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Composition calculation and cracking estimation of concrete at early ages
Расчет состава и оценка трещинообразования бетона в раннем возрасте

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Ключевые слова: трещинообразование; фундамент моста; растягивающее напряжение; максимальная температура; прочность на растяжение; температурное режим; термонапряженное состояние

Abstract. Recently, variety of large-scale constructions from monolithic concrete structures have been built in different regions of Vietnam. The application fields of these structures are extensive including the marine construction, underground structures, the high-rise building erection and others. However, structures damage and cracking, caused by temperature stresses, become more popular and strong impact on operation reliability and durability. In this study, the American standard ACI 211.1-09 was used to determine the composition of heavyweight concrete for bridge foundation construction with sized 8 x 6 x 2.5 m. Assessment of the crack formation possibility in the concrete at an early age was made by analysis of temperature regime and the thermal-stress. The conducted studies' result provided the possibility of obtaining heavyweight concrete from Vietnam local raw materials with the workability of concrete mixture on 95 mm standard cone, compressive strength of 36.3 MPa heavyweight concrete at the age of 28 days of normal hardening and an average water resistance of 0.32 MPa samples. By applying the computer program MIDAS CIVIL, the maximum temperature in the concrete foundation center which was determined after 72 hours from the commencement of mixing of raw materials with water, equal to T_{max} = 73.04 °C. At the same time, the structure temperature difference between the center (node 97) and surface (nodes 141 and 98) was 31.7 °C. In addition, at nodes 141 and 98 (in the external nodes) of the concrete foundation at 30 hours of concrete hardening, the tensile stress is greater than the tensile strength of the concrete leading to crack formation on concrete surface. Therefore, in order to prevent cracking, it is necessary to ensure proper care of the foundation surface during the concrete hardening. In the center of the concrete foundation (node 97), the tensile stress is higher than the allowable tensile strength at 590 hours of hardening concrete. Meanwhile, its strength is also quite high, the risk of concrete foundation center cracking caused by the heat release during cement hydration will not be serious great.

Аннотация. В разных городских районах Вьетнама построено много крупномасштабных сооружений из монолитных бетонных конструкций. Однако, повреждение и растрескивание конструкций, вызванное температурными напряжениями, становятся все более распространенными и сильно сказываются на их надежности и долговечности эксплуатации. В работе для определения состава тяжёлого бетона для строительства фундамента моста был использован американский стандарт ACI 211.1-02. Оценка возможности трещинообразования в бетонном фундаменте в раннем возрасте была выполнена путём анализа температурного режима и возникающего в нём термонапряжения. В результате проведённых исследований была доказана возможность получения тяжёлого бетона из местных сырьевых материалов Вьетнама, с удобоукладываемостью бетонной смеси по осадке стандартного конуса 95 мм, обладающего прочностью на сжатие 36,3 МПа в возрасте 28 суток нормального твердения и средней водонепроницаемостью серии образцов 0,32 МПа для строительства моста фундамента размером 8 x 6 x 2,5 м. С помощью компьютерной программы MIDAS CIVIL была определена максимальная температура в центре бетонного фундамента по истечении 72 часов с момента затворения водой, равная T_{max} = 73,04 °C. В это же время, перепад температур между центром фундамента (узел № 97) и его внешними

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поверхностями (узлы № 141 и 98) составил 31,7 °С. Кроме того, было установлено, что в наружных узлах бетонного фундамента № 141 и 98 к моменту продолжительности гидратации цемента 30 часов величина растягивающего напряжения превысит допустимое растягивающее напряжение, что приведёт к образованию трещин на его поверхности. Поэтому, необходимо обеспечить надлежащий уход за поверхностью фундамента во время твердения бетона. В центре бетонного фундамента (узел № 97) величина растягивающего напряжения превысит допустимое значение к 590 часам твердения бетона, но поскольку к этому моменту его прочность станет достаточно высокой, то опасность появления трещин в центре фундамента из-за возникновения температурных напряжений, вызванных тепловыделением при гидратации цемента, будет не слишком высокой.

1. Introduction

Concrete and reinforced concrete structures are almost used in construction buildings and structures because of their advantages and the constantly expanding of design scope. Concrete is durable, resistant corrosion environment and well - protected the reinforcement. The reinforced concrete structure operation cost is usually lower than in steel structure with the same purpose.

Depending on the production method, the concrete structures are distinguished to monolithic, prefabricated, precast-monolithic concrete, the reinforced concrete structures are contained non-stressed and tensioned reinforcement. The monolithic structures are erected directly at the construction site where equipment are installed and the concrete is mixed in the formwork.

In modern construction industry, monolithic reinforced concrete structure erection method is increasingly used through the integrated systems. It is ensure that the multi-storey facilities are deployed at shortest possible time without high capital cost requirement for the prefabricated structure plants ‘construction and operation.

The high-rise building construction, large-span bridges, hydraulic projects and other structures, made of monolithic reinforced concrete structures, are widespread nowadays in Vietnam [1].

However, in monolithic reinforced concrete buildings and constructions, the solution component of concrete hardening can be shrinked leading to the shrinkage cracks in a contact zone with more rigid filler. The crack size is close to the largest aggregate grain size [2–4]. Additionally, because of the large size of hardening structures, the heat, released during the hydration of the binder at an early age, is difficult to redistribute from the inner layers to the outside, resulting in a large temperature difference between the structure's central zone and the outer layers [5–8]. Thus, the significant heat generation during the cement hydration can lead to excessive tensile stresses due to the emergence of extreme temperature gradients in the massive concrete structures hardening. It is often result of concrete structure cracking both at the center and on the surface, why reduces the building and structure's strength, reliability, operability and durability [9–14].

Therefore, monitoring Athe temperature regime and thermal-stress are extremely important for assessing the probability of concrete structure cracks at an early age of hardening concrete [15–17]. Practically, the controlling organization is often such difficulty, especially in large dimensions such as the underground parts of skyscrapers, foundations in the long span bridges and others (Figure 1) [18, 19].

Figure 1. Construction of the foundation's bridge in Vietnam

In this paper, the calculation composition of concrete mixture is applied in accordance with the standard ACI 211.1-09, the American standards requirements and the fresh concrete, concrete properties.

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The maximum temperature, temperature distribution and thermal-stress state by time to estimate of cracking risk are also discussed.

2. Materials and Methods

– Portland cement (PC): type CEM I 42.5 N, manufactured at "Tam Diep" factory (Vietnam), specific weight of 3.12 g/cm^3. The maximum heat of hydration of cement 209 J/g at 28 days. The results of physical and mechanical properties and cement's mineralogical composition are presented in Table 1 and 2 respectively.

Table 1. Mineralogical Composition of cement "Tam Diep"

Mineral composition (%)				
C_3S	C_2S	C_3A	C_4AF	Other
55.7	22.9	4.5	12.8	4.1

Table 2. Physical and mechanical properties of Portland cement CEM I 42.5N "Tam Diep"

Specific weight (g/cm^3)	Soundness Le Chatelier (mm)	Surface area (cm^2/g)	Time of setting (min)		Compressive strength (MPa)			Standard consistency (%)
			Initial	Final	3 days	7 days	28 days	
3.12	2	3630	135	240	37.91	42.41	54.23	28.2

– Quartz sand (QS): originally from the golden sand of "Lo River" (Vietnam), M_k=2.85, specific weight of 2.67 g/cm^3. The volume of compacted state is 1540 kg/m^3.

– Crushed limestone (CL): produced from the quarry "Kien Khe" (Vietnam) with the size of 5–20 mm, specific weight of 2.66 g/cm^3. The volume of the compacted state is 1650 kg/m^3.

– Ordinary clean tap water (W) was used for both mixing concrete and curing of test pattern.

2.1. Methods

– Method of calculation preliminary compositions of concrete mixture is applied in accordance with ACI 211.1-09 (American).

– The concrete mixture workability is determined by the standard slump cone with dimensions of 100 x 200 x 300 mm in accordance with ASTM C143 / C143M-10a: 2012.

– In this study, the pattern's size and shape, used for compressive strength, was cylinders with size of 150 × 300 mm in accordance with the requirements of ASTM C39 / C39M. These samples are demolded after 24 hours casting, then placed in a 20 ±5 ^{0}C water curing tank until the experiments. The concrete compressive strength are measured at the ages of 3, 7, 14 and 28 days.

– The cement hydration heat is determined by standard ASTM C186-17.

– Using the computer program MIDAS CIVIL, the maximum temperature and thermal-stress state in the concrete foundation were calculated. Evaluation of crack formation possibility in concrete at an early age was based on the magnitude of the allowable tensile stresses, which arising in it.

2.2. Experimental Plans

In this experimental program design, the determination of the concrete mix composition is according to standard ACI 211.1-02 and the calculation of the maximum temperature in the concrete foundation at an early age is using the computer program MIDAS CIVIL, which is basis for assessing its propensity to crack in the construction, as can be seen in Figure 2. The MIDAS CIVIL computer program, based on the finite-element method, will analyze the thermal behavior of the bridge foundation.

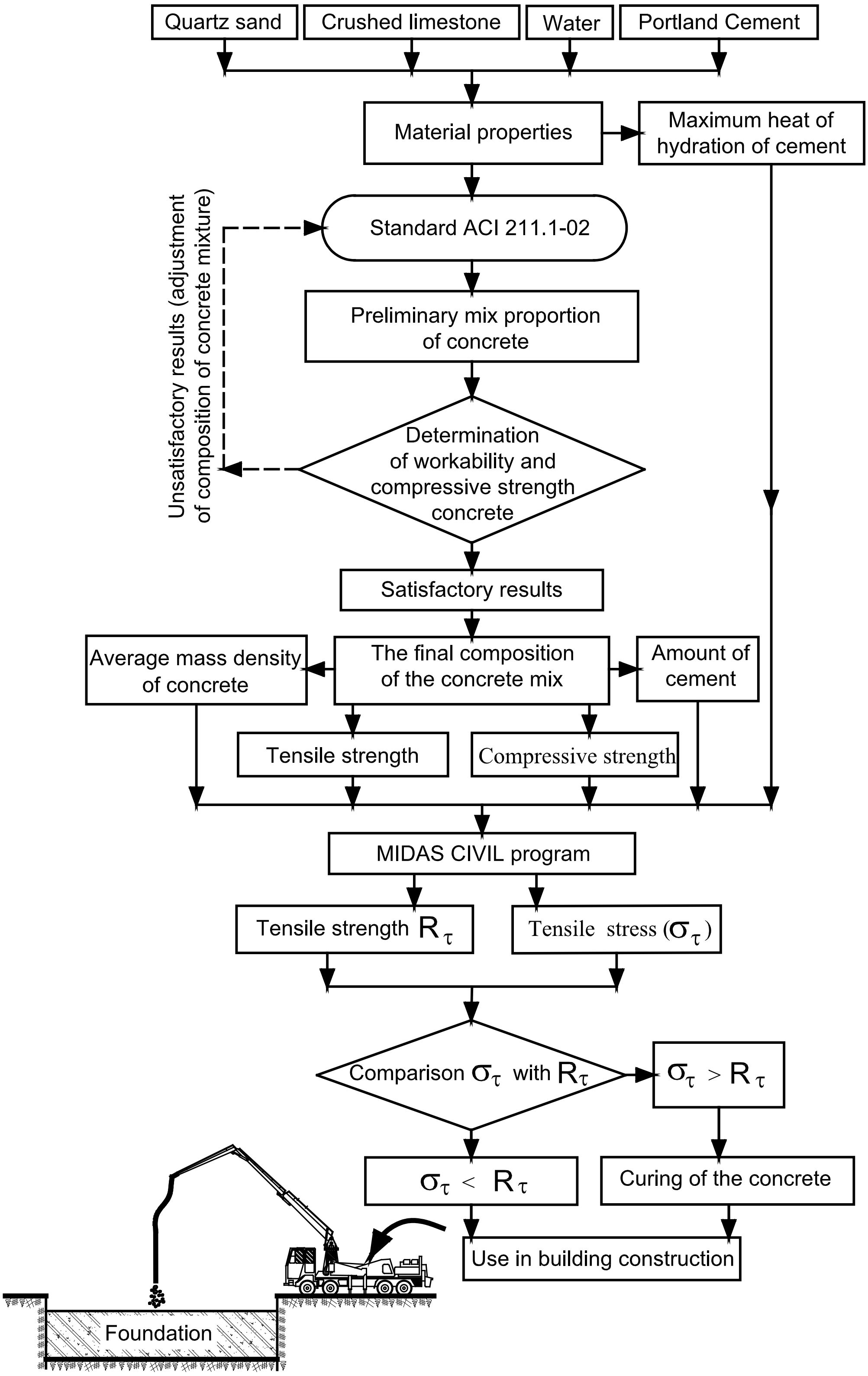

Figure 2. Experimental program

3. Results and discussion

3.1. Calculation of the concrete mixture composition

It is necessary to determine the heavyweight concrete mixture composition of foundation's bridge construction which size is 8 x 6 x 2.5 m (Figure 3) in the central part of Vietnam in the summer.

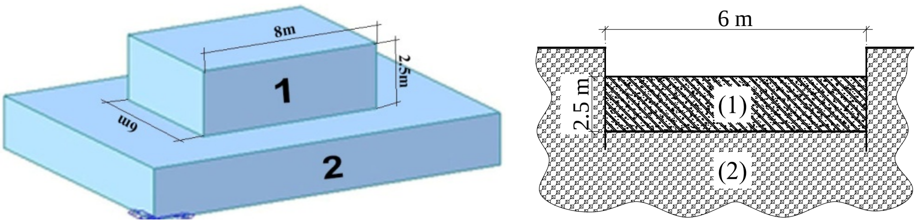

Figure 3. Sketch and cross-section of the concrete foundation of the bridge
1 – foundation's bridge with a size of 8 x 6 x 2.5 m, 2 – ground under the foundation.

Development of high performance concrete must possess:

- The fresh concrete effect on workability is determined by the standard slump cone 75–100 mm.
- The compressive strength at the age of 28 days is higher than 35 MPa.
- The relative volume of entrapped air is not more than 1%.

The standard ACI 211.1-02, which is used to determine the concrete mixture composition, requires the standard slump cone of 75–100 mm and allows to obtain 35 MPa compressive strength concrete at the age of 28 days with ordinary hardening. The fresh concrete properties as well as the heavyweight concrete properties are represented in Table 3 and 4.

Table 3. Mixture composition and fresh concrete properties

Concrete mixture compositions (kg/m^3)				Fresh concretes properties		
PC	*QS*	*CL*	*W*	$\frac{W}{PC}$ (*)	Average density (kg/m^3)	Slump (mm)
436	696	1023	205	0.47	2360	95

Note: (*) $\frac{W}{PC}$ ratio by weight.

Table 4. Properties of heavyweight concrete

Average density of concrete (kg/m^3)	Average compressive strength at different ages (MPa)				Average tensile strength at the age of 28 days (MPa)	Water resistance of concrete (MPa)
	3 days	7 days	14 days	28 days		
2285	19.45	24.97	31.66	36.33	3.11	0.32

It can be seen from these above tables that the calculation of the concrete mixture composition and the specified workability allow to obtain the required concrete strength. In addition, the test results showed that the concrete strength is obtained quickly. In details, the compressive strength at the age of 3 days is 54 % in comparison to 28 days period (in Table 4).

Furthermore, the MIDAS CIVIL program can calculate the maximum temperature at the center of the concrete foundation and its thermal-stress state.

3.2. Fundamentals of the heat transfer theory and the relationship between the exertion and temperature in material and concrete

Significant thermal induced stresses are developed as a result of the heat field of cementitious material hydration in heavyweight concrete. The temperature distribution through the foundation's bridge and its time evolution depend on the following elements:

- Concrete properties.
- Cement amount.
- Climatic factors.
- Construction procedure.
- Thickness of lifts.
- Initial temperature of concrete mixture, and

– Interval between their successive placements.

These thermally induced stresses can be significant enough to provoke concrete structure cracks. The recent development in sophisticated software (based on advanced numerical methods) and the continually increasing computer power concede the complex analyses for such temperature stress problems.

a) Finite element method of temperature field:

According to the studies [20, 21], at any point in the calculation field R, the unstable temperature field T (x, y, z, τ) must satisfy the following continuous thermal conduction equation (1):

$$\frac{\partial}{\partial x}\left(k_x(\mathrm{T})\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(\mathrm{T})\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z(\mathrm{T})\frac{\partial T}{\partial z}\right)+G=\rho c\frac{\partial T}{\partial \tau}, \quad (1)$$

where T – the material temperature (°C);

k_x(T), k_y(T), k_z(T) – the thermal conductivities (W/m°C) dependent on the temperature in the directions x, y and z, respectively;

G **–** the rate of internal heat generation (internal energy) per unit volume (W/m^3);

c **–** the specific heat (J/kg.°C);

ρ – the density concrete (kg/m^3);

τ – time (day).

To solve equation (1), it is necessary to know two main types of boundary conditions are Drichlet and Cauchy boundary [22], which can be written respectively as:

$$T=T_p, \quad (2)$$

$$k_x\frac{\partial T}{\partial x}l_x+k_y\frac{\partial T}{\partial y}l_y+k_z\frac{\partial T}{\partial z}l_z+q+h(T_s-T_f)=0, \quad (3)$$

where T_p – the values of the nodal temperatures on the boundaries (°C);

q – heat from surface (kcal/m^3);

h – the film coefficient;

T_s – temperatures at the boundary nodal points (°C);

T_f – the ambient temperature (°C);

l_x, l_y and l_z – the direction cosines of the outward normal to the surface under consideration on the x, y and z axes respectively.

Determination of temperature conditions for massive concrete structures is quite complex due to not only the structure spatial shape but also the internal and external factors influence. Therefore, approximate methods are used in massive monolithic reinforced concrete structure design. In recent years, the most complete factor consideration for temperature problem solution possibly applies numerical methods, particularly, the finite element method through MIDAS CIVIL, ANSYS, ADINA, ABAQUS programs and others [23–25].

b) Determination of the relationship between thermal-stresses and temperature in concrete:

According to the results of studies [26–28], the ratio between the thermal-stress and temperature in concrete block is determined by the formula (4):

$$\sigma = RE\alpha\Delta T, \quad (4)$$

where σ – thermal-stresses (N/mm^2);

R – restraint (0 < R< 1);

ΔT – temperature drop (°C);

α – coefficient of thermal expansion (1/°C);

E – concrete elasticity modulus (N/mm^2).

c) Evaluation of concrete cracking due to heat generation during cement hydration at an early age:

In study [29], cracking happens in concrete block when the tensile stress becomes higher than the tensile strength of concrete. Then, if $R_t(\tau_e) < \sigma_t(\tau_e)$, concrete thermal cracks will appear due to heat generation during cement hydration.

where $R_t(\tau_e)$- the tensile strength of concrete at time τ_e (MPa);

$\sigma_t(\tau_e)$ – the tensile stress of concrete at time τ_e (MPa).

3.3. Definitions of temperature regime and thermal-stress state of the concrete foundation at early ages

The purpose of this article is to use the MIDAS CIVIL computer program to determine the temperature regime and the thermally stressed state in the foundation of heavyweight concrete and its composition (shown in Table 2) to evaluate the cracking probabilities at the center and concrete structure surface.

The study object is concrete bridge foundation, sized 8 x 6 x 2.5 m (Figure 3). This foundation block of monolithic concrete was laid on bridge foundation, which has been built in June 2013 in the central part of Vietnam.

The ambient temperature significantly effects on the maximum temperature at the center of concrete block during the hardening process. It is determined by the average temperature monthly seasonally and/or annually. According to the study [30], the summer temperature in Central Vietnam change according to the equation (5):

$$t_{air} = 30 + 5\sin(\frac{2\pi\tau}{24}), \tag{5}$$

where t_{air} – daily average air temperature (°C);

τ – time (hours).

The initial temperature of laying concrete mixtures, which depends on the fresh concrete temperature, is 20 °C in this study

According to [31], the concrete heat release at the instant time τ was determined by the formula (6):

$$q = \frac{1}{24} c\rho t_{\max} e^{\frac{-\alpha\tau}{24}}, \qquad t(\tau) = t_{\max}(1 - e^{-\alpha\tau}), \qquad t_{\max} = \frac{qPC}{c\rho}, \tag{6}$$

where q – total heat (W/m^3);

c – specific heat coefficient (J/kg.°C);

PC – cement amount (kg);

ρ – concrete mass density (kg/m^3);

$t_{(\tau)}$ – concrete temperature in adiabatic conditions at the age of τ days (^{0}C);

t_{max} – temperature rise in exothermic process under adiabatic conditions (^{0}C);

α – constant, depending on the concrete mixture casting temperature, according to the study [32] α = 0.833.

Table 5 presents the heavyweight concrete and ground under bridge foundation properties, which are considered as inputs for analyzing the temperature regime and the thermally stressed state in a concrete foundation during the fresh concrete hardening of at normal condition.

Table 5. Material properties in thermal behavior analysis

Physical characteristics	Heavyweight concrete	Ground
Coefficient of thermal conductivity (W/(m.°C)	2.31	3.64
Coefficient of specific heat (J/kg.°C)	0.96	0.84
Mass density (kg/m^3)	2285	2700
Coefficient of heat transfer from the exposed surface of concrete-air (W/m^2.°C)	13.88	13.88
Elastic modulus (N/m^2)	2.56.10^{10}	2.0.10^{10}
Coefficient of thermal expansion (1/°C) [31, 32]	1.0.10^{-5}	1.0.10^{-5}
Poisson's ratio [31, 32]	0.20	0.20
Maximum heat of hydration of cement at 28 days (J/g)	209	-
Amount of cement (kg/m^3)	436	-
Placement temperature (°C)	20	-
Average compressive strength at 28 days (MPa)	36.33	-
Average tensile strength at 28 days (MPa)	3.11	-

The results of calculating temperature field in bridge foundation during the concrete mixture development are shown in Figure 4.

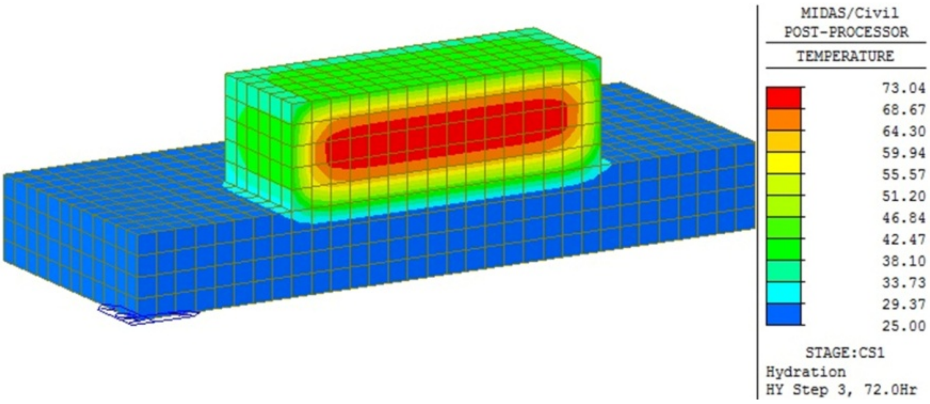

Figure 4. The temperature distribution process in a concrete foundation after 72 hours of hardening concrete

It can be seen from Figure 5 that the maximum temperature at the center of the concrete foundation after 72 hours of the hardening process is T_{max} = 73.04 °C. Since then, this temperature begins to decrease. The thermal-stress state in concrete foundation at this time is shown in Figure 5.

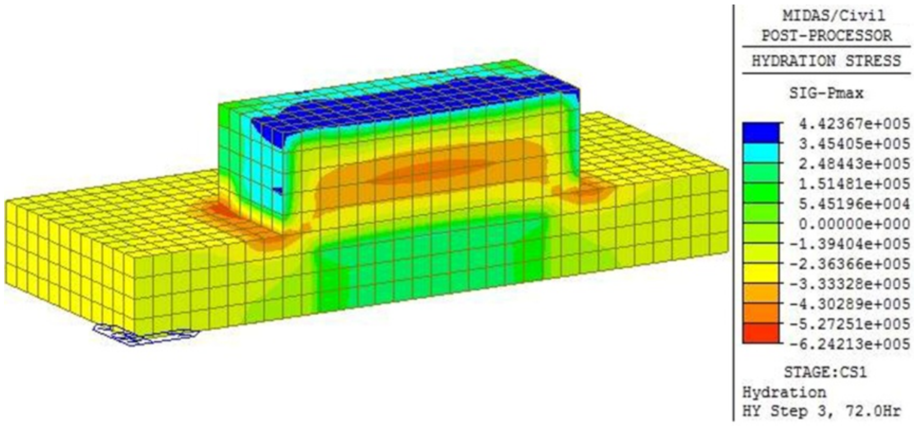

Figure 5. Thermal-stress state in concrete foundation after 72 hours of hardening concrete

The temperature difference between the concrete block center and surface exceeds the allowable limitation leading to excessive stresses due to the appearance of extreme temperature gradients during the concrete hardening. Its result will often appear crack in structure body or surface. Therefore, the temperature regime and the thermally stressed state analysis of concrete structure at three hazardous locations, including the center – node 97, the outer upper part surface - node 141 and the outer right part – node 98, are shown in Figure 6 and 7.

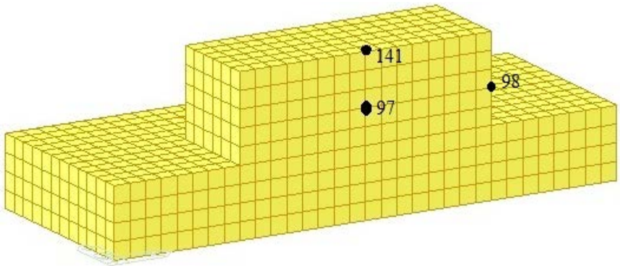

Figure 6. Analysis of the temperature regime and the thermally stressed state in three hazardous locations in this concrete foundation's bridge

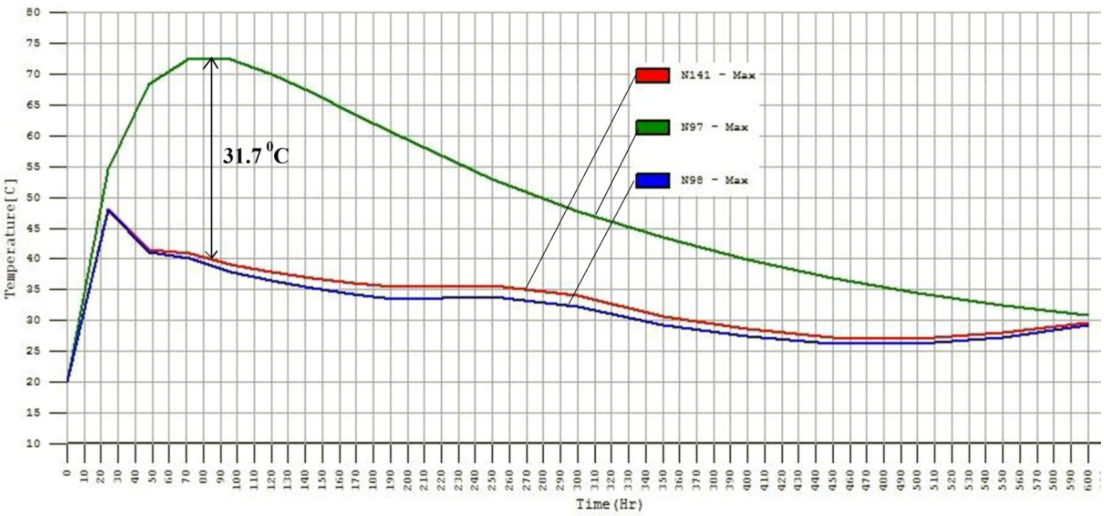

Figure 7. Temperature distribution and evolution at the center (node 97) and on the surface (nodes 141 and 98)

Following the Figure 7, the temperature difference between the center (node 97) and the surfaces (nodes 141 and 98) of the concrete foundation is 31.7 °C after 72 hour of pour concrete mixture. Then, this temperature drops gradually to 0 °C.

The thermal-stress state arising at three dangerous places of the concrete foundation during its hardening are shown in Figure 8–10.

Figure 8. The change in thermal-stress at node 97

<u>Note</u>: A – cracking at node 97 when the tensile stress becomes higher than the tensile strength of the concrete.

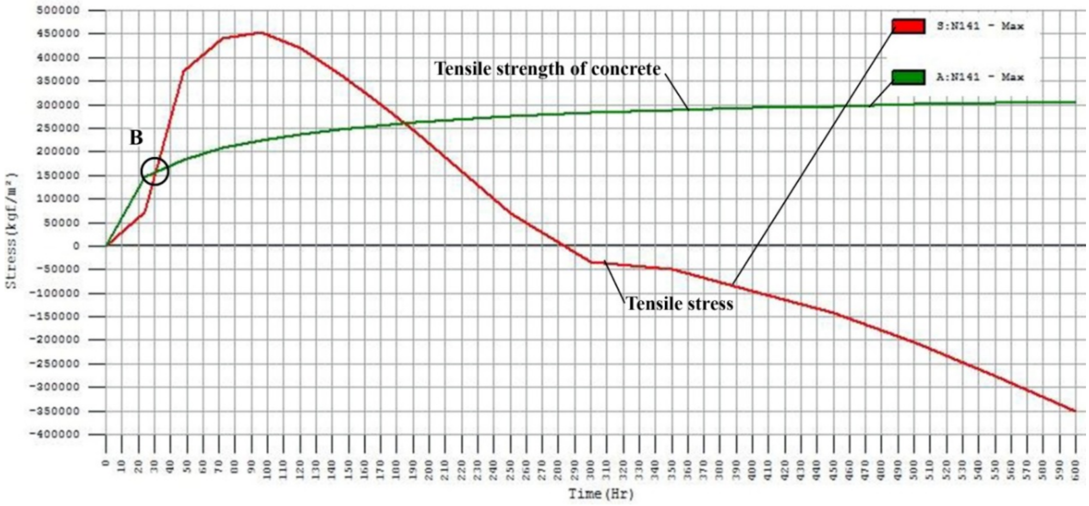

Figure 9. The change in thermal-stress at node 141

Note: B – cracking at node 141 when the tensile stress becomes higher than the tensile strength of the concrete.

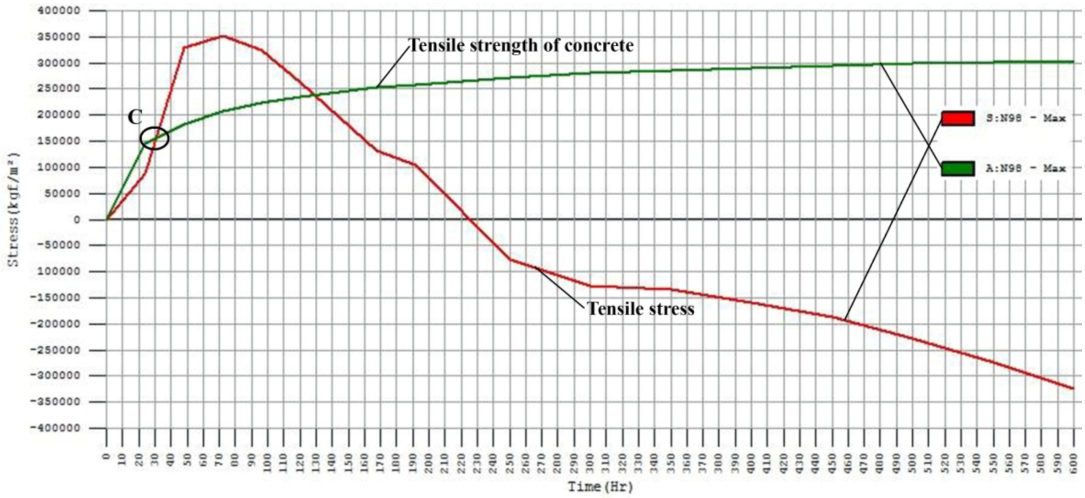

Figure 10. The change in thermal-stress at node 98

Note: C – cracking at node 98 when the tensile stress becomes higher than the tensile strength of the concrete.

At node 97 – the concrete foundation center, during 96 hardening hour, the temperature rises and the concrete volume also tends to grow up, leading to compressive stress increase to counteract an expansion. After 96 hardening hour, this temperature starts to decrease, resulting of 0 MPa tensile stress at 370 hours. Besides, the thermal-stress, which increases and exceeds the allowable tensile strength after 590 hardening hour, changes from compression to tension (Figure 8). Thus, the cracks were created at the concrete block center.

At node 141 – outer upper part surface, during 96 hardening hour, the temperature rapidly decreases because of air effect, meaning that the volumetric concrete tends to be compressed. However, at the same time, the volume at the center (node 97) which is being expanded, prevent the shrinkage at outer surface (node 141). Thus, the tensile stress increase at this stage. It can be seen from Figure 9 that at time of 30 hardening hour, the tensile stress hardening on the upper surface will exceed the allowable tensile strength of concrete. Thus, cracks are formed on foundation block surface.

At node 98 – outer right part, after 30 mixing hour of raw materials with water, cracks are also formed on the concrete foundation block surface (Figure 10).

In conclusion, in order to prevent and minimize the development of structure cracks, it is necessary to concern to the concrete hardening process, especially after 30 hours of laying the concrete mix in the formwork.

4. Conclusion

1. It is proved that it is possible to produce heavyweight concrete from Vietnamese local raw materials to build the foundation's bridge sized 8 x 6 x 2.5 m, with relate to the concrete mixture workability on 95 mm standard cone, 36.3 MPa compressive strength at the age of 28 days with normal hardening and 0.32 MPa average water resistance.

2. By using the computer program MIDAS CIVIL, the maximum temperature in the central zone was determined as T_{max} = 73.04 °C after 72 hours from the commencement of mixing of raw materials with water. Then, this temperature value begins to decrease gradually. At the same time, the temperature difference between the center (node 97) and surfaces (nodes 141 and 98) was 31.7 °C.

3. At nodes 141 and 98, after 30 hardening hour, the concrete tensile stress becomes higher than the tensile strength resulting to the cracks formation on concrete surface. Therefore, in order to prevent cracking, it is necessary to concern to concrete hardening process, especially at point of 30 hours since mixing of raw materials with water.

4. In the concrete foundation center (node 97), the tensile stress will exceed the allowable tensile strength by 590 hardening hour. At the time of high strength value, the risk of cracks at the concrete foundation center due to the temperature stress occurrence caused by the heat release during cement hydration will not be too high.

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