) - thermal crack index; \( f_t(\tau) \) - the maximum thermal stress at day \( \tau \); and \( f_{sp}(\tau) \) - the tensile strength of concrete at day \( \tau \).

The cracking tendency is estimated by the thermal cracking index and is presented in Table 2.

| Crack control Criteria                  | Thermal Crack Index \((I_{cr})\) |
|-----------------------------------------|----------------------------------|
| The prevention of cracks                | \( I_{cr} \geq 1.5 \)           |
| Possibility of limited cracks           | \( 1.2 \leq I_{cr} \leq 1.5 \)   |
| Limiting the occurrence of dangerous cracks | \( 0.7 \leq I_{cr} \leq 1.2 \)   |

The temperature difference requirements are formed based on the practice for mass concrete construction. It does not take into account special construction cases and the influence of other factors. In order to effectively use the criteria, it is necessary to know the maximum temperature, temperature difference and maximum tensile stress in concrete blocks during construction. All such information can be obtained by numerical methods for calculating the temperature regime and the thermally stressed state in mass concrete during construction [21]. Midas civil is one of the modern software based on the finite element method used to determine the temperature field, thermal stress state taking into account the influencing factors [21].

2.2. Object of study

In this paper, we assess the possibility of cracking (according to the temperature difference and thermal stress state) in a mass concrete during construction. We considered a concrete column with a plan size of \( 10.0 \times 15.0 \) m and a final height of \( 30.0 \) m, located on the base massif with dimensions of \( 30.0 \times 30.0 \times 10.0 \) m. The ambient temperature is assumed to be constant and equal to \( 26.5 \) °C (corresponds to the conditions of construction in the summer of North Vietnam). The temperature of the concrete mix to be laid is assumed to be \( 25 \) °C.

Figure 1. The design scheme of the concrete massif and the FEM grid

The construction schedule (vertical column erection speed) is assumed to be \( V = 0.3 \) m/day (often used in the construction of concrete gravity dams). The construction schedule is carried out in the
following calculation: the height of concrete layers is assumed to be 3 m and the break time between pouring periods is 10 days. The schematic model of the research and modeling by the finite element method is shown in Figure 1 (half of the model is used in the FEA). The thermophysical characteristics of the concrete and the foundation were used in the numerical analysis and are shown in Table 3.

### Table 3. The estimated physical characteristics of the materials

| Characteristics, units                                      | Concrete Values | Foundation Values |
|-------------------------------------------------------------|-----------------|-------------------|
| The coefficient of thermal conductivity, W/(m.°C)            | 2.60            | 2.00              |
| Specific heat, kJ/(kg.°C)                                  | 0.95            | 0.84              |
| The density of the material, kg/m³                          | 2400            | 2650              |
| The coefficient of convective heat transfer, W/m².°C        | 12.00           | 14.00             |
| Modulus of elasticity, N/m²                                 | 2.7×10¹⁰        | 1.8×10¹⁰          |
| The coefficient of linear expansion, 1/°C                    | 1×10⁻⁶          | 1×10⁻⁵            |
| Poisson’s ratio                                             | 0.18            | 0.20              |
| Cement content, kg/m³                                       | 350             | -                 |
| Maximum heat release during hydration of cement, kJ/kg      | 300             | -                 |

### 2.3. Heat transfer theory in concrete structures

The numerical method is based on solving the differential equation of heat transfer theory [2-4]:

\[
\frac{\partial}{\partial t}(k_x \frac{\partial t}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial t}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial t}{\partial z}) + q_v = \rho c \frac{\partial t}{\partial \tau},
\]

where: \(t\) - temperature function depends on space and time, °C; \(k_x, k_y, k_z\) - thermal diffusivity of the material in the direction of the coordinate axes ox, oy, oz \((k_x = k_y = k_z = \lambda/c_\rho)\), m²/s; \(q_v\) - the amount of heat generated by internal sources at a given point in time (for example, during the process of cement hydration, W/m³); \(c\) - specific heat, kJ/kg.°C; \(\rho\) - concrete density, kg/m³; \(\tau\) - concrete hardening time, day.

When solving equation (8), it is necessary to know the initial and boundary conditions [5]. The initial temperature used is as follows: the temperature on the nodes of the foundation is assigned a temperature of 25 °C and the temperature of the concrete block is equal to the initial temperature of the concrete mixture of 25 °C.

The following boundary conditions were set on the surfaces of the computational domain. On the surfaces of the concrete block and the foundation at the contact with air, the third boundary condition is used (boundary conditions of heat exchange with the environment).

\[
\lambda \frac{\partial t}{\partial n} = h(t_s - t_a),
\]

where: \(n\) - external normal; \(h\) – the heat transfer coefficient, W/(m².°C); \(t_s\) - the concrete surface temperature, °C; \(t_a\) - the ambient temperature, °C.

On the vertical surface of the base, boundary conditions with no heat transfer were modeled (equivalent to the absolute surface insulation). In special cases, the third boundary condition is used as a formula (9).

To solve the problem of the temperature regime in mass concrete blocks, finite element method was applied with the help of Midas software.

### 3. Results and Discussion

Predicting the temperature regime in concrete blocks can be made by predictive models, which are developed by using the methodology of factor analysis [8]. Based on the mathematical model [8], with
concrete block size, cement content, maximum heat release during hydration of cement and construction conditions, the maximum temperature in concrete blocks reaches a value of ~ 64.4 °C. When the surface temperature of concrete is approximately 27 °C, the temperature difference between the center and the surface of the concrete block is approximately 38 °C. Clearly, this shows that the value of temperature difference is much larger than the permissible value (20-27) °C according to the Russian standard SP357.1325800.2017 [12] and 20 °C according to the Vietnam standard TCVN 305.2004 «Mass Concrete - code of practice of construction and acceptance». Therefore, the results of the prediction of the temperature regime obtained show the high probability that cracking in concrete blocks.

Using the Midas software program, the temperature field and thermal stress state of the concrete column during the construction period was calculated.

Some results of calculating the temperature regime of concrete columns are shown in Figures 2-3. Figure 2 shows the temperature distribution in concrete structures during construction at different times and elevations. The maximum temperature value in the center of the concrete block reaches (62-65) °C in accordance with the value predicted by the previous mathematical model.

**Figure 2.** The temperature regime of the concrete column during construction: (a) - at 1200 hours after placing the concrete (elevation +15.0 m); (b) - at 2400 hours after placing the concrete (elevation +30.0 m)

**Figure 3.** The temperature regime in concrete blocks during the construction period: (a) - Graphs of temperature changes of the nodes (1÷10) in the mass concrete over time; (b) - Graphs of temperature change along with the height of concrete blocks at different times

Figure 3 shows the temperature change at 10 nodes in the center of concrete layers over time (see Figure 1a). The maximum temperature of all nodes occurs approximately 100 hours after the concrete
layers had been placed and reach approximately 64 °C. However, a slight discrepancy was noticed in node 1 located on the surface of the base. Under the influence of base to maximum temperature at node 1 is reduced and is equal to 62 °C. It is obvious that the cooling of the concrete layer near the foundation is faster than other concrete layers.

Figure 3b shows the temperature change along the height of the concrete block at different times after the start of construction. The temperature on the surface of the mass concrete being built, which is in accordance with the obtained results varies in the range of ~ (27-33) °C. Therefore, the temperature difference between the center and the surface of the concrete layers along the concrete column reaches (31-35) °C, which significantly exceeds the permissible 20 °C. In Figure 3a, we can see that the cooling time in concrete blocks is relatively long, up to approximately 240 hours. In addition, it should be borne in mind that the elasticity and strength of concrete changes over time. It can be concluded that the high risk of cracking formation is reliable.

To answer the question of the possibility of cracking in concrete blocks during construction, it is necessary to consider the thermal stress state in concrete blocks by the Midas software program. The graph of the maximum thermal stress changes of 20 nodes (see Figure 1) over time is shown in Figure 4. In addition, Figure 4 also displays the allowed change of tensile stress of concrete. It can be seen that tensile stresses appear at 10 nodes of the concrete center after (250-500) hours after placing concrete. However, their stress value is always smaller than the allowable stress. So, the maximum tensile stress of node 1 reaches 1.6 MPa at 1920 hours after placing the concrete (see Figure 4a). It can be seen that thermal cracks in the central area of concrete blocks cannot occur.

Another picture of thermal stresses is observed at nodes along the surface of the concrete massif and is shown in Figure 4b. All the nodes along the height of the concrete column (nodes 11-20), the tensile stress appears immediately after placing the concrete and reaches a maximum value of 4.6 MPa at the time of 100 hours. The results showed that the values of the tensile stress exceed the allowable tensile stress value of 2.8 MPa at the same time. Over time, the tensile stress value that exceeds the allowable value is maintained for a period of (200-240) hours. This indicates a high probability of the occurrence of cracks on the surface in mass concrete.

In the actual design, construction and operation of gravity concrete dams, the allowable temperature difference depends on the condition «pinching» and their location in the dam body [6, 7]:

• For «free» areas of concrete blocks (away from the base), the temperature difference is defined as the difference in temperature between the center and its surface.

• For the «pinching» area, which is the area near the base (the height of this area is half the length of the concrete block body l_b). The main cause of thermal cracking in this area is the difference in the
average temperature of the exothermic process and the average temperature of the concrete block during the operation period.

So it is very important to consider changes in temperature and thermal stress on the two sections corresponding to the two areas. For section 1-1 is a «pinching» area and section 2-2 is a «free» area (the position of the sections is shown in Figure 1). For section 1-1 («pinching» area), the temperature and maximum thermal stress changes at times $\tau = 120$, 240 and 360 after placing concrete are shown in Figure 5.

![Figure 5](image_url)

**Figure 5.** The change in temperature at different times (a) and maximum thermal stresses (b) in section 1-1 of a concrete column.

It can be seen that the temperature in section 1-1 reaches a maximum of 62 °C in the center of the block at time $\tau = 120$ hours after placing concrete and gradually decreases over time and equals air temperature. The temperature difference between the center and the surface of the concrete block is 29 °C at time $\tau = 120$ hours after placing concrete.

The maximum thermal tensile stresses occur on the surface of the block and at time $\tau = 120$ hours after laying the first concrete layer reaches of 4.53 MPa (while the allowable value is 2.95 MPa at this time).

The same results for section 2-2 in the “free” zone are presented in Figure 6.

![Figure 6](image_url)

**Figure 6.** The change in temperature at different times (a) and maximum thermal stresses (b) in section 2-2 of a concrete column.

It can be noted that the maximum temperature in the center of this section reaches 64.05 °C at a time of 1068 hours. The surface temperature of the concrete block at the appropriate time is 35 °C.
Thus, the temperature difference between the center and the surface of the concrete block at this point in time is 29.05 °C. (see Figure 6a). The temperature difference exceeds the permissible value and the risk of cracking is great. Over time, the temperature at the center and surface of the concrete blocks decreases.

Figure 6b shows the maximum thermal stress changes in section 2-2 of concrete blocks. It can be seen, that tensile stress occurs at the surface of concrete blocks. As the temperature difference decreases during cooling, then the thermal stress also decreases. It is noticeable that the thermal stress on the cross-section 2-2 is smaller than the thermal stress on the 1-1 cross-section. The tensile stress on the surface of the concrete block in section 2-2 reaches 2.90 MPa at a time of 1068 hours, which is approximately equal to the allowable value of 2.95 MPa (corresponds to the tensile stress of concrete at the same time). These results indicate that the risk of cracking on the concrete surface is negligible.

From the results of the study of the temperature field, the state of thermal stress by numerical methods obtained the following notes: under the assumed conditions, the thermal crack on the surface of concrete blocks will certainly appear. In order to prevent the formation of cracks in mass concrete, it is necessary to devise appropriate measures during construction [22].

4. Conclusions
Based on the results obtained, the following conclusion can be made:

1. Currently, there are many criteria to allow a detailed assessment of thermal cracks commonly occurs during mass concrete construction. At the same time, it can be noted that there is a large number of factors affecting cracking formation. So, this may not be true in all cases when the approximate method is used in order to assess the formation of thermal cracks.

2. There is much software based on finite element methods was used to simulate the number. In particular, the Midas software program allows the determination of temperature field and thermal stress in mass concrete structures during construction, taking into account most of the current factors.

3. Based on the results of calculating the thermal regime and thermal stress state in the concrete during the construction period, it is possible to assess the possibility of cracking and propose measures to prevent them.

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