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Artikel Penelitian

Numerical Calculation of Thermal Stress in Cement Rotary-Kiln Foundation at an Early Age

Adek Tasri

Mechanical Engineering Department, Universitas Andalas, Padang 25163, Indonesia

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E-mail: adek.tasri@eng.unand.ac.id

A B S T R A C T

This article discusses the early-age thermal stress, caused by the hydration heat, of a rotary kiln concrete foundation. We measure the hydration heat using an adiabatic calorimeter and perform finite volume numerical calculations to obtain the temperature distribution and finite element calculation to determine the thermal stress. The numerical simulation showed significant temperature differences between the core region and surface of the concrete. Compressive stress developed at the core, and tensile stress developed at the surface of the concrete during a heating period. The compressive stress was lower than the concrete compressive strength. The tensile stress was higher than the concrete tensile strength. So that crack developed in the surface. Heat treatment such as post-cooling or pre-cooling was needed to avoid the crack.

1. INTRODUCTION

It has well known that stress in the concrete at an early age can occur due to changes in the volume of concrete caused by some conditions such as a reduction in the amount of water due to chemical reactions between cement and water, evaporation of water into the environment and heat generated by hydration reactions [1,2]. During the heating period, the heat generated by the hydration reaction is mainly confined to the core of the concrete due to the thermal conductivity is not large enough to transfer the heat to the concrete surface. While on the surface, heat escapes to the environment by convection, so that the core region of the concrete becomes hotter than the surface. The core tends to expand faster than the surface result in an internal restraint in the concrete. The internal restraint cause

compression in the core region and tensile stress in the surface.

When the heat generated by the hydration reaction is less than the amount of heat transferred to the surroundings, the concrete undergoes cooling and volume shrinkage. If the change in volume shrinkage is blocked by external forces such as friction between the concrete and lean surface, an external restraint will be developed. The external restraint causes a tensile that produces additional stress on the surface.

The thermal stress, produced by external and internal restraint, leads to crack in early age concrete [3]. The early age thermal stresses are mainly studied numerically because of the limitations of carrying out experiments in large sizes of concrete.

Azenha and Faria [4] studied temperature and stress distribution in early age mass concrete. Luna and Wu [5] predict the temperature and stress in the RCC dam by considering the effect of temperature on the elastic and creep modulus of the concrete. Tasri [6, 7] studied temperature and thermal stress around the post-cooling pipe of mass concrete. The effect of the volume on concrete stress and temperature was reported by Aniskin et al. [8].

Most of the temperature and stress data reported in the publications only apply to the cases analyzed in the report. Temperature and stress predictions in a particular mass concrete cannot be used in other mass concrete cases even though they are the same size because there are differences in material and environment. So that temperature and stress predictions must be made for each mass concrete. In this study, numerical prediction of thermal stress in the foundation of a rotary kiln used in cement plants was carried out using Ansys 2002 R2 software. The heat of hydration data needed in the simulation was obtained from an experiment using an adiabatic calorimeter as suggested by Balliem [9].

2. MODELLING AND DESCRIPTION

The foundation studied in this work is a foundation of a rotary kiln that has a capacity of 2.4 million tons of clinker per year. For this purpose, the foundation is expected to have a compressive strength of up to 31.2 MPa. The composition of the concrete components, to obtain this strength, consists of 0.186 kg of cement, 0.089 kg of water, 0.277 kg of sand and 0.416 kg of gravel per kg concrete.

The foundation has a rectangular cross-section of 15m×15m with 2.5m height. The foundation is placed on a lean surface of 0.05m thick. The lean surface is laid on soil modelled as a large volume of 30m×30m×7m so that the soil surface can be modelled as a constant-temperature surface. The calculation domain and mesh used in this work is shown in Figure 1.

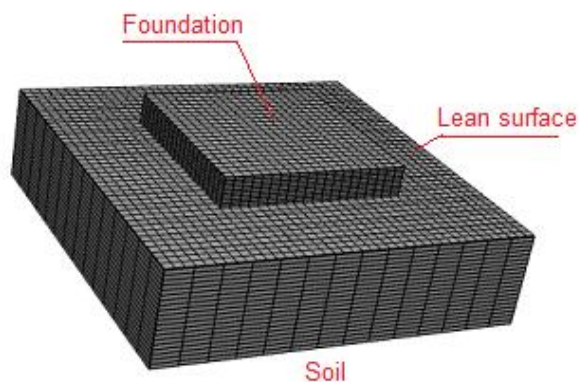


Figure 1. The calculation domain and mesh

3. GOVERNING EQUATION AND NUMERICAL MODEL

Thermal stress in the foundation is determined using ANSYS 2020 R2. The calculation was started by calculating temperature distribution. The temperature distribution was then used to obtain the stress distribution. The temperature distribution is obtained by solving the energy equation for the solid media.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + \dot{q} \quad (1)$$

where ρ , k , C_p and T are the density, thermal conductivity, heat capacity and temperature respectively. \dot{q} is hydration heat per unit of volume. The equation for \dot{q} was obtained from hydration heat data determined by measuring concrete samples using an adiabatic calorimeter. The equation of \dot{q} is as in Eq. (2).

$$\dot{q} = \frac{c_p \rho (T_0 - T_p) \left(-0.04t^{0.13} \right) \left(-\exp\left(-0.04t^{0.13} \right) \right)}{3600} \quad (2)$$

where \dot{q} is hydration heat in (W/m³); T_p and T_o are pouring and maximum temperature in (°C); t is time (hour), c_p is heat capacity concrete (J/kgC); ρ is density (kg/m³). In the numerical simulation, the

equation of \dot{q} was written in C++ code combined with ANSYS 2020 R2 as a user defined-function.

The stresses in the foundation were found using the minimum potential energy concept stated that the actual deformation in a equilibrium system is the value that minimizes the potential energy of the system. The potential energy consist of the strain energy E_s and the energy of the external force E_x

$$E_p = E_s + (-E_x) \quad (3)$$

The strain energy, E_s is the product of the strain energy density and volume of the structure

$$E_s = \int_{\Omega} \frac{1}{2} [D] \{\varepsilon\}^2 d\Omega - \int_{\Omega} [D] (\{\varepsilon_r\} + \{\varepsilon_T\}) d\Omega \quad (4)$$

$[D]$ is stiffness matrix; ε , ε_{cr} and ε_T are total strain, thermal strain and creep strain respectively. Product of stiffness and strain in Eq. (4) represents the strain energy density.

The external energy is product of external force, F and displacement d .

$$E_x = \{F\} \{d\} \quad (5)$$

Replace E_s and E_x in Eq. (3) with Eq. (4) and Eq. (5), followed by minimizing the potential energy E_p result the integral form of governing equation of displacement

$$\int_{\Omega} [B]^T [D] [B] d\Omega \{d\} = \{F\} + \int_{\Omega} \varepsilon_T d\Omega + \int_{\Omega} [B]^T [D] \{\varepsilon_{cr}\} d\Omega \quad (6)$$

$\{d\}$ obtained from Eq. (6) is used to determine stress inside the foundation:

$$\{\sigma\} = [D] (\{\varepsilon\} - \{\varepsilon_{cr}\} - \{\varepsilon_T\}) \quad (7)$$

where $\{\varepsilon\}$ is first derivative of the displacement vector.

4. BOUNDARY CONDITION

The foundation was located in an open space where the hydration heat losses from the concrete surface to the environment by forced convection at air velocity on the surface of 2 m/s. The convection coefficient was approximated by the convection coefficient of a flat plate.

$$h = 9.60 + 1.12U \quad (8)$$

The mass of the soil was made large enough to absorb conduction heat from the concrete without experiencing a significant temperature change. The outer surface of the soil domain can be considered a constant temperature of 30°C.

5. RESULT

Figure 2 shows the temperature distribution along the vertical axis of the foundation. The temperature at the foundation's core region was higher than the temperature at the surface as heat conduction from centre to surface was lower than heat loss from the surfaces to the environment. At the upper surface and the side of the foundation, the heat was lost to the environment by convection, while at the bottom, the heat was lost to the soil by conduction. The conduction loss was lower than convective loss due to the lower conductivity of concrete and soil.

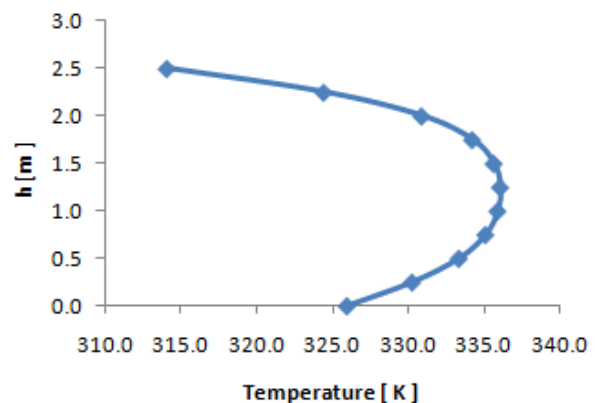


Figure 2. Temperature along vertical axis of the foundation

The high temperature at the core of the foundation causes this part to expand faster than the surface. So

that, the core region of the foundation experienced pressure stress, and the surface part experienced tensile stress, as shown in Figure 3. Figure 4 shows the distribution of normal stresses along the vertical axis of the concrete. Maximal compressive stress at the core region was 1.27 MPa. This value was still lower than the compressive strength of 31.20 MPa. Maximal tensile stress at surface was 2.84 MPa that above the tensile strength of 2.70 MPa, estimated using compressive and tensile strength relation suggested by Grebovic [10]:

$$f_{ts} = 0.5f_{cs}^{0.5} \tag{9}$$

where f_{ts} and f_{cs} were tensile strength and compressive strength, respectively.

The uppers surface was prone to cracking. The crack can be ovoid if the temperature difference between the core region and surface was reduced. Reducing the temperature difference can be carried out by pre-cooling or post-cooling treatment [6,7].

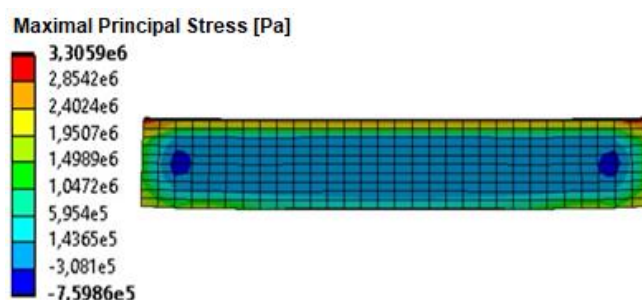


Figure 3. Maximal principal stress on the cross section of the foundation

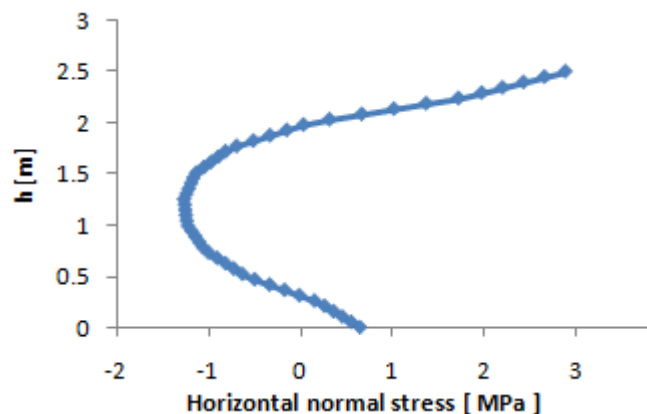


Figure 4. Horizontal normal stress along vertical axis of the foundation

6. CONCLUSION

Numerical simulations were carried out to obtain the thermal stress of concrete, used as a rotary kiln foundation, at an early age. The following conclusions were drawn:

1. During the expansion period, the core region of the concrete experiences compression stresses and the surface of the concrete experiences tensile stresses.
2. The compression stress was below the compression strength of the concrete. Cracks did not occur in the core region of the concrete.
3. The tensile stress on the surface exceeded the tensile strength. Cracks occurred on the concrete surface.
4. The temperature differential causes compression stresses and tensile stresses in the concrete. Heat treatment such as pre-cooling or post-cooling were needed to reduce the temperature differential.

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