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Numerical prediction of rotary-kiln foundation temperature at an early age

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Abstract

The hydration heat confined to the core of the mass concrete during the hydration reaction causes a temperature rise and irregular temperature distribution in the concrete. High temperatures in concrete cause Delay Ettringite Formation (DEF) that cause damage several years after pouring, especially if the concrete is in an acidic environment. The uneven temperature distribution causes thermal stresses that can initiate cracks in the concrete surface. This article discusses a prediction of temperature distribution inside a mass concrete used as a rotary kiln foundation. We measure the heat of hydration of the concrete sample using an adiabatic calorie meter and derive the heat of hydration equation from the measurement data. The hydration heat was used in numerical calculations to obtain the temperature distribution, maximal temperature and temperature differential. The numerical calculation shows that the maximum foundation temperature was 64.01 ^{0}C. This temperature is still below the limit temperature for the occurrence of Delayed Ettringite Formation (DEF). The core region has the highest temperature, while the surfaces have the lowest temperature. The difference between the highest and lowest temperatures is 37.40 ^{0}C. However, the temperature differential exceeds the safe limit, 20 ^{0}C, so heat treatment to prevent cracking needs to be done.

Keywords: Mass concrete, hydration heat, numerical calculation

1. Introduction

As is well known, the chemical reaction between cement and water releases heat that causes a temperature rise in the concrete. If the temperature rises to 70 ^{0}C or higher, the ettringite (C3A·3CaSO4·H32) formed from a chemical reaction of water and cement decomposed to hydrate monosulphate [1]. The monosulphate ion reacts to reform the ettringite several years or moth later. This process is known as Delayed Ettringite Formation (DEF). The ettringite formed in second rection have a large volume than the reactant, so that it causes a crack in the concrete as the concrete has hardened. In addition to the DEF problem, there are a certain amount of heat trapped in the core region due to the concrete low thermal conductivity, while certain amount of heat flows to the environment by convection from the surface, so that the core temperature becomes higher than the surface. Because of the temperature differences, the core region tends to expend more than the surface. The core region undergoes compressive stress while the surface experience tensile stress. American Concrete Institute [2] and Portland Cement Association [3] reported that if temperature differences are more than 20 ^{0}C, the compressive and tensile stress could initiate cracks that cause structural integrity failure and shorten the concrete's service life. The hydration heat, as well as the temperature distribution, are influenced by many factors, such as the compound composition of cement [4], cement finesse [5], and cement to water ratio [6]. Prediction of hydration heat can be made semi-empirically [7] by using an equation derived from the chemical reaction between cement and water or through measurement using using an adiabatic calorimeter [8]. While, the prediction of distribution temperature inside concrete can be carried out by numerical simulation as done by Couto et al. [9] and Schutter [10]. Tasri and Susilawati [11] use finite volume simulation to predict the temperature distribution in piped cooling concrete.

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The data of hydration heat and temperature distribution of one mass concrete cannot be used on other mass concretes because of the difficulty in controlling the factors that affect the hydration and temperature. The heat of hydration measurement and temperature prediction must be carried out on each concrete. So that, many data of the hydration heat and temperature distribution of mass concrete, such as mass concrete used as kiln foundation, have not yet been available in the literature. At the same time, these data are necessary for planning heat treatment to prevent foundation cracking at an early age. In this study, the hydration heat of mass concrete used as a foundation of a 50 ton/day cement rotary kiln was determined using a calorimeter. The hydration heat data was then used to determine the temperature distribution in form of maximal temperature and temperature differential using commercial software Ansys fluent 2021R1.

2. Method

Hydration heat measurement

The foundation has a compressive strength of up to 31.2 MPa. Based on the Indonesian standard for concrete [12], the strength can be achieved by using the following composition; 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 volumetric hydration heat was obtained as the time differential of the concrete temperature during the hydration process. The concrete temperature was obtained from measurements using an adiabatic calorimeter with a procedure similar the one used by Balliam [8]. The initial temperature of the fresh concrete during the calorimetric measurement was 35 ^{0}C. The equation for the volumetric hydration heat obtained from the experiment data is shown in Eq. 1

$$\dot{q} = \frac{T_0\, c_p\, \rho\left(-0.04t^{0.13}\right)\left(-\exp\left(-0.04t^{0.13}\right)\right)}{3600} \tag{1}$$

where $\dot{q}$ is hydration heat $\left(wm^{-3}\right)$; T_0 is differences between maximum temperature and initial temperature $\left({}^0C\right)$; c_p is heat capacity concrete $\left(jkg^{-1}\,C^{-1}\right)$; ρ is density in $\left(kgm^{-3}\right)$ and t is time $\left(hour\right)$.

Model description

The foundation of the rotary kiln is sized 15 m x 15 m x 2.5 m. The foundation is located on the lean surface with a thickness of 0.05 m. The soil is modelled as a large mass of 30 m x 30 m x 7 m to be approximated as a heat sink with a constant temperature surface. The concrete and mesh used in the numerical calculation are shown in Fig. 1. The numerical simulation to determine temperature distribution inside mass concrete performed using Ansys Fluent 2021 R1 that solve the heat transfer problem inside the concrete using the finite volume method. The governing equation for the finite volume solution is the energy equation in the solid region.

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + \dot{q} \tag{2}$$

ρ, k, T, and $\dot{q}$ are the density, thermal conductivity, temperature and hydration heat per unit of volume, respectively. The hydration heat $\dot{q}$ determine from adiabatic calorimeter measurement as in Eq. (1). The equation was written in C^{++} code and is included in the fluent solver as a used defined function.

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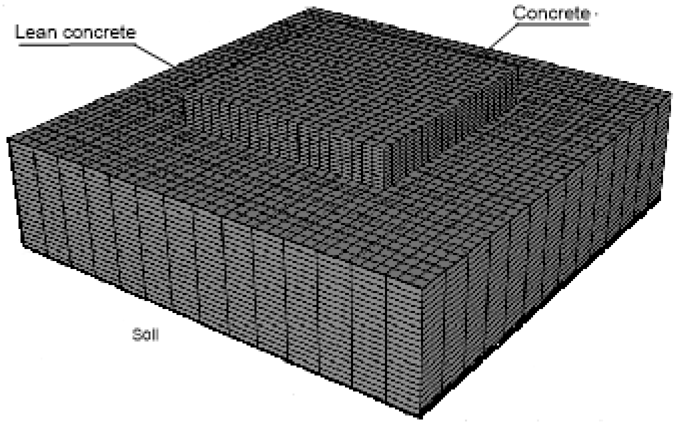

Figure 1. The calculation domain and finite volume mesh

Boundary condition

The rotary kiln foundation was located in the open air where the hydration heat moves from the foundation surface to the atmosphere through a convection process with a convection coefficient depend of air velocity [9] as in Eq. 3.

$$h = 9.60 + 1.12U \tag{3}$$

where U is wind velocity. A wind speed of 2 m/s, the average wind speed in many locations in Indonesia, was used in this simulation. At the base of the foundation, heat is transferred to lean concrete by conduction. Some of the heat is transferred to the soil, and some are lost to the atmosphere by convection. Soil is a large mass so that it can be modelled as a heat sink with a constant surface temperature of 30 ^{0}C.

3. Results and Discussion

Referring to the chemical reaction process of hydration [14], the increase in concrete temperature (Fig. 2) was mainly caused by the heat released by the reaction of water with Alite (C3S) and Belite (C2S), which are the main components of PCC cement used in this study [15]. The rate of the heat of hydration is influenced by several factors [16] such as cement composition, cement fineness, cement to water ratio, cement content and casting temperature. The numerical simulation data in Fig. 2 shows that the core temperature rises from the casting temperature of 35 ^{0}C to 64.08 ^{0}C, 85 hours after the mixing. The increase in the concrete core temperature occurs because the rate of heat generated was faster than the rate of heat being transferred from the core.

The speed of heat transfer in solid materials such as concrete is strongly influenced by the thermal conductivity of the concrete [17, 18]. The low thermal conductivity of concrete causes prolonged heat flow living the core during the hydration, cause in increasing of the core temperature, as shown in Fig. 3. On the other hand, heat on the surfaces moved faster through a convection mechanism to the environment. The increase in surface temperature was much smaller, where the surface temperature only changed from 35 ^{0}C to 36 ^{0}C during the first 10 hours of the hydration reaction. Even though there was an increase, the concrete temperature was well below the temperature for the decomposition of hydrate monosulphate of 70 ^{0}C [1]. The Delayed Ettringite Formation (DEF) did not occur.

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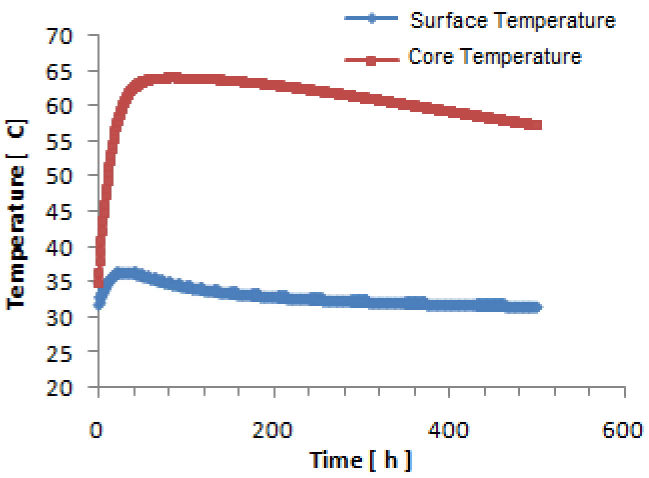

Figure 2. Minimum and maximum temperature inside the foundation

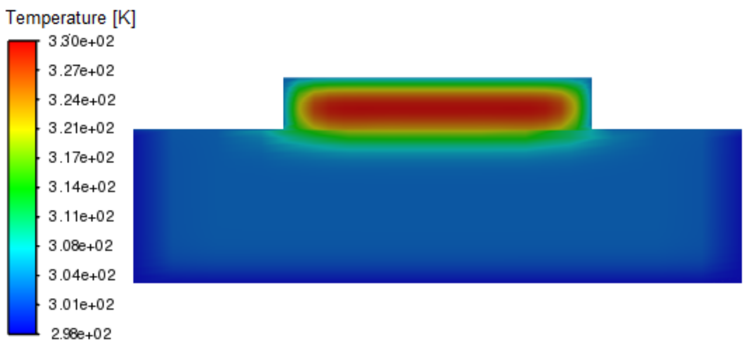

Figure 3. Distribution temperature in the foundation

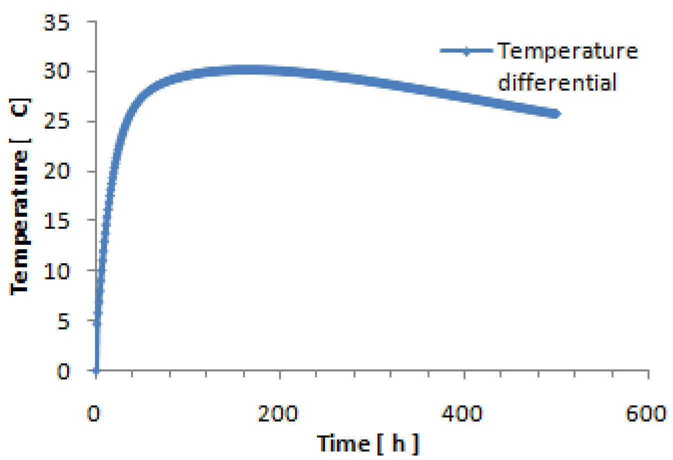

Figure 4. Temperature differential in the foundation

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Fig. 4 shows that the temperature differential, the core and surface temperature difference, increases from 0 ^{0}C at fresh concrete to 30.19 ^{0}C, 166 hours after the mixing concrete component where hydration reaction reaches a steady-state rate in most concrete. This temperature differential causes the core region to expand faster than the surface, which has a lower temperature so that the core region experiences compression and the surface experiences tensile stresses that have the potential to cause cracks in the concrete if the temperature differential exceeds 20 ^{0}C as reported by FitzGibbon [19].

4. Conclusion

A numerical simulation has been carried out to determine the temperature distribution in the rotary kiln foundation caused by the heat released from the hydration reaction. The following data and conclusions were obtained:

1. Maximum concrete temperature does not exceed the temperature limit for DEF
2. The maximum temperature difference in the concrete was 30.19 0C, which occurs 166 hours after mixing the concrete component.
3. The maximum temperature difference exceeds the permissible limit, so that heat treatment to reduce the difference is required.

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