Identify heat of hardening and transient thermal properties in concrete structures

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New technique of diagnostics of concrete materials based on so-called smart technologies is proposed. Method can be divided into three parts: i) online temperature measurement during hardening of concrete in specially prepared one dimensional mold; ii) solution of an inverse problem allowing identification of crucial, thermophysical material properties (especially heat of hardening) for reliable simulation of its further behavior; iii) accurate, multi-physic numerical modeling of maturing process in 2D and 3D cases based on own finite element method code to predict the probability of thermal crack generation; The combination of these three modules consist of software tools, hardware sensing system and some optional algorithms. The proposed method may be useful for monitoring and quality control of massive concrete structures. The results of the model are verified experimentally, this paper presents results for concretes with fly ashes for 2D case.

1 INTRODUCTION

When cement is mixed with water, a series of exothermic reactions starts (liberated heat is called heat of hydration), but when we add admixture, reactions become more complicated, and liberated heat is commonly known as heat of hardening. During hardening, a concrete structure is exposed to a risk of cracking, so identification of parameters is crucial for avoiding thermal cracks. There is no an accuracy model to determine heat of hardening (or heat of hydration) of arbitrary mortar, because it is very difficult to extract the heat generated by any reaction. Using calorimetric tests for individual concrete mixture is laborious and time-consuming. Also the dimensions of the calorimeters not allow measurements of concrete with coarse aggregate. Therefore we decided to develop method based on inverse problem to determine heat of an arbitrary concrete. We construct special, one dimensional form to tests (Fig. 1). In the case of our form we can use concrete vibrators to consolidate freshly poured concrete, which is impossible in calorimetric tests too. Thus, the test concrete is exactly the same as used in the industry.

The proposed technique can be divided into three parts. First the temperature of concrete in prepared samples is recorded for three days by data acquisition system constructed in IPPT. Next the inverse problem is solved. We tested gradient and non-gradient optimization techniques to choose the best one for our problem, and we decided to use pattern search algorithm which does not require functions to be differentiable or continuous. Next, on the basis of determined parameters we could predict temperature field and areas at risk of cracking in concrete in higher dimensions cases. For this purpose own finite element code implemented in Matlab is used.

In the next paragraphs the measurement method is presented and the inverse and direct problems are formulated. Last experimental and numerical results with conclusions are presented.

Nomenclature			
A	area	q	function defining the boundary condition
∂A	boundary of A	ρ	density
α	thermal diffusivity	S	heat of hardening
a, b	parameters	$s = S/(\rho c_p)$	source term
c_p	specific heat capacity	T	temperature
∇	del operator	t	time
e	fitting error	T^e	temperature from experiment
k	thermal conductivity	T^m	modeled temperature
N_i	interpolation functions	x, y	spatial variables
p	function defining the boundary condition	$\lVert \cdot \rVert$	Euclidean norm

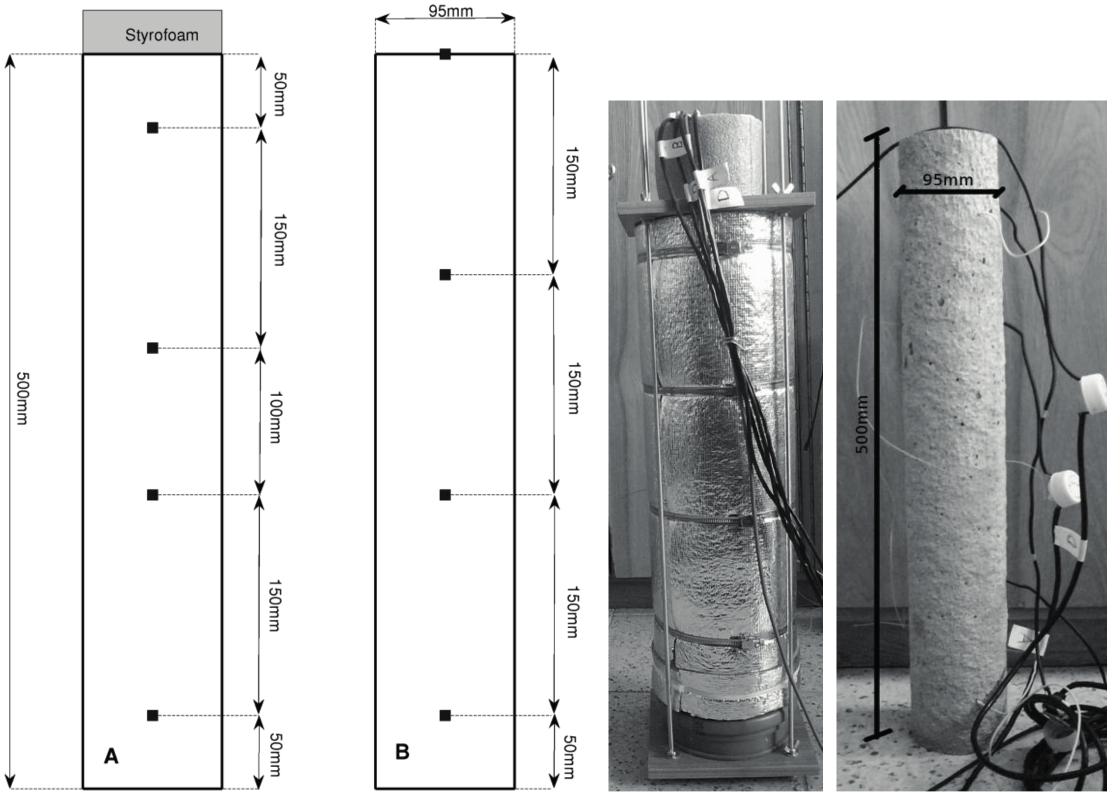


Figure 1. Location of temperature sensors in so called A and B procedure (left). One dimensional measuring form and concrete batch after measurement (right).

2 METHOD

2.1 Temperature measurement

We use two molds with different insulations conditions, that the model was better conditioned. We call them procedure A and B. In procedure A the form is closed at the top by styrofoam stopper, while in procedure B there is free exchange of heat with the ambient. Nine temperature sensors are used: 8 for online temperature measurement of concrete during hardening process (four in each mold) and one for measurement temperature of ambient. Data is recording every two seconds by data acquisition system (Fig. 2) and then is smoothed using a moving average procedure. Finally preprocessed data is using by main optimization procedure.

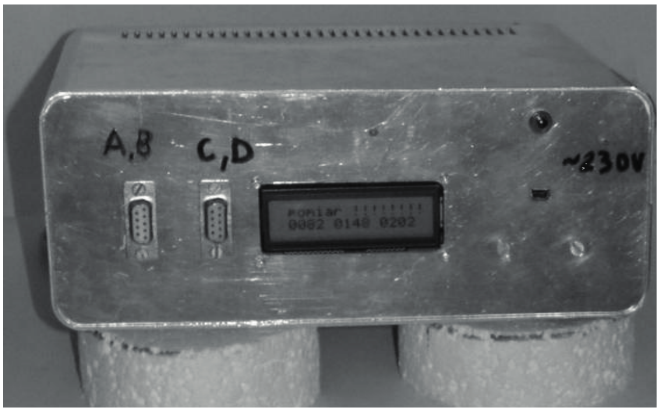


Figure 2. Data Acquisition System

2.2 Inverse problem

Temperature field in hardening concrete can be described using Fourier Law (Carslaw 1959):

$$\rho c_p \frac{\partial T}{\partial t} - \nabla(k \nabla T) = S \tag{1}$$

In one dimensional form transient heat conduction can be expressed as:

$$\frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \alpha \frac{\partial T}{\partial x} = s \tag{2}$$

with specified boundary and initial conditions:

$$T(x, t = 0) = T_0(x) \tag{3}$$

$$p(x, t, T) + q(x, t) \frac{\partial T}{\partial x} = 0 \tag{4}$$

For one dimensional case equation (2) is solved using Matlab pdepe procedure, which realize finite difference method (Skeel 1990). Functions α and s are parametrized by linear interpolation functions N_i. Therefore, the inverse problem of estimating these function is reduced to the problem of estimating a finite number of parameters a_i and b_i, where the number of parameters is chosen in advance. Explicit formulation of these functions can be expressed as follows:

$$\alpha = \sum_i a_i N_i \tag{5}$$

$$s = \sum_i b_i N_i \tag{6}$$

Then the inverse problem is solved as a optimization problem:

$$min\ (e) = min\ (\|T^e - T^m\|^2) \tag{7}$$

As mentioned we tested several method to find global minimum of expression (7). For example genetic algorithms, simulated annealing and pattern search. In our opinion pattern search algorithm gives the best results both the speed of convergence and quality of fit. However, other methods are also used (Phillips 2007).

2.3 Direct numerical modeling

A number of models have been proposed to predict the temperature evolution in early age concrete structures (Ilc 2009). We decided to develop our own code, which is coupled with the inverse problem described above. In two dimensional case equation (1) could be expressed in finite element method sense as follows (Bhatti 2005):

$$\iint_A \left(k_x \frac{\partial T}{\partial x} \frac{\partial N_i}{\partial x} + k_y \frac{\partial T}{\partial y} \frac{\partial N_i}{\partial y} + \rho c_p \frac{\partial T}{\partial t} \right) = \iint_A SN_i + \int_{\partial A} p(T, t) \tag{8}$$

(transition between two-and three-dimensional case is straightforward). Equation (8) render equation (1) into an approximating system of ordinary differential equations, which are then

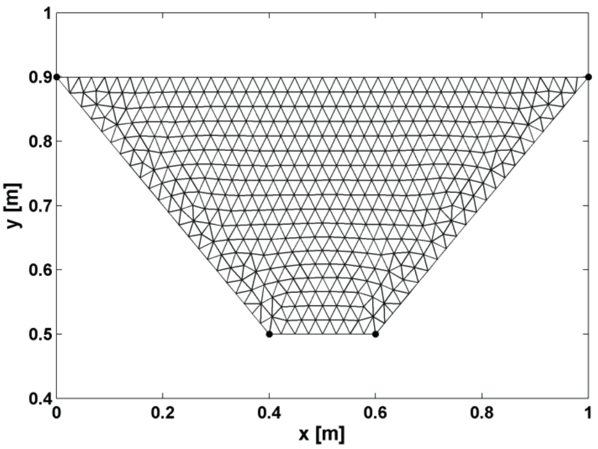


Figure 3. 2D mesh for trapezoidal form

numerically integrated using Matlab ode15s procedure, which is dedicate to stiff differential equations.

In this paper we modeled two dimensional trapezoidal form (Fig. 3), which is under construction now, and soon we will be able to compare model results with measurements.

3 RESULT

3.1 Temperature measurement

Our database contains 12 measurement series. Mortars are composed of typical Polish cement CEM 42.5R, calcium fly ash, sand, coarse aggregate (amphibolite) and tap water. Table 1 shows the composition of mixtures. Each measurement series lasted for 72 hours.

Figure 4 presents typical shape of temperature distribution. The lowest values are obtained at the top of mold B. In deeper parts the temperatures are much higher and quite similar in shape both in A and B procedure. In this case (L-60-30-60 sample) maximum temperature was about 30^{o}C, but in other mortars temperatures reached up to 60^{o}C (L-60-00-00). Generally maximum temperatures depend on the amount of calcium fly ashes and coarse aggregate and decrease with the addition any of them. Also the time of maximum is different for each sample and these relation are not linear. It shows that generated heat is a very complicated function depending on time, temperature, chemical composition etc. Therefore it is impossible to develop general analytical model of heat of hardening.

Table 1. The list of tested concrete with calcium fly ash

Specimen	cement content [% of binder]	sand content [% of binder]	coarse aggregate content [% of mortar]	fly ash content [% of binder]	water/binder ratio
L–60–100–60	0	124	60	100	0.6
L–60–100–40	0	124	40	100	0.6
L–60–100–00	0	124	0	100	0.6
L–60–70–60	30	124	60	70	0.6
L–60–70–40	30	124	40	70	0.6
L–60–70–00	30	124	0	70	0.6
L–60–30–60	70	124	60	30	0.6
L–60–30–40	70	124	40	30	0.6
L–60–30–00	70	124	0	30	0.6
L–60–00–60	100	124	60	0	0.6
L–60–00–40	100	124	40	0	0.6
L–60–00–00	100	124	0	0	0.6

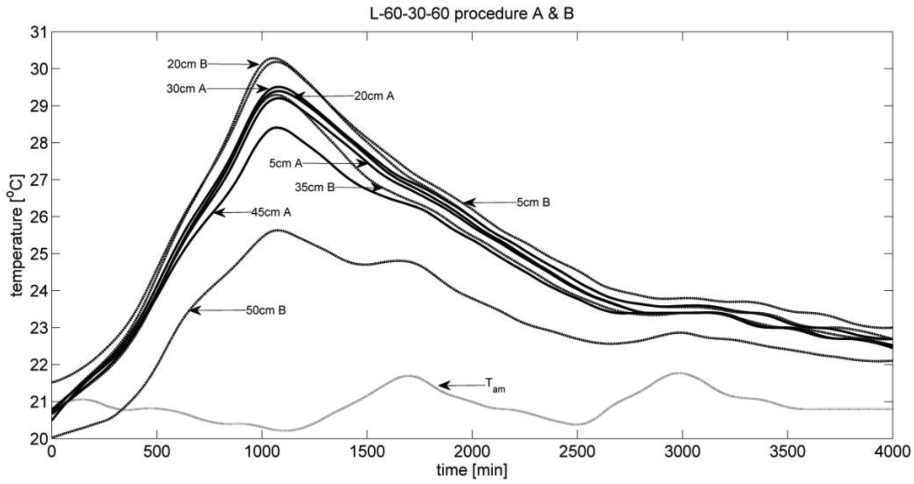


Figure 4. Temperature distribution in L-60-30-60 sample in form A and B.

3.2 Inverse problem

Simulation were performed on computer with AMD Athlon™ II X2 255 Processor and 3.7GB RAM memory. Simulation time is strongly depend on number of parameters to estimate and initial values. Therefore random initial values were ineffective and we decided to estimate in first step heat of hardening as proportional to temperature and thermal diffusivity as a constant. This procedure accelerated convergence. To reduce the number of unknown, temperatures from two external sensor were used as Dirichlet boundary condition. Thus the model was fitted to two internal sensors in each mold. The parameters *a* and *b* were calculated with one hour time resolution in three points in each mold. These points were located in the middle between each two sensors.

Figure 5 shows solution convergence for sample L-60-100-00, the final function value was 59.8, and in our opinion it is a satisfactory result. Comparison of measured and modeled temperature for sample L-60-30-60 shows figure 6a. The differences are small and are easier to see on figure 6b. In this case maximum difference is less than 0.25°C, what is an acceptable accuracy. Generally quality of the fit varied around this level for all studied mixtures. Next figure (fig. 7) shows an example result of estimated heat of hardening for sample L-60-00-00, which is a good qualitative result, comparable with calorimetric measurements. Moreover the thermal diffusivity does not show strong dependence on temperature, but increases with time and decreases with the amount of calcium fly ash.

3.3 Direct numerical modeling

Based on result from inverse problem we could model massive concrete structures in higher dimension. Here is an example for a two dimensional case – a trapezoidal form. The boundary condition were set as insulation on three sides (bottom, left, right) and as nonzero Neumann condition on top. Standard triangular discretization was used (fig. 3). Sample results are shown in the following diagrams. Figure 8 presents the temperature distribution in measurement mold at selected point in time (*t = 1000 min*) and figure 9 shows result for the same case for middle point of trapeze (point *x=0.5m*, *y=0.7m*; compare with fig. 3). Temperature reaches 45°C at ambient temperature around 20°C. Even in this simple case there is a risk of thermal cracks, because the temperature gradients can exceed the critical value and the thermal stresses increase with temperature difference (Fu 2007). So, based on temperature distributions, you can create maps of areas at risk from temperature gradients. This is an important task for the monitoring of construction because the induced thermal cracks (they are often invisible micro-cracks) continue to propagate at later stage.

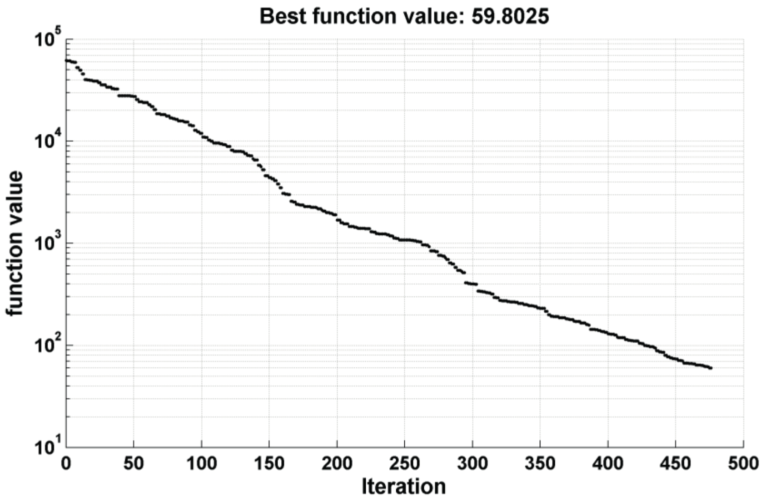


Figure 5. Solution convergence – sample L-60-100-00

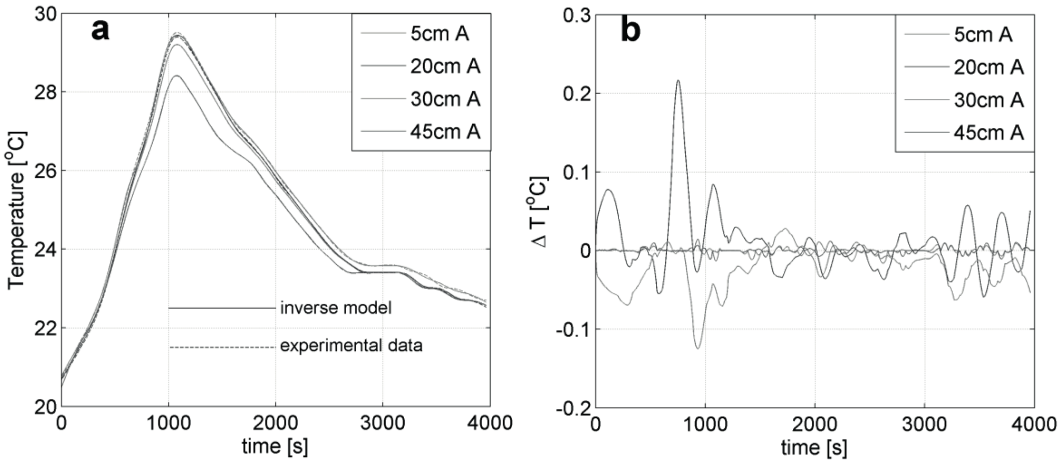


Figure 6. a – comparison of solution and experimental data. b - differences between solution and experimental data. Sample L-60-30-60.

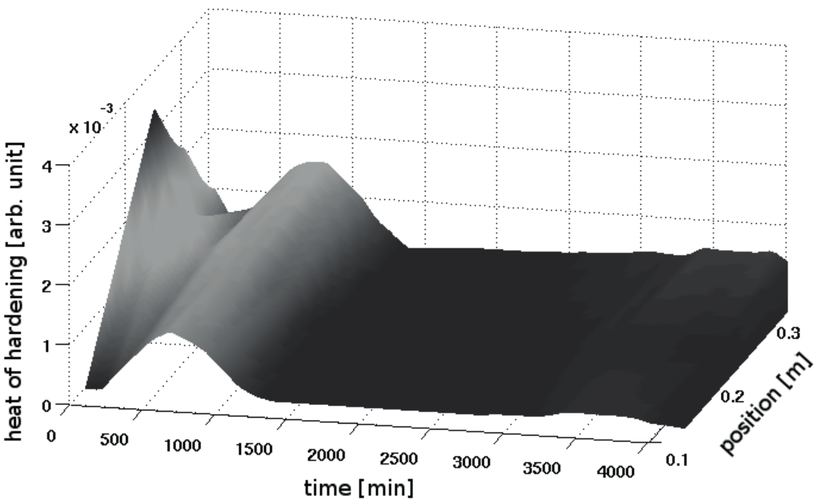
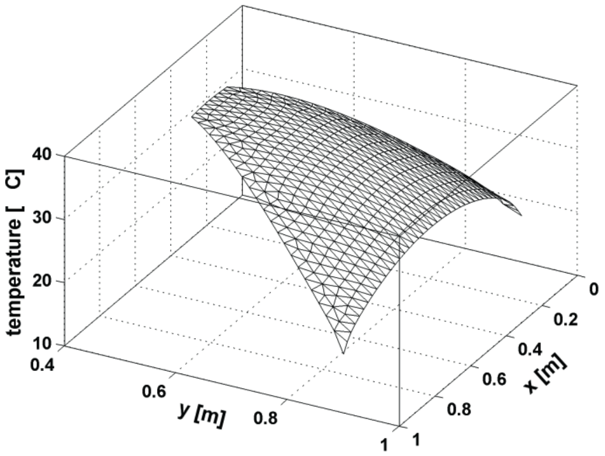


Figure 7. Heat of hardening – L-60-00-00.



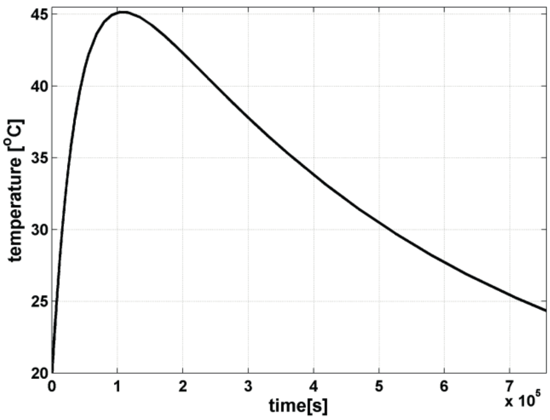


Figure 8. Temperature distribution in 2D trapezoidal form, *t=1000min*.

Figure 9. Temperature profile in 2D mold in point (0.5m,0.7m) – see Fig. 3.

4 CONCLUSIONS

The article shows an idea of new technique of diagnostics concrete materials at early ages. First qualitative result are promising and work on further development of this model is in progress. The advantage of our model is the fact that we use a time and temperature dependent material parameters which allows to achieve a more accurate modeling than in the models, which assume a constant thermal properties. In the next stage of work it is planned to combine this method with monitoring of cracks development using ELGRID system (Kokot 2008, 2009) for better monitoring and quality control of massive concrete structures.

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