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Identification of thermal properties of hardening concrete by means of evolutionary algorithms

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In this paper, the evolutionary computation procedures for identifying thermophysical properties in hardening massive concrete structures are presented. The heat of cement hydration, thermal conductivity and specific heat are determined for the purpose of modeling temperature evolution in massive concrete elements. Knowledge about temperature fields is very important due to their link with undesirable thermal stresses that can cause a weakening of structures because of thermal cracking. The proposed method is based on point temperature measurements in a cylindrical mould and the numerical solution of the inverse heat transfer problem by means of the finite element method and evolutionary computation.

Keywords: thermal properties of concrete, inverse heat transfer problem, early age concrete, evolutionary algorithm, FEM.

1. Introduction

Properly determining the thermophysical properties of hardening concrete plays a key role in building correct models of concrete structures. The problem is difficult due to the complexity of the process of transforming concrete mix into hardened concrete and its changing properties over time. High temperature gradients associated with exothermic chemical reactions of cement hydration may occur between the interior and the surface at the early age of concrete, when its strength is low [12]. Cracks occur when temperature gradients cause tensile stresses, which exceed the tensile strength of the young concrete. Thermal distortions have greater influence especially on the stresses affecting massive structures with specific characteristics [9]. Enlarging the cross section of massive concrete structures and using stronger cement or increasing the dosage all lead to increased stress.

In cases of restriction of deformation capacity cracking may be produced. The way in which individual structural elements of a massive concrete structure are connected plays an important role here.

For construction of concrete blocks such as dams, foundations and bridgeheads, foundation slabs, etc. concrete should be used that guarantees high durability, minimizes the formation of traces of thermal gradients and provides a small amount of heat generated by hydration. This is of significant importance when constructing radiation shielding structures in nuclear power plants or other nuclear facilities. Such massive containment structures are designed to restrict the spread of radiation and radioactive contamination to the public [1, 5, 6, 8, 11], therefore no cracks in concrete are acceptable. In such critical applications, the temperature field in hardening concrete should be determined, and limits imposed on the temperature development to prevent early-age cracking.

The causes of damage in hardening concrete are related to different mechanisms, depending on the strength-development phase after the final setting of cement. The first phase is defined as 6–8 hours for fresh concrete. During this time, plastic shrinkage is caused by the concrete mixture settling. The second phase concerns young concrete. During the time from 6–8 hours up to 24–48 hours the damages can be caused by stress due to a non-homogeneous temperature field and humidity in concrete pores. In mid-mass concrete constructions, forced stresses due to a quasi-homogeneous cycle of temperature changes can be observed. After 24–48 hours, concrete undergoes a hardening phase which in massive structures causes stresses by quasi-homogeneous cycles of temperature variations, as well as stresses induced by shrinkage and chemical processes. However, the described phenomena associated with the kinetics of hardening are very much dependent on the composition of cement [2].

Thermophysical characteristics of concrete are described by: thermal conductivity, specific heat and heat of cement hydration (reaction of cement with water), which evolve during hardening and depend on the maturity of concrete. In practice, such parameters can be determined by means of different experimental measurements (e.g., calorimetric), a hot plate apparatus and several transient dynamic techniques. Thermophysical characteristics are identified in this paper by minimizing the norm between measured and computed values of temperature. The minimization procedure is performed by means of an evolutionary algorithm (EA). EA, as a global optimization technique for searching parameters describing thermophysical properties of hardening concrete, is applied. When compared to conventional optimization methods, the superiority of EA is evident in many aspects. For example, a fitness function does not have to be continuous, information about the objective function gradient is not necessary, choice of the starting point may not influence the convergence of the method, and regularization methods are not needed [10, 11]. Applications of EA to identification problems give a great probability of finding an optimal global solution.

2. Formulation of identification problem

From a mathematical point of view, the identification problem is expressed as the minimization of the defined functional. The following functional has been proposed:

$$\min_{\mathbf{x}} \; f(\mathbf{x}) = \sum_{i=1}^{n}\sum_{i=1}^{m}\left(T_{ij}(\mathbf{x}) - \widehat{T}_{ij}(\mathbf{x})\right)^2, \tag{1}$$

where n is the number of sensors, m is the number of time intervals, T_{ij} and $\widehat{T}_{ij}$ respectively represent computed and measured temperature values in a particular point in time and space, while $\mathbf{x}$ is the vector of design variables.

The vector of design variables $\mathbf{x}$ contains parameters that define heat of hydration, specific heat and thermal conductivity. The identification problem is solved by finding the vector of design variables $\mathbf{x}$ by minimizing the functional (1). In-house implementation of EA, with the floating-point gene representation is used. The solution of this problem is given by the best chromosome whose genes represent design. The general flowchart of EA is presented in Fig. 1.

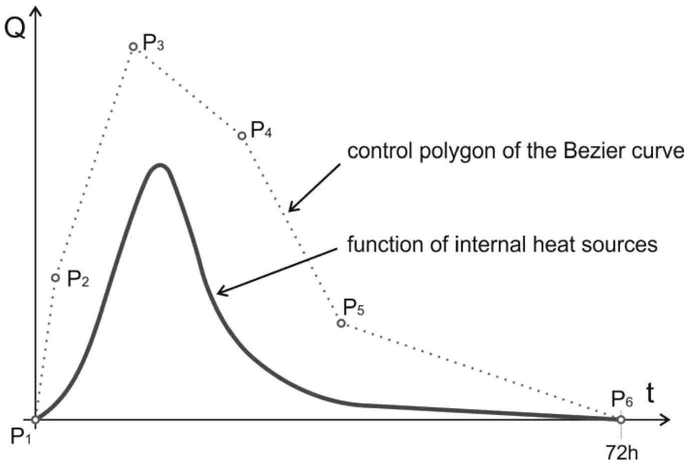

Fig. 1. The method of parameterization of the heat of cement hydration.

The transient heat conduction equation in hardening concrete is defined in the following form:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q=\rho c_p\frac{\partial T}{\partial t}, \tag{2}$$

where T – temperature of concrete [K], k – thermal conductivity [W/m K], x, y, z – spatial coordinates, q – internal heat source [W/m^3], t – time [s], ρ – density of concrete [kg/m^3], c_p – specific heat of concrete [J/kg K].

Equation (2) allows to calculate the temperature in time and space, including proper definition of internal heat sources. Such sources represent the time rate of heat evolution by the hydrating cement.

As mentioned previously, identification of the thermophysical parameters of the hardening concrete concerns: thermal conductivity, specific heat and the heat of cement hydration. Several researchers have assumed the first two parameters to be constant or linearly changeable during the process of hardening. In this study, thermal conductivity and specific heat are assumed to be constant, and therefore one design variable is needed to represent each of these parameters. The heat of cement hydration evolves during the hardening of concrete. At the beginning of the process, the exothermic reaction of cement hydration rapidly rises and then slowly decreases. The moment of release of the maximum amount of heat can vary for different concrete mixtures. For example, for concretes with calcareous fly ash, the time of maximum temperature occurrence shifts and the peak value decreases as well. To properly model the internal heat sources, parametric (Bezier) curves are used. This approach allows very flexible representation of this function, even for a small number of control points. A Bezier curve of the fifth order is used for modeliing the function of internal heat sources. Coordinates of the four control points (P_2–P_5) are the design variables, which are responsible for the shape of the curve (the first and the last point of the control polygon are fixed). Figure 1 shows the method of parameterization of the heat of cement hydration.

3. Experimental measurement

The temperature distribution in time was measured in a thermally-isolated cylindrical mould of a 96 mm inner diameter and 500 mm height filled by the maturing concrete [7]. The mould was made of PVC and was specially developed for the tests. It was insulated with two layers of 10 mm polyethylene foam with closed cells. The top of the test cylinder was left open and covered only with thin polyethylene foil to prevent a loss of moisture from the concrete. Due to the arrangement of the insulation around the test cylinder, the heat generated during the hydration of the cement was dissipated in the predominant majority by the non-insulated upper surface. This way, a one-way flow of heat was achieved in the sample. The sensor points, where temperature is measured (temperature detectors), are located along the longitudinal axis of the cylindrical concrete specimen. Figure 2 shows the schema of the mould with the positions of temperature sensors.

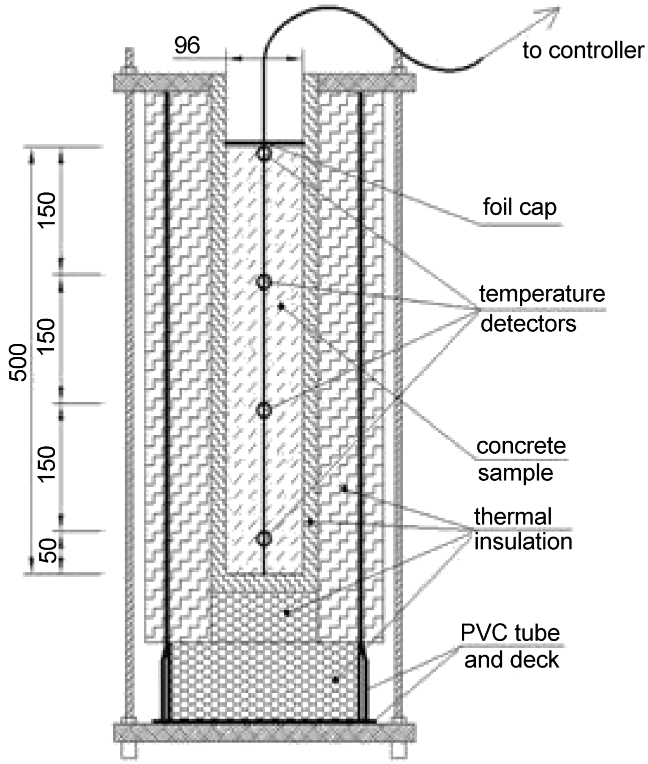

Fig. 2. Model of the mould.

The temperature sensors were placed along the central axis of the mould at 50 mm, 200 mm, 350 mm and 500 mm across the bottom. The temperature of ambient air was also measured with the fifth sensor placed near the top of the mould. The testing equipment was kept in a room where the average temperature oscillated around 22°C and its daily fluctuations were in a range of 3–4°C. The test lasted up to 72 hours after filling the mould with concrete.

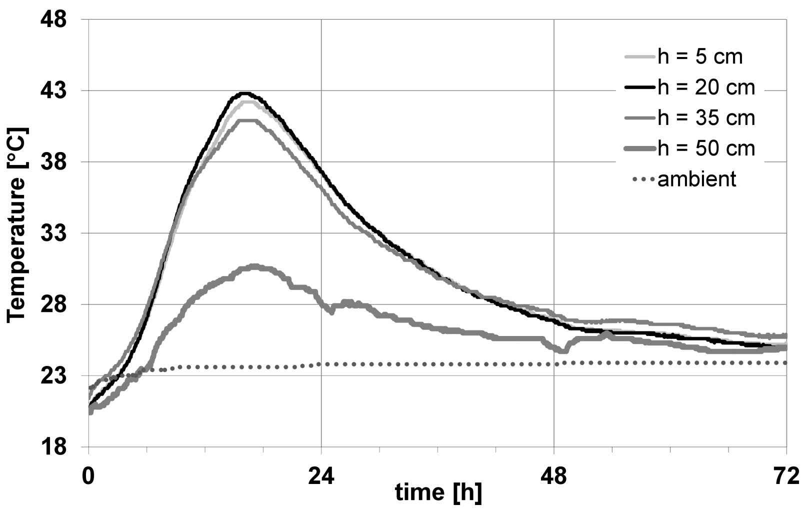

Fig. 3. An exemplary temperature record.

A specially built controller and interface were used to transmit measurement data to a PC set. After finishing measurements, the recorded values from the sensors were averaged for every 60 seconds, and on this basis the temperature values were calculated with an accuracy of 0.1°C. An example of temperature recording is shown in Fig. 3. The obtained results were used to determine the thermal parameters of the hardening concrete: specific heat, thermal conductivity and heat source function values.

4. Numerical model and identification algorithm

The problem of transient heat conduction was solved by means of FEM [13]. A two-dimensional numerical model of the hardening concrete specimen (described in the previous paragraph), consisting of 200 elements was prepared (Fig. 4b). Four-node quadratic elements with linear shape functions were used.

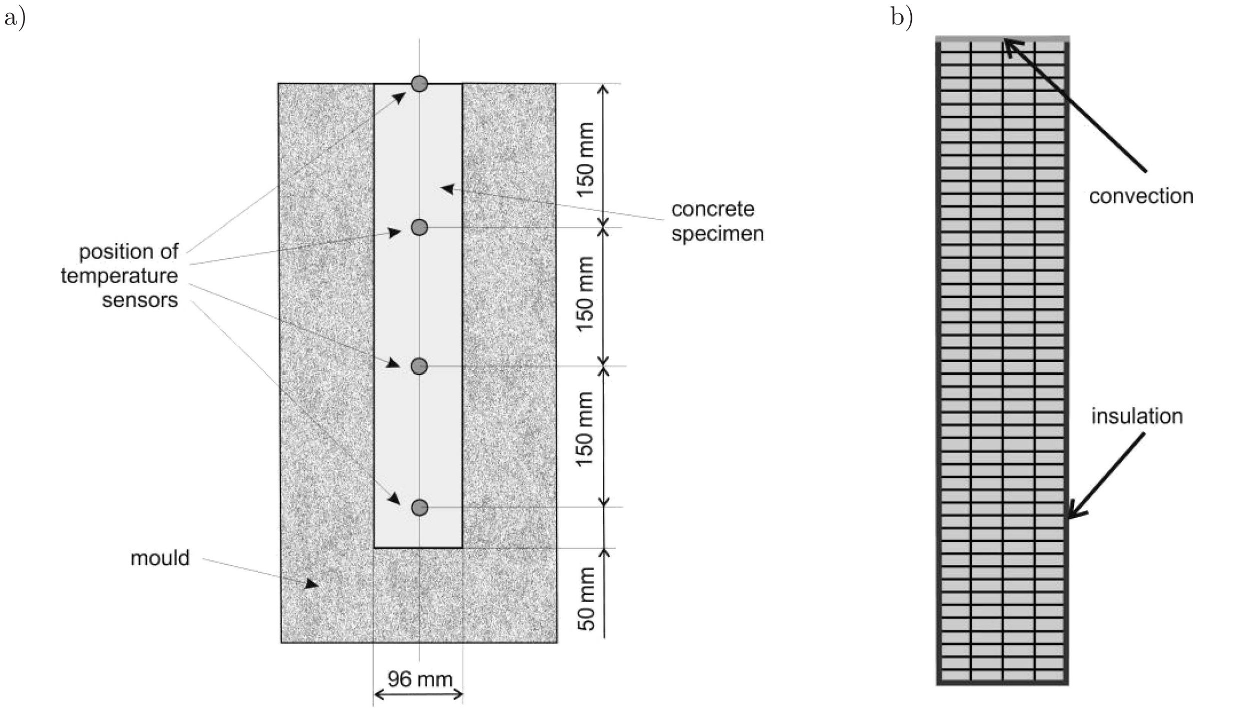

Fig. 4. a) Model of concrete specimen, b) two-dimensional (2D) numerical model with boundary conditions.

Adiabatic boundary conditions were applied on the left, right and bottom segments of the boundary, whereas on the upper part, a third type thermal boundary condition was applied (convection). An initial condition for the temperature was equal to 20°C. The time of the analysis was 72 and 90 hours for the validation of identification method and the real identification data respectively. The values of the temperature in the nodes which correspond to the location of the sensors (Fig. 4a) were used for calculation of the identification functional (1).

Figure 5 presents a flowchart of the identification algorithm. It consists of two main parts: the block of EA and the block of the fitness functional calculation.

An in-house implementation of EA (genetic algorithm with floating point representation) was used. The following evolutionary operators were implemented: uniform, boundary and Gaussian mutation, simple and arithmetic crossover, and rank selection method. This algorithm was tested on several mathematical benchmark problems and real engineering problems as well, obtaining satisfactory results [3, 4]. To calculate the identification functional, FEM commercial software MSC Mentat/Marc was adopted. Application of the preprocessor of such software as well as solver was

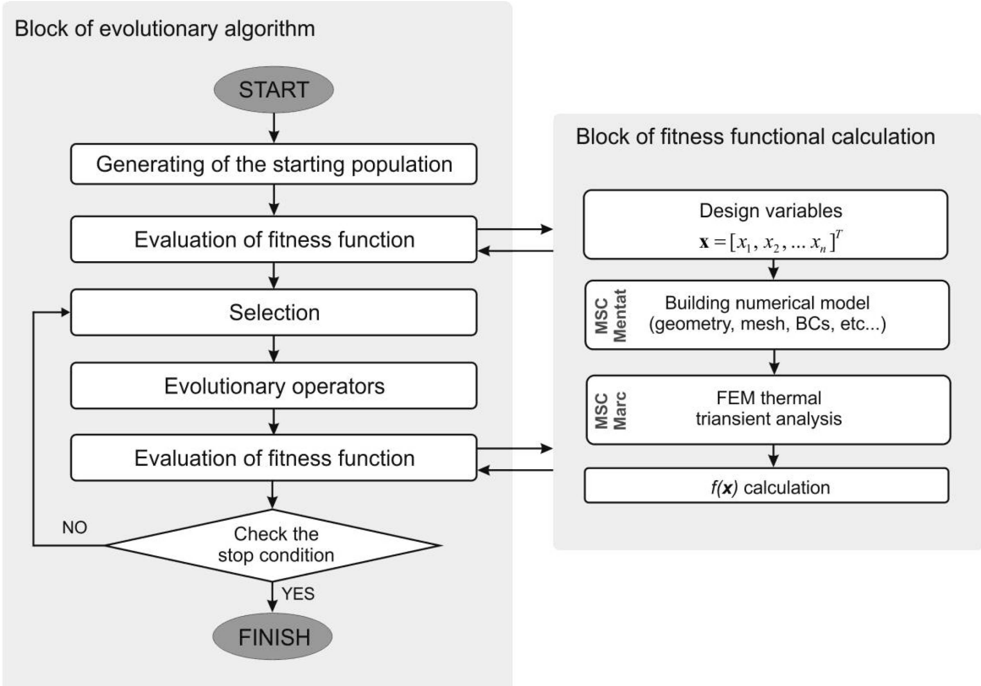

Fig. 5. Flowchart of the identification algorithm.

used. This allowed for generation of all steps for solving the boundary-value problem automatically. Such an approach required preparation of the additional procedures by means of internal script language (implemented in preprocessor module) and additional procedures in C++. The numerical model of the concrete specimen is very simple, while the proposed method is very flexible and allows for solving the boundary-value problem with complicated geometry and boundary condition relatively easily.

The proposed identification algorithm was verified on the test example, before it was used to identify thermophysical parameters based on real experimental data. Ten design variables for the test example are assumed. The thermal conductivity and specific heat are the first two parameters. The remaining ones are responsible for the parameterization of the heat of cement hydration (the method was described in Sec. 2). The parameters of EA are as follows: population size – 50, number of generations – 200, probability of Gaussian mutation 0.7, probabilities of uniform mutation, simple and arithmetic crossover – 0.1, and rank selection pressure – 0.3. Several numerical tests were performed, whereas the results presented in the paper are for the best run. The fitness function evolution of the best individual test, presented in Fig. 6b, is rather typical, where great changes of fitness function value occurs at the beginning of the test. Table 1 contains a comparison between actual and identified values of thermal conductivity and the specific heat, whereas Fig. 6a presents a graph for the heat of cement hydration.

Comparison between actual temperature (solid lines) and identified temperatures (dotted lines) in the sensor point of temperature is presented in Fig. 7. The mean square error for the test is equal to 0.03846°C.

Table 1. Comparison between actual and identified values of thermal conductivity (k) and the specific heat (c_p).

Parameter	Actual	Found	Error
k [W/m K]	1.7	1.72	1.26%
c_p [J/kg K]	950	1019.3	7.3%

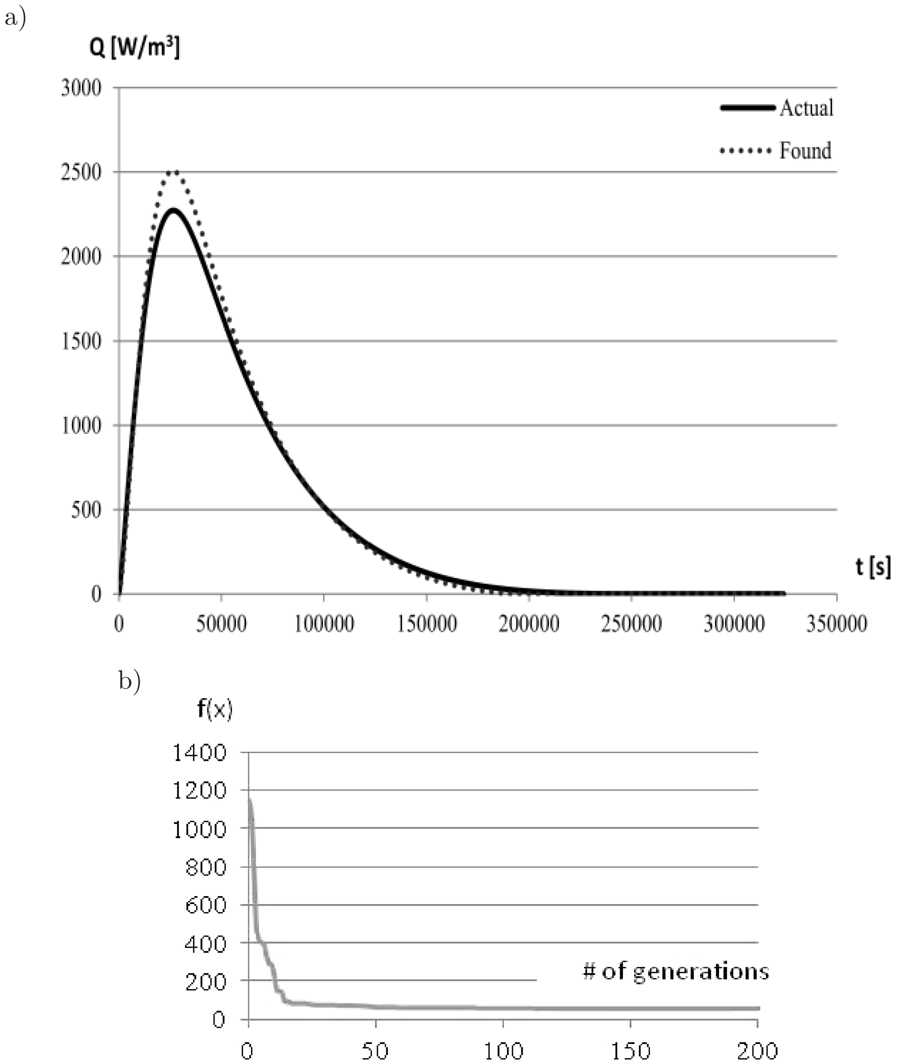

Fig. 6. a) Comparison between actual and identified function of heat of the cement hydration, b) graph of the fitness function value at consecutive generations.

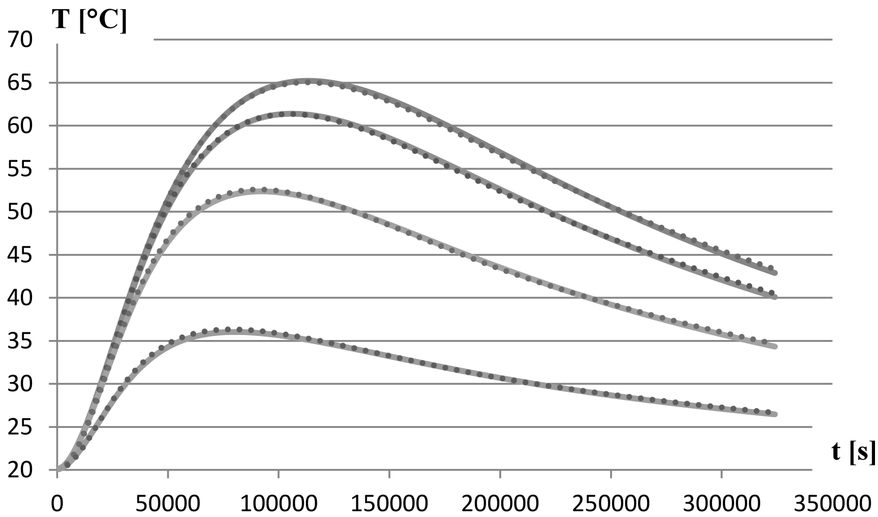

Fig. 7. Results for the verification test. Actual temperature (solid lines) and identified temperatures (dotted lines) in the sensor point of temperature.

5. Results of identification for experimental data

The proposed method was applied for identification of thermal conductivity, specific heat and the internal heat source for the experimental data. The hardening of the concrete specimen is a long process (90 hours), so additionally, the internal heat source (Q) includes the function of heat losses (Q_{loss}), which models the effect of an imperfect thermal isolation:

$$Q = Q_{\mathrm{hydr}} - Q_{\mathrm{loss}}. \tag{3}$$

The following formula was proposed as a function of heat losses

$$(a + b \cdot \Delta T) \cdot \Delta T, \tag{4}$$

where a and b are coefficients and ΔT is the difference between the temperature of the mixture at a given point and the ambient temperature.

In this work [12], values of such coefficients were estimated on the basis of experiment of cooling heated sand. In this paper, values of the coefficients are treated as unknowns, therefore the total number of design variables for the identification task, when taking into account data from the experiment, is equal to 12.

The identification tasks were performed for experimental data for different concrete mixtures, named T26, T49, T50 and T51. For the first mixture (T26) the density was 2997 kg/m^3, and the limitation for the thermal conductivity and specific heat k and c_p were as follows: k (1.4–2.4) and c_p (500–800). For the mixtures T49, T50 and T51 density was 2303 kg/m^3, whereas limitations were k (2.75–3.75) and c_p (600–900). The total number of generations for EA was equal to 250. Values of the remaining parameters are the same as in the verification test, described in the previous paragraph. Figures 8–11 present results (identified heat of the cement hydration and comparison

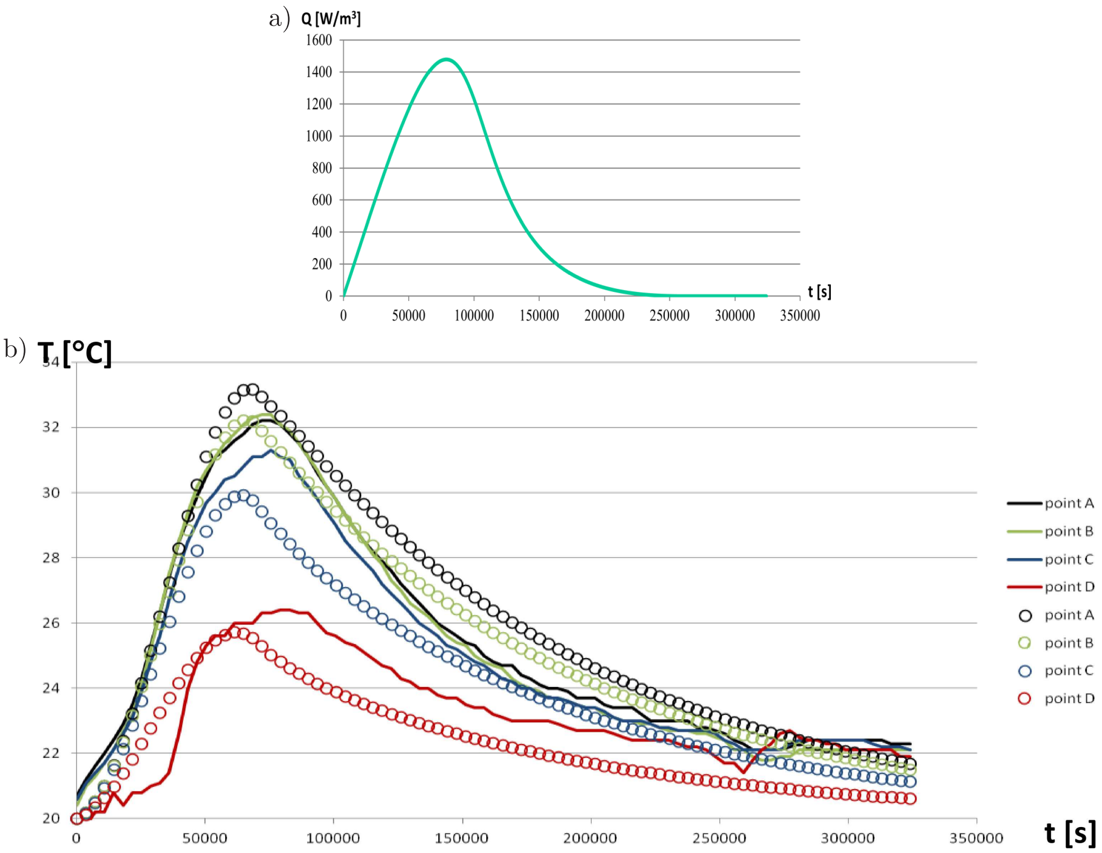

Fig. 8. Results for the verification (mixture T26): a) identified function of the heat of the cement hydration, b) comparison between measured and identified temperatures in the sensor points.

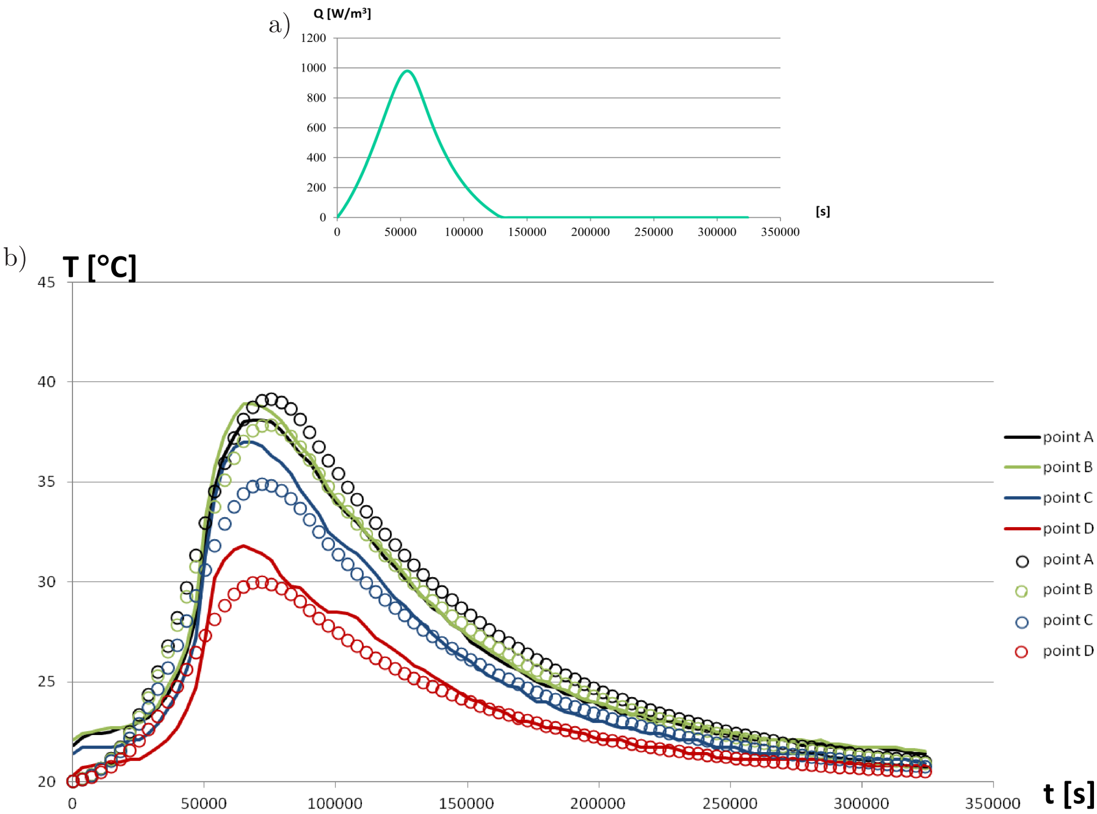

Fig. 9. Results for the verification (mixture T49): a) identified function of the heat of the cement hydration, b) comparison between measured and identified temperatures in the sensor points.

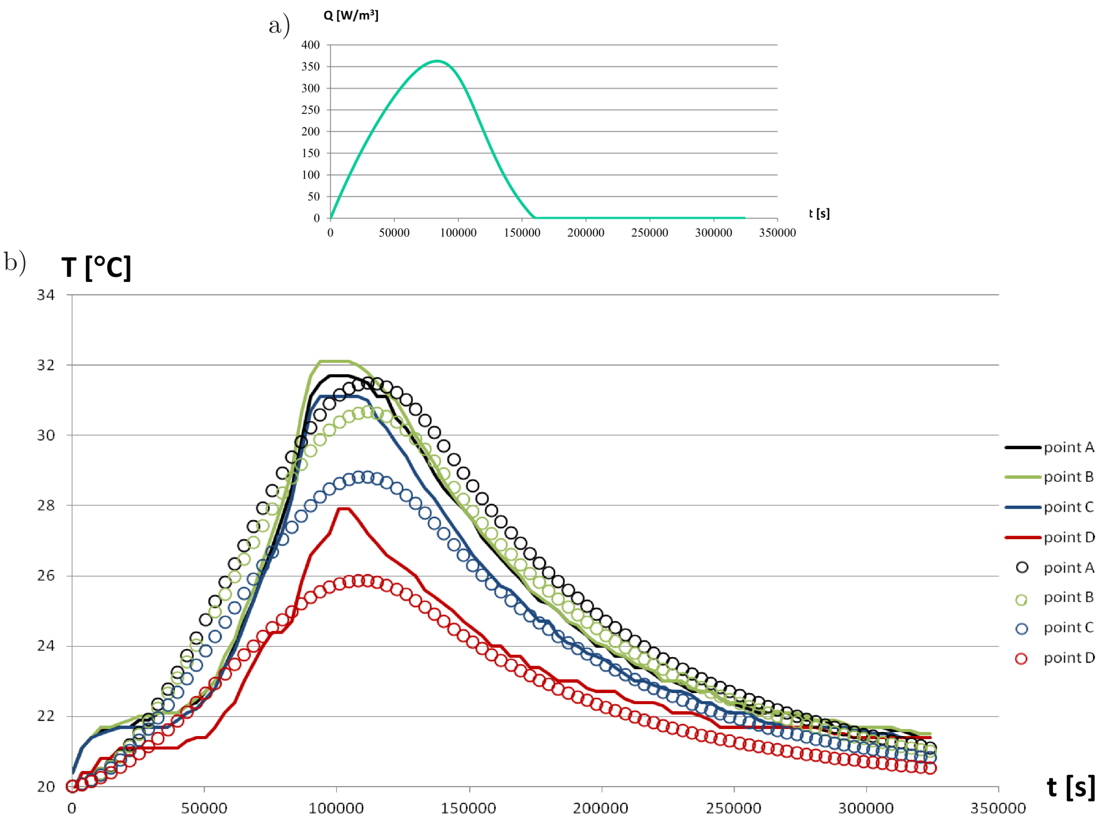

Fig. 10. Results for the verification (mixture T50): a) identified function of the heat of the cement hydration, b) comparison between measured and identified temperatures in the sensor points.

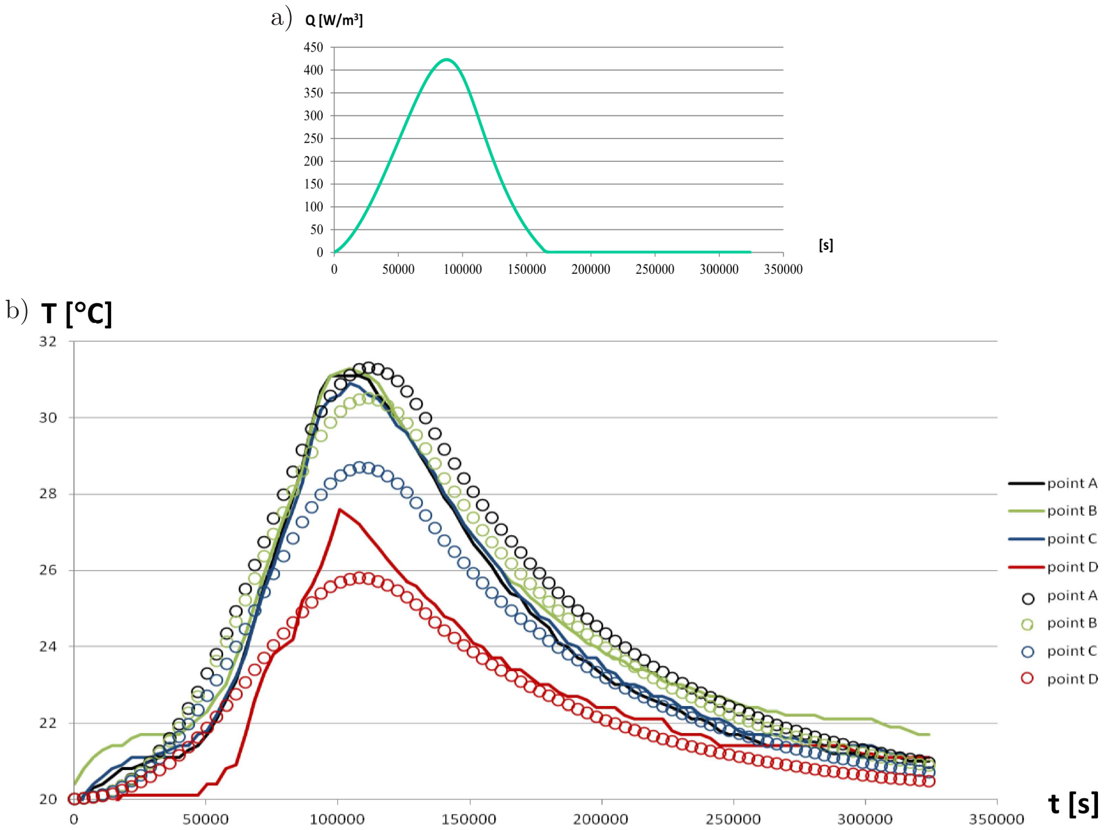

Fig. 11. Results for the verification (mixture T51): a) identified function of the heat of the cement hydration, b) comparison between measured and identified temperatures in the sensor points.

between measured and identified temperatures in the sensor points) of the identification for different concrete mixtures. The mean-square error for concrete mixtures T26, T49, T50 and T51 are 0.909°C, 0.925°C, 0.759°C and 0.615°C, respectively. Table 2 includes the identified values of thermal conductivity (k), the specific heat (c_p) and coefficients for the function of heat losses (a, b) – Eq. (4) for the different concrete mixtures.

Table 2. Identified values of thermal conductivity (k), the specific heat (c_p) and coefficients for the function of heat losses (a, b) – Eq. (4) for different concrete mixtures.

Parameter	T26	T49	T50	T51
k [W/m K]	2.4	3.75	3.75	3.75
c_p [J/kg K]	555.5	600	622.1	600
a	36.883	14.729	6.784	10.314
b	0.586	0.031	0.01	0.01

6. Concluding remarks

This paper is devoted to identification of thermophysical properties of hardening concrete. The inverse problem was solved by minimization of the functional, which represents a norm between calculated and measured values of temperature. The minimization problem was solved by means of EA. Application of EA in identification of thermal properties of hardening concrete is very useful (no need of regularization of fitness function, no need of calculation of the gradient of fitness function, or resistance for stacking in local minima). Parameterization of the heat of cement hydration by means of Bezier curves provides flexible manipulation of the cure and can significantly reduce the total number of design variables. Results of identification for the test verification problem are very good (mean-square error is 0.03846°C). For the real experimental data identification, results are satisfactory – mean- square error for all concrete mixtures did not exceed 1°C.

The model of the hardening concrete specimen was considered as 2D. In the future an axisymmetric model of the specimen will be taken into account.

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