TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ENVIRONMENTAL ENGINEERING | ŚRODOWISKO
2-Ś/2015

MICHAŁ GRODECKI*

NUMERICAL SIMULATIONS OF THE HEAT FLOW IN A CONCRETE ROD

NUMERYCZNE SYMULACJE PRZEPŁYWU CIEPŁA W PRĘCIE BETONOWYM

Abstract

This paper discusses the results of numerical simulations of unsteady heat flow in a concrete rod. The temperature distributions obtained are compared with experimental results. The main goal of this paper is to find soil thermal parameters values for concrete which leads to obtaining the best correlation between the measured and calculated temperatures.

Keywords: concrete, heat flow, FEM, temperature

Streszczenie

W artykule przedstawiono rezultaty symulacji numerycznych nieustalonego przepływu ciepła w pręcie betonowym. Uzyskane rozkłady temperatur porównano z wynikami badań laboratoryjnych. Głównym celem pracy jest określenie parametrów cieplnych betonu prowadzących do uzyskania najlepszej korelacji pomiędzy pomierzonymi a obliczonymi wartościami temperatury.

Słowa kluczowe: beton, przepływ ciepła, MES, temperatura

DOI: 10.4467/2353737XCT.15.227.4613

* PhD. Michał Grodecki, Department of Geotechnics, Faculty of Environmental Engineering, Cracow University of Technology.

Symbols

α – thermal diffusivity [m²/s]
λ – heat conductivity [W/(mK)]
c – heat capacity [J/m³K]
q – heat flux [W/m²]
t –- time [h], [min]
T – temperature [K]
W – internal heat source power [J/(m³ ·s)]

1. Introduction

The main subject of the study is an unsteady heat flow in a concrete rod. I present: a mathematical model of the problem, a laboratory experiment, and numerical simulations of it. The temperature distribution obtained from numerical simulations is compared with the results of laboratory tests. The main goal is to find soil thermal parameter values for concrete which leads the best correlation between measured and calculated temperatures.

The problem of unsteady heat flow is described by Fourier's law:

$$\mathbf{q} = -\lambda\, \mathbf{grad} T \tag{1}$$

where:
q – heat flux,
T – temperature [K],
λ – heat conductivity [W/(mK)].

The following was obtained using the heat balance equation:

$$c\dot{T} - \lambda\Delta^2 T = W \tag{2}$$

where:
W – internal heat source power [J/(m³ ·s)],
c – heat capacity [J/m³K].

In the case of no internal heat source: $W = 0$. This leads to:

$$c\dot{T} - \lambda\Delta^2 T = 0 \tag{3}$$

$$c\dot{T} = \lambda\Delta^2 T \tag{4}$$

$$\frac{c}{\lambda}\dot{T} = \Delta^2 T \tag{5}$$

By introducing thermal diffusivity $\alpha = \frac{\lambda}{c}$, the following equation is obtained:

$$\frac{1}{\alpha}\dot{T} = \Delta^2 T \tag{6}$$

Equation (6) shows that this problem is governed by one material parameter, thermal diffusivity $\alpha = \lambda/c$ [m^2/s].

According to [3] thermal effects have great importance for hydrotechnical concrete structures. Changes in the concrete temperature caused by annual variation in the water and air temperatures are the main source of deformation of such structures. It's worth mentioning that heat flow in gravity concrete dams is an example of an unsteady flow. As mentioned in [1], a thermal analysis must be performed to predict the cracking response of the concrete.

According to [1], the heat conductivity of the concrete is not a constant material property, it depends mainly on aggregate volume fraction and moisture condition.

So a proper estimation of the concrete's thermal parameters must be performed before any thermal and mechanical analysis of the concrete structure under thermal influence.

2. Numerical experiment

Numerical simulations of the heat flow in a concrete rod (50 cm long, 10 × 10 cm square in plane – Fig. 1) isolated with 10 cm Styrofoam were performed.

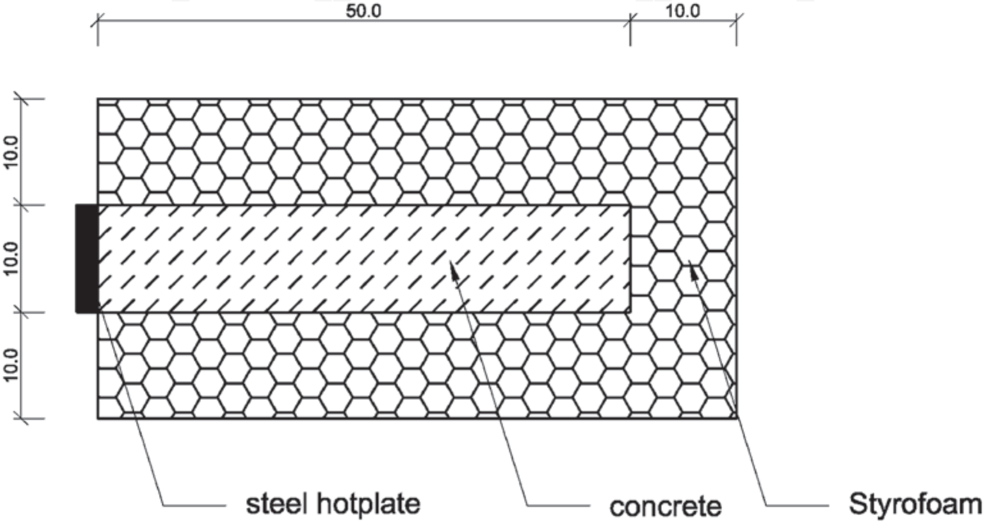

Fig. 1. Analysed concrete rod with Styrofoam heat isolation (dimensions in cm)

The experiment described in [6] was simulated. The initial (first estimate) values of material properties for the concrete are summarized in Table 1.

Table 1

Initial set of heat flow parameters for concrete based on sandstone aggregate

Source	λ [W/(m · K)]	*c* [kJ/(m³K)]	α [m²/h]
A.M. Neville „Właściwości betonu” (Eng: Properties of concrete)	2.9	2016–2808	$3.718 \cdot 10^{-3}$ $5.1798 \cdot 10^{-3}$
Standard PN-91/B-02020 – Ochrona cieplna budynków (Eng: Thermal protection of buildings)	1.8	2016	$3.214 \cdot 10^{-3}$

The experiment described in [6] shows that 10 cm thick thermal isolation consisting of Styrofoam leads to one-dimensional heat flow (no heat flow in the direction perpendicular to the axis of the rod). Such observation was verified during numerical simulations. In the 3D model, a Styrofoam isolation layer was introduced and a convection boundary condition on the outer surface of the isolation was used. In the 1D model, the Styrofoam layer was not introduced and “no heat flow” boundary condition on the outer surface of the concrete was used. In both models, the temperature boundary condition was used at the steel hotplate, describing the temperature change program used in the experiment described in [4].

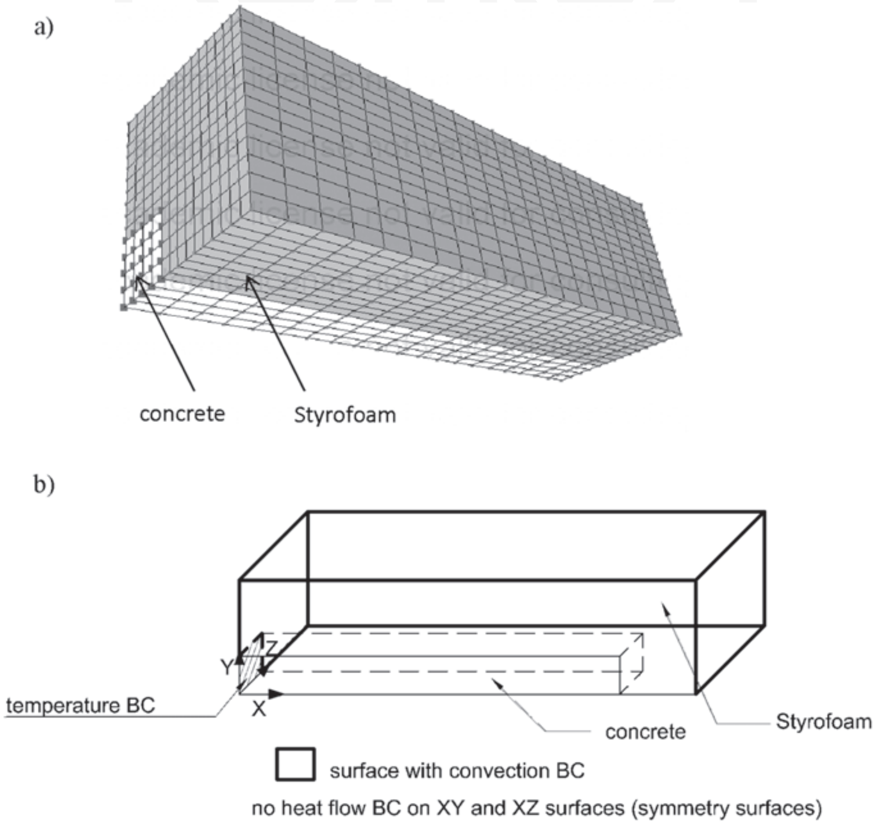

Fig. 2. 3D model a) overview b) boundary conditions

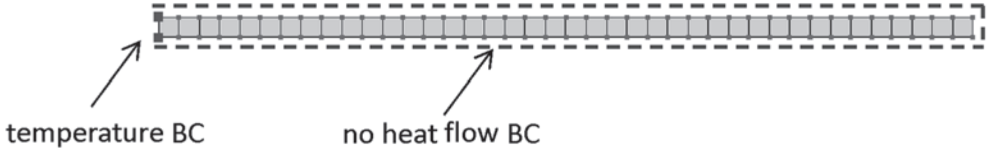

Fig. 3. Overview of the 1D model, with boundary conditions

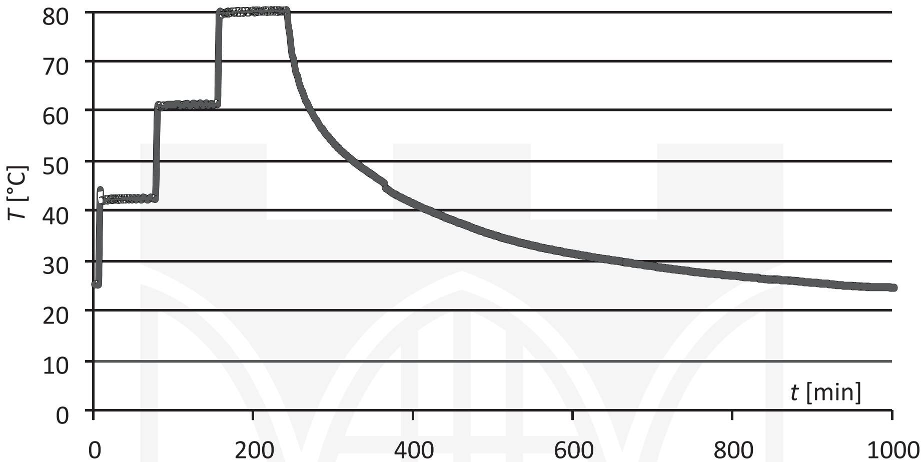

Fig. 4. Boundary condition at the steel hotplate – temperature changes in time

The results obtained show almost no difference between the 1D and 3D models for the obtained temperature field – the differences do not exceed 2°C. Hence, the 1D model is used in this paper from this point.

Then, the calculations for different values of thermal diffusivity α were performed to obtain a good correlation between numerical and experimental results (temperature field). The best correlation (minimum of sum of the squares of the temperature differences) was obtained for $\alpha = 2.441^{-3}$ m^2/h, which is a lower value than was suggested in [1] or [5]. The time-space temperature distribution obtained for $\alpha = 2.441^{-3}$ m^2/h are presented in Fig. 5–7. Comparison of the calculation results with measured temperatures shows a relatively good correlation in the heating phase, much worse in the cooling phase. The delay in the obtaining maximal temperature observed, especially for points located far from the cooling plate, shows that the observed heat flow is really transient. Maximum temperature drops down from 80°C at the hotplate to 31°C at a distance of 30 cm. As can easily be seen in Fig. 7 the location of the maximal temperature migrates from its location at the hotplate during the heating phase to a point located 20 cm from the hotplate in about 800 min.

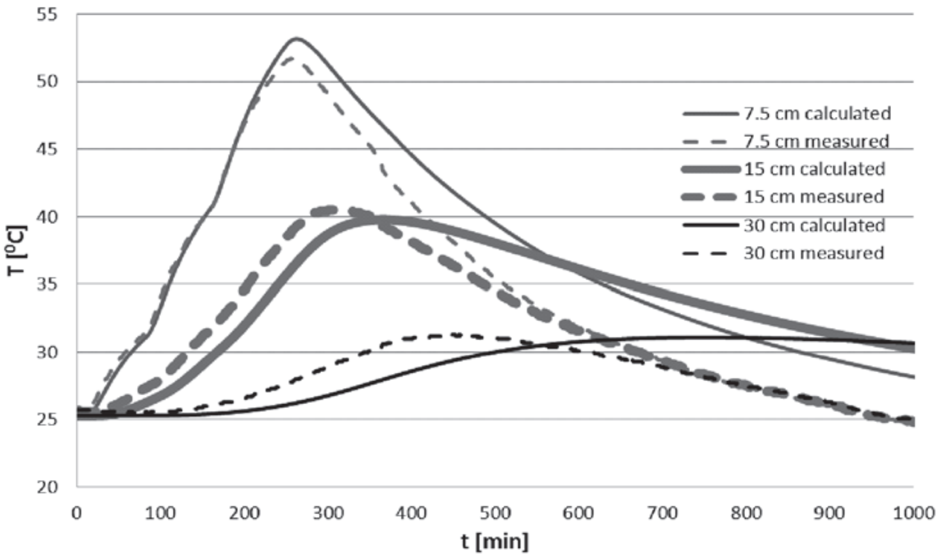

Fig. 5. Temperature changes in time at a different distance from the hotplate for α = 2.441^{-3} m²/h

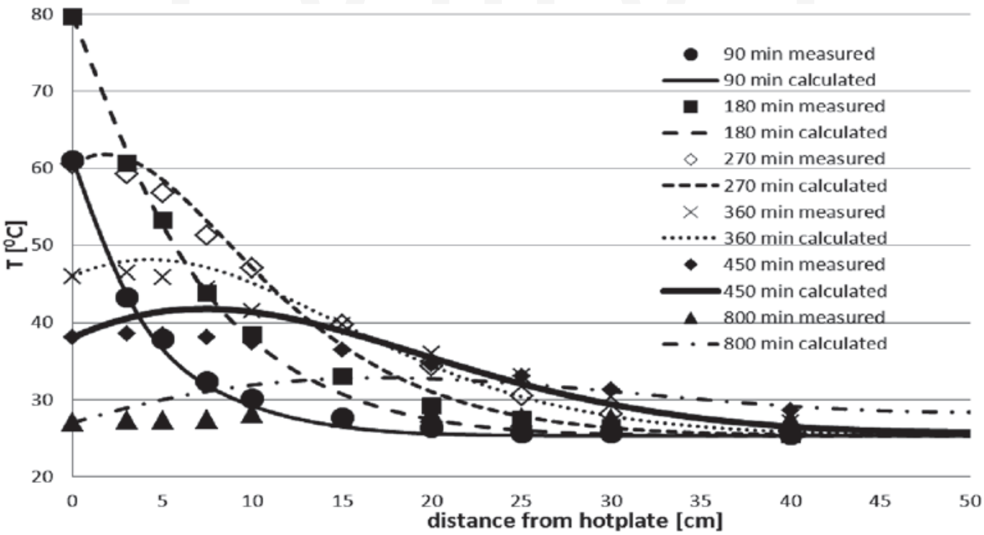

Fig. 6. Temperature distribution along the rod for different time instants for α = 2.441^{-3} m²/h – calculated (lines) and measured (points)

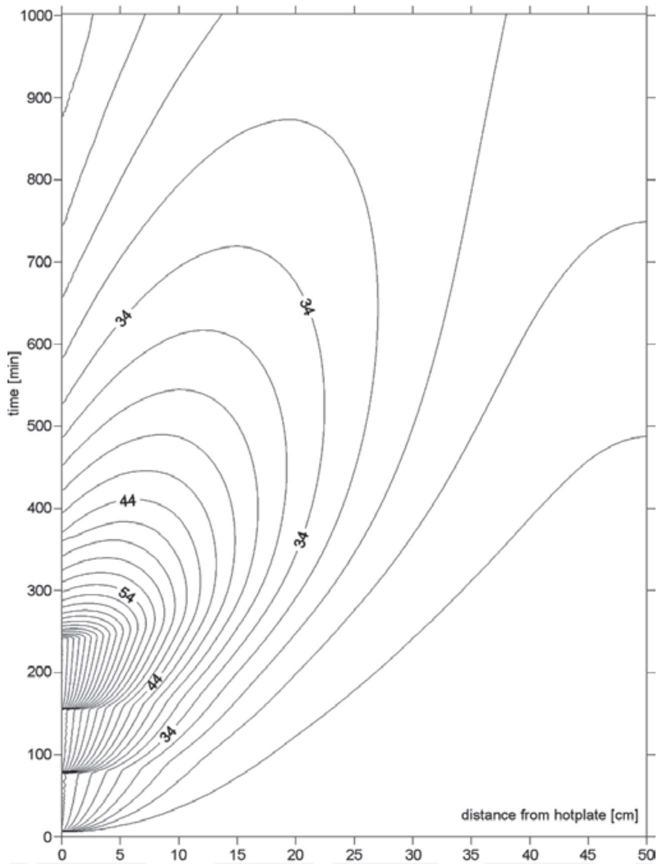

Fig. 7. Time – space temperature distribution – isolines of the calculated temperature [°C] for $\alpha = 2.441^{-3}$ m^2/h

3. Final remarks

The temperature distributions obtained from the numerical simulations show much better correlation with experimental values in the heating phase than in the cooling phase. In the cooling phase, the reaction of the numerical model is slower than it should be (compared to experimental results). This observation raises the question of whether heat conductivity has the same value when the concrete temperature rises and when it falls. No cracking during the cooling phase and no air humidity changes (which could have an influence on the heat flow) were observed in the real experiment. However, the maximum difference in obtained temperature does not exceed 6°C, which is quite acceptable. The maximum temperatures in different points of the rod are also properly estimated in the model.

References

[1] Kook-Han K., Sang-Eun J., Jin-Keun K., Sungchul Y., *An experimental study on thermal conductivity of concrete*, Cement and Concrete Research 33 (2003) 363–371.

[2] Neville A.B., *Właściwości betonu (Eng. Characteristics of concrete)*, Wyd. 4, Polski Cement Sp. z o.o., 2000.

[3] Urbański A., *Numerical modeling of thermal, filtration and mechanical phenomena in a selected section of a gravity dam*, Numerics in Geotechnics and Structures 2010, 93–108.

[4] Zając B., *Laboratory testing of transient heat flow in concrete*, in this issue of Technical Transactions.

[5] Polish standard PN-EN ISO 6946 Komponenty budowlane i elementy budynku Opór cieplny i współczynnik przenikania ciepła. Metoda obliczania, 1999 (Eng. Building components and elements of the building. Thermal resistance and heat transfer coefficient. The method of calculation)

[6] *"Z_Soil.PC, Theoretical Manual"*, ZACE Services Ltd., Lozanna 2014.