Evaluation of early-age cracking risk in mass concrete footings under different placement conditions

Evaluación del riesgo de fisuración temprana en zapatas de hormigón de masa de concreto bajo diferentes condiciones de colocación

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Fecha de Recepción: 23/11/2020
Fecha de Aceptación: 04/04/2021
PAG 05-13

Abstract

This article presents the assessment of early-age cracking risk in a mass concrete footing which is cast under different construction conditions. A finite element (FE) model was developed for predicting temperature, thermal stress, and cracking potential in a concrete footing at early age. Different scenarios of concrete placement were considered to investigate the effect of construction stages on thermal cracking potential in the concrete. *The analysis method in this study can help engineers optimize* construction schedules to control temperature and reduce cracking risk *in mass concrete structures*.

Keywords: *Maximum temperature, temperature difference, mass concrete, placing temperature, thermal crack*

Resumen

Este artículo presenta la evaluación del riesgo de agrietamiento a temprana edad en una zapata de hormigón en masa que se vierte bajo diferentes condiciones de construcción. Se desarrolló un modelo de elementos finitos (EF) para predecir la temperatura, la tensión térmica y el potencial de agrietamiento en una zapata de hormigón a una temprana edad. Se consideraron diferentes escenarios de colocación del hormigón para investigar el efecto de las etapas de construcción sobre el potencial de agrietamiento térmico en el hormigón. El método de análisis de este estudio puede ayudar a los ingenieros a optimizar los programas de construcción para controlar la temperatura y reducir el riesgo de fisuración en las estructuras de hormigón en masa.

Palabras clave: Temperatura máxima, diferencia de temperatura, hormigón en masa, temperatura de colocación, fisura térmica

1. Introduction

Concrete structures such as dams, bridge foundations, piers, and abutments are often classified as "mass concrete" (ACI, 2000), (ACI, 2005), (Do, 2014). When a larger volume of fresh concrete is poured, a larger amount of heat releases from the cement hydration process. The temperature at the inside portion of the concrete is increasing while that at the surface is quickly decreasing due to the exposure to the air. This creates a large temperature difference between the core and the outer surface of the concrete, leading to high tensile stresses that may exceed the concrete tensile strength, which will cause thermal cracks (ACI, 2005), (Tian et al., 2012), (Tía, 2013), (Do, 2014). As long as cracking occurs in the concrete, it begins to affect the regular service and durability of the structure (Maruyama and Lura, 2019). Therefore, it is necessary to analyze the temperature and the corresponding stress fields in mass concrete structures for controlling temperature and preventing crack initiation in the early-age concrete (Nguyen and Luu, 2019), (Nguyen and Bui, 2019)

There are different measures to reduce the temperature difference and thermal tensile stress in mass concrete such as use of lower cement content, use of aggregates (Klemczak et al., 2017) with a low coefficient of thermal expansion, casting concrete at night or in the early morning (Do, 2019), use of ice water, use of liquid nitrogen, pre-cooling of mix constituents, post cooling using embedded pipes (Hong et al., 2017), (Nguyen et al., 2019), and use of insulating formwork (Do, 2020), (Do et al., 2014a), (Do et al., 2013). Recently, laboratory (Zhao et al., 2019), (Do et al., 2019a) and field tests (Sargam et al., 2019) on early-age properties and thermal cracking of concrete have been also conducted to evaluate the cracking risk as well as the efficiencies of thermal control methods to control cracking in mass concrete. Each measure has both advantages and disadvantages depending on construction conditions. Among these measures, the control of concrete placement stages has not been widely used because of its costs. Hence, the aim of this study is to determine the temperature and thermal stress in a concrete footing cast in different placement conditions, thus suggesting the best scenario for reducing cracking risk in the structure.

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2. Materials and Methods

2.1. Description of the mass concrete footing

In this study, an assumed 8-m×6-m×3-m concrete footing cast on soil is modeled. The modeled soil layer is assumed to have dimensions of 16-m×12-m×4-m. The concrete footing has two planes of symmetry, therefore only one-quarter of the footing is analyzed in order to reduce the computation time. The geometry and dimensions of the footing are shown in (Figure 1).

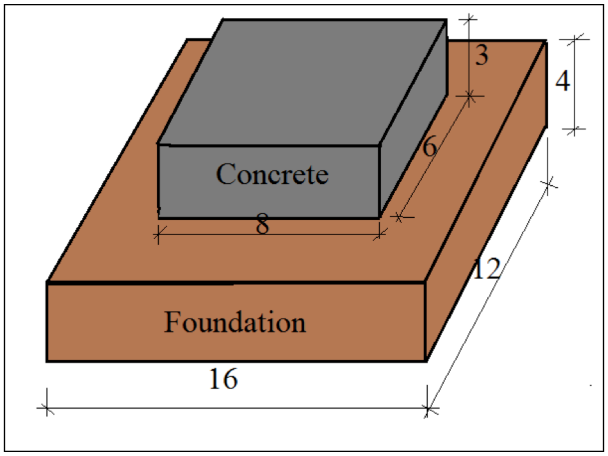


Figure 1. Geometry and dimensions of footing (units: m).

The ambient temperature can be simulated using the the (Equation 1) (Léger et al., 1993):

$$T_{env} = 5\sin\left(\frac{\pi t_{day}}{12}\right) + 26.5^{o}C \qquad \textbf{(1)}$$

where T_{env} is the ambient temperature (℃), and t_{day} is the time (days).

The temperature of the foundation under the concrete block is considered 25℃ and the initial concrete temperature is assumed to be 30℃. The concrete mix proportion is shown in (Table 1) (Tia et al., 2016), (Do, 2016). The adiabatic temperature rise for the concrete mix was tested and is shown in (Figure 2). The thermal and physical characteristics of the concrete and the soil foundation used in the analysis are presented in (Table 2).

Table 1. *Mix design of concrete*

Concrete mixture	Cement (kg/m^3)	Fly ash	Fine Aggregate	Coarse Aggregate	w/cm
		(kg/m^3)	(kg/m^3)	(kg/m^3)	
FB	290	156	642	1010	0.36

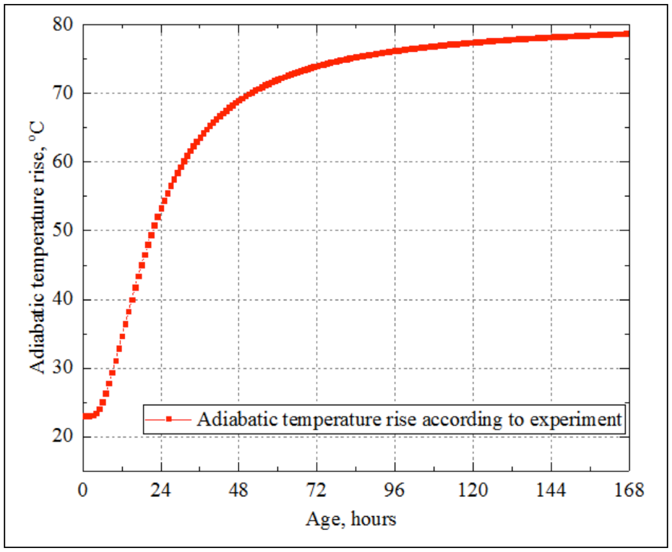


Figure 3. *Adiabatic temperature rise of concrete*

Table 2. *Thermal and mechanical properties of concrete and soil foundation*

Property	*Concrete*	*Foundation*
Thermal conductivity (W/m-℃)	*2.90*	*1.98*
Specific heat capacity (J/kg-℃)	*1047*	*850*
Density (kg/m^3)	*2259*	*2600*
Surface convection coefficient (W/m-°C) *- Boundary 1 (free contact with air)* *- Boundary 2 (steel shuttering)*	 *10.00* *13.94*	*14.00*
Coefficient of thermal expansion (/℃)	*10^{-5}*	*10^{-5}*
Modulus of elasticity (N/m^2)	*2.7×10^{10}*	*1.8×10^{10}*
Poisson's ratio	*0.20*	*0.28*
Design compressive strength, (MPa)	*38.00*	*-*

The ambient temperature can be simulated using the the (Equation 1) (Léger et al., 1993):

$$f_{sp}(t) = 0.56\sqrt{f_c^{'}} \qquad \textbf{(2)}$$

$$E(t) = 4700\sqrt{f_c^{'}} \qquad \textbf{(3)}$$

where $f_{sp}(t)$ is the splitting tensile strength (MPa), E(t) is the Young's modulus (MPa), and f_c' is the compressive strength (MPa).

During the construction of the concrete footing, there are many factors that affect its thermal regime especially construction conditions. In this study, the calculation cases are assumed as follows (Figure 3) :

Case 1: no construction joints are used,

Case 2: the concrete is placed in two lifts (1.5 m each) and 5-day time interval for placing each lift,

Case 3: the concrete is placed in three lifts (each lift 1 m) and 3-day time interval for placing each lift.

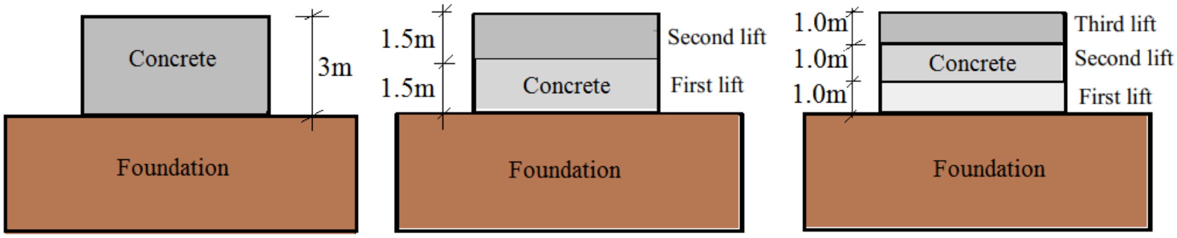


Figure 3. *Calculation cases*

2.2. FE basis for solving heat transfer problem

The governing equation of a 3D unsteady heat transfer problem is based on the principle of energy conservation and Fourier's law of heat conduction and expressed in (Equation 4) (Cengel, 2014):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+q_v=\rho c\frac{\partial T}{\partial t}, \qquad \textbf{(4)}$$

where t is the material temperature (°C), k_x, k_y, k_z are the thermal conductivity coefficients of the material dependent on the temperature in the directions x, y and z, respectively, (W/m-°C), q_v is the amount of heat released by internal sources (for example, exothermic heating) to a given moment in time (W/m^3), c is specific heat (J/kg-°C), ρ is the density concrete (kg/m^3), t is time (s).

Two types of heat transfer boundary conditions are often used to analyze heat problems, which are expressed by (Equation 5) and (Equation 6) (Cengel, 2014):

$$T=T_p, \qquad \textbf{(5)}$$

$$k_x\frac{\partial T}{\partial x}l_x+k_y\frac{\partial T}{\partial y}l_y+k_z\frac{\partial T}{\partial z}l_z+q_v+h(T_s-T_f)=0, \qquad \textbf{(6)}$$

where T_p is the temperature of the surface or foundation (°C), q_v is the heat generated per unit volume (J/m^3), h is the convective coefficient (W/m^2-°C), T_s is the temperature of concrete or foundation (°C), T_f is the ambient temperature of the construction area (°C), l_x, l_y, and l_z are the directional cosine of the surface according to the x, y and x axes, respectively.

The problem of heat transfer is solved using the following matrix equation (Equation 7), (Zienkiewicz and Taylor, 2000):

$$[K]\{T\}+[C]\left\{\frac{\partial T}{\partial t}\right\}=[Q], \qquad \textbf{(7)}$$

In the problem of unstable heat transfer, it is necessary to analyze time into steps Δt as follows (Equation 8):

$$\left\{\frac{\partial T}{\partial t}\right\}=\frac{1}{\Delta t}\left[\{T(t_n)-T(t_{n-1})\}\right], \qquad \textbf{(8)}$$

(Equation 9) is obtained by combining (Equation 7) and (Equation 8) and expressed as follows:

$$[K]\{T\}+\frac{[C]}{\Delta t}[\{T(t_n)-T(t_{n-1})\}]=[Q], \qquad \textbf{(9)}$$

where [K] is conductivity operator, [C] is capacity operator, and [Q] is heat load due to heat of hydration, $\Delta t = \Delta t_n - \Delta t_{n-1}$ is the time step.

Solving (Equation 9) gives temperature fields in the concrete block at different time steps.

Thermal stress in the concrete is determined by (Equation 10) (Zienkiewicz and Taylor, 2000):

$$\{\sigma\}=[D][B]\{u\}=[D](\{\varepsilon\}-\{\varepsilon^{th}\}), \qquad \textbf{(10)}$$

where {σ} is the thermal stress vector, [D] is the elasticity matrix, [B] is the strain-displacement matrix, based on the element shape functions, {u} is the nodal displacement vector, $\{\varepsilon\}=\{\varepsilon_x\ \varepsilon_y\ \varepsilon_z\ \varepsilon_{xy}\ \varepsilon_{yz}\ \varepsilon_{zx}\}$ is the strain vector, and $\{\varepsilon^{th}\}$ is the thermal strain vector. The determination of temperature field in a mass concrete structure is a complex problem because it depends not only on the shape of the structure but also on other factors such as the internal heat generation, construction conditions, and the ambient temperature. In recent years, numerical approaches such as finite difference and FE methods have been widely used to predict temperature and stress fields in mass concrete structures (Nguyen et al., 2019), (Trong et al., 2019), (Aniskin et al., 2018), (Do et al., 2020), (Do et al., 2020a), (Do, 2013). In this study, the Midas/Civil software (MIDAS, 2011) based on the FE method was used to model the early-age behavior of the concrete footing depicted in (Figure 1).

2.3. Crack index for evaluation of early-age cracking risk

The prediction of crack formation in an early-age concrete structure plays an important role in minimizing the cracking risk and/or controlling crack growth. Criteria for evaluating early-age thermal cracking in concrete vary from country to country (Do et al, 2020b). In the United States, the ACI guidelines for assessing thermal cracking are not specified except for a recommended limiting value for the temperature difference between the core and the outer surface of the concrete. In other countries such as Korea and Japan, "crack index" is preferably used as a measure for assessing early-age cracking potential in the concrete. Crack index is determined by (Equation 11) (Kim, 2010), (Japan Concrete Institute, 2017):

$$I_{ct}=\frac{f_{sp}(t)}{f_t(t)} \qquad \textbf{(11)}$$

where I_{ct} is the crack index, $f_t(t)$ is the maximum tensile stress (MPa), and $f_{sp}(t)$ is the splitting tensile strength of the concrete (MPa).

The tendency of cracking can be evaluated using "crack index" based on engineering experience as introduced in (Table 3) and (Figure 4), (Kim, 2010).

Table 3. *Thermal crack index (I_{ct})*

Criteria	***Crack index***
No cracking	$I_{ct} \geq 1.5$
To minimize cracking	$1.2 \leq I_{ct} \leq 1.5$
To minimize harmful cracking	$0.7 \leq I_{ct} \leq 1.2$

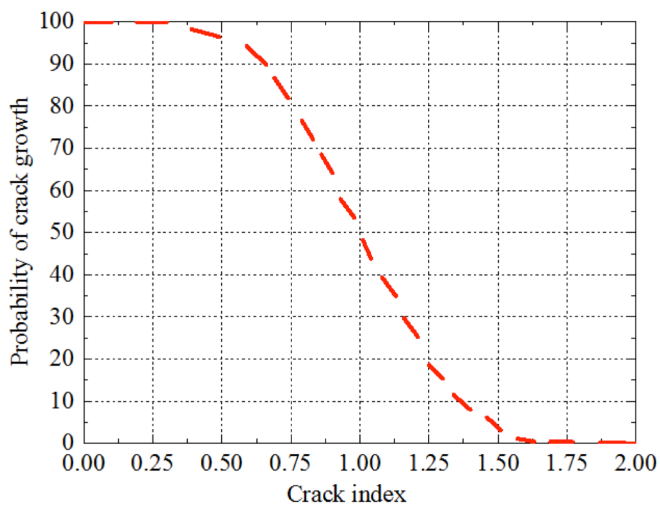


Figure 4. *Relationship between cracking probability (%) and cracking index (I_{ct})*

3. Analysis Results and Discussion

The 3-D FE model was created using the Midas/Civil software. The element used in the thermal analysis is a 3-D eight-node thermal solid element, which has one degree of freedom - temperature - at each node. The concrete and foundation in the stress analysis are modeled with a 3-D eight-node structural solid element, which is coupled with the 3-D thermal solid element. The temperature distribution obtained from the thermal analysis is then served as "thermal loading" in the stress calculation. The FE model geometry is depicted in (Figure 5).

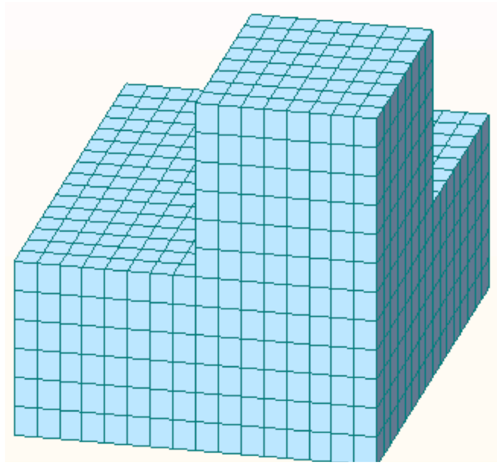
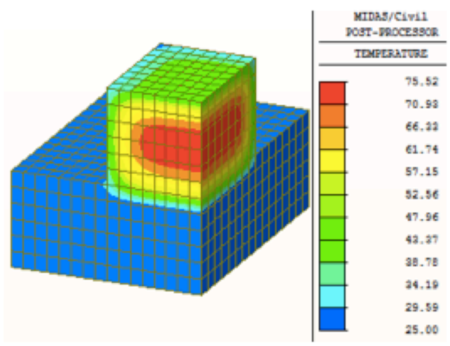
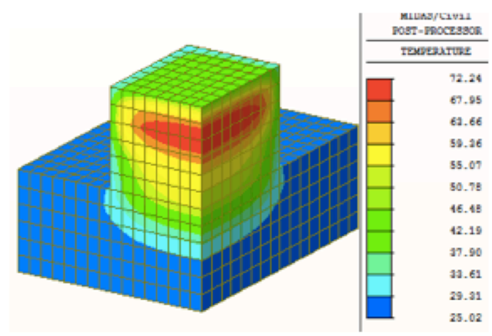


Figure 5. *Model geometry of 1/4 concrete footing*

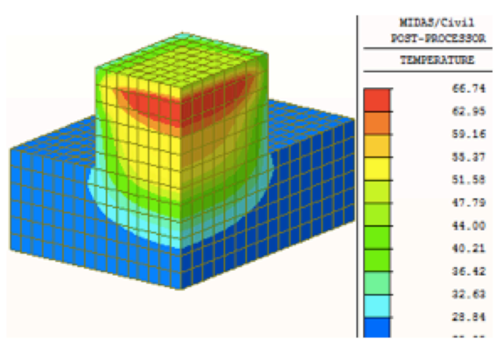
The (Figure 6) shows the maximum temperature development at the center of the concrete footing under different construction cases. The maximum temperature decreases as the thickness of each lift decreases during the cement hydration. The maximum temperature value and time of occurrence are listed in (Table 3). The maximum temperatures at the concrete center are 75.52°C, 72.24°C, and 66.74°C in Cases 1, 2, and 3, respectively. It may be noted that in Case 3, the maximum temperature and temperature difference are the smallest compared to Cases 1 and 2. After reaching the peak temperature, it begins to cool down. As predicted, the maximum temperature in the concrete will take a long time to decrease to a stable temperature. The crack index calculated at the surface is also listed in (Table 4).



a) Case 1



a) Case 1



a) Case 1

Figure 6. *Maximum temperature at the footing center in different cases*

Table 4. *The maximum temperature and its occurrence time in different cases*

Case	Max. temperature (°C)	Temperature difference (°C)	Ocurrence time (h)
1	75.52	33.6	96
2	72.24	27.78	192
3	66.74	18.57	252

Table 5. *The thermal crack index with different construction cases*

Case	Crack index	$f_{sp}(t)$ - tensile strength (MPa)	f_t (t) - tensile stress (MPa)	Probability of crack occurrence (%)
1	0.75	2.77	3.74	81
2	0.91	2.98	3.28	50
3	1.26	2.79	2.22	20

The (Figure 4) and (Table 4) together show that the probabilities of cracking in the concrete footing are 81%, 50%, and 20%, in Cases 1, 2 and 3, respectively. It can be included that thermal cracking in the concrete in Case 3 is not likely to occur at early ages, thus suggesting the proposed method of concrete pouring is effective. In other hand, other measures should still be taken in Cases 1 and 2 for controlling early-age cracking in the concrete.

4. Conclusions

- *The 3-D FE model created in this study has identified the temperature and thermal stress fields in the concrete footing at early ages in different construction scenarios. The results show that the construction schedules significantly affect the temperature development and thermal cracking risk in the concrete.*

- *When the concrete is cast with a maximum volume of 8-m×6-m×3-m in three lifts (as investigated in this study), thermal cracking will be not likely to occur. Thus, dividing large volume of mass concrete into reasonably smaller lifts can help minimize cracking risk in the concrete.*

- *For future work, the numerically predicted results (temperature field and crack index) should be compared with experimental results. As long as the research results have been verified, they can be used in the sustainable design and construction of mass concrete structures.*

- *The developed model can be used to perform thermal and stress analyses, and assess the risk of thermal cracking of other essential concrete members. The research methodology can help engineers/contractors optimize the construction stages and reduce the project schedule.*

5. Acknowledgements

This research is funded by Vietnam Ministry of Education and Training under grant number B2021-GHA-06

6. References

ACI (2005). 207.1 R-05 Guide to Mass Concrete.

ACI (2019). ACI 318-19. Building code requirements for structural concrete and commentary. 2019: American Concrete Institute, Farmington Hills, MI.

ACI, (2020). 116R-00. Cement and Concrete Terminology. American Concrete Institute, Farmington Hills, MI.

Aniskin, N.A., et al. (2018). Determination of the temperature field and thermal stress state of the massive of stacked concrete by finite element method. Vestnik MGSU, 2018. 13(11): p. 1407-1418.

Cengel, Y. (2014). Heat and mass transfer: fundamentals and applications. 2014: McGraw-Hill Higher Education.

Do, T.A. (2013). Finite element modeling of behavior of mass concrete placed on soil. 2013: University of Florida.

Do, T.A. (2014). Influence of footing dimensions on early-age temperature development and cracking in concrete footings. Journal of Bridge Engineering, 2014. 20(3): p. 06014007.

Do, T.A. (2016). Determination and evaluation of hydrothermal heat of some concrete binder mixtures used for mass concrete structures. Journal of Transport Science 2016.

Do, T.A. (2020). A Combination of Finite Difference and Finite Element Methods for Temperature and Stress Predictions of Early-Age Concrete Members, in Finite Element Methods and Their Applications. 2020, IntechOpen.

Do, T.A., et al. (2013). Importance of insulation at the bottom of mass concrete placed on soil with high groundwater. Transportation Research Record: Journal of the Transportation Research Board, 2013(2342): p. 113-120.

Do, T.A., et al. (2014). Determination of required insulation for preventing early-age cracking in mass concrete footings. Transportation Research Record: Journal of the Transportation Research Board, 2014(2441): p. 91-97.

Do, T.A., et al. (2014). Effects of thermal conductivity of soil on temperature development and cracking in mass concrete footings. Journal of Testing and Evaluation, 2014. 43(5): p. 1078-1090.

Do, T.A., et al., (2019) A combined finite difference and finite element model for temperature and stress predictions of cast-in-place cap beam on precast columns. Construction and Building Materials, 2019. 217: p. 172-184.

Do, T.A., et al. (2019). The degree of hydration and strength development in high strength concrete Journal of Transport Science, 2019.

Do, T.A., et al. (2020). Adiabatic Temperature Rise and Thermal Analysis of High-Performance Concrete Bridge Elements, in ICSCEA 2019. 2020, Springer. p. 413-423.

Do, T.A., et al. (2020). Evaluation of heat of hydration, temperature evolution and thermal cracking risk in high-strength concrete at early ages. Case Studies in Thermal Engineering, 2020: p. 100658

Do, T.A.; Minh, Ha; Thac, Nguyen; Duc, Tran; Thang, Quoc (2020). Evaluation of methods for analyzing early-age cracking risk in concrete walls of tunnel structures. Transport and Communications Science Journal, 2020.

Hong, Y., et al. (2017). Thermal field in water pipe cooling concrete hydrostructures simulated with singular boundary method. Water Science and Engineering, 2017. 10(2): p. 107-114.

Kim, S.G. (2010). Effect of heat generation from cement hydration on mass concrete placement. Thesis, Master of Science. 2010, Iowa State University.

Klemczak, B., et al. (2017). Analysis of cracking risk in early age mass concrete with different aggregate types. Procedia engineering, 2017. 193: p. 234-241.

Japan Concrete Institute (2017). Guidelines for control of cracking of mass concrete 2016. 2017.

Léger, P. J. (1993). Venturelli, and S. Bhattacharjee, Seasonal temperature and stress distributions in concrete gravity dams. Part 1: modelling. Canadian journal of civil engineering, 1993. 20(6): p. 999-1017.

Maruyama, I.; Lura, P. (2019). Properties of early-age concrete relevant to cracking in massive concrete. Cement and Concrete Research, 2019. 123: p. 105770.

MIDAS (2011). Heat of Hydration – Analysis Manual. 2011: MIDAS Information Technology.

Nguyen, T.C. ; Bui, A.K (2019). Evaluation of the impact of parameter inputs of concrete mix on the distribution of temperature in the mass concrete structure. IVK-Structural Integrity and Life, 2019. 19(1): p. 8-12.

Nguyen, T.-C.; Luu,X.B. (2019). Reducing temperature difference in mass concrete by surface insulation. Magazine of Civil Engineering, 2019. 88(4).

Nguyen, T.C.; Huynh,T.C.; Tang, V.L. (2019). Prevention of crack formation in massive concrete at an early age by cooling pipe system. Asian Journal of Civil Engineering, 2019. 20(8): p. 1101-1107.

Sargam, Y., et al. (2019). Predicting thermal performance of a mass concrete foundation–A field monitoring case study. Case Studies in Construction Materials, 2019. 11: p. e00289.

Tia, M., et al. (2013). Pilot project for maximum heat of mass concrete. 2013, Florida. Dept. of Transportation.

Tia, M., et al. (2016). Maximum heat of mass concrete-phase 2. 2016.

Tian, Y.; Jin, X.Y.; Jin, N.G. (2012). Thermal cracking analysis of concrete with cement hydration model and equivalent age method. Shuili Xuebao(Journal of Hydraulic Engineering), 2012. 43: p. 179-186.

Trong, C.N.; Viet, C.M.; Xuan, B.L.. (2019). Temperature distribution in concrete structure under the action of fire using Ansys software. in E3S Web of Conferences. 2019. EDP Sciences.