INNOWACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI

UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ
ROZWOJU REGIONALNEGO

Research project „Innovative cement based materials and concrete with high calcium fly ashes"
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**Michal A. Glinicki**

# Determination of Thermal Properties of Unconventional Concrete During Hardening

Institute of Fundamental Technological Research
Polish Academy of Sciences
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# Outline of presentation

1. Introduction/motivation
2. Objectives of investigation
3. Model formulation and IHTP solution (TMC software)
4. Experimental data input (1D)
5. Verification in 2D
6. Predicted and measured temperature in large blocks
7. Conclusions

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# $CO_2$ emission in cement industry in Poland

- Average emission from 251 European cement plants :
  **868 kg $CO_2$/ton clinker**, average biomass content in fuel 6,7%
- Actual emission in cement industry in Poland:
  **823 kg $CO_2$/ton clinker**
- Empirical benchmark (Directive 2003/87/EC) from 10% of the best low emission cement plants in Europe: **766 kg $CO_2$/ton clinker** (biomass factor >25%)

**Advantages:** low electricity consumption; high fuel substitution (45%); high clinker substitution (CF = 0.77 )

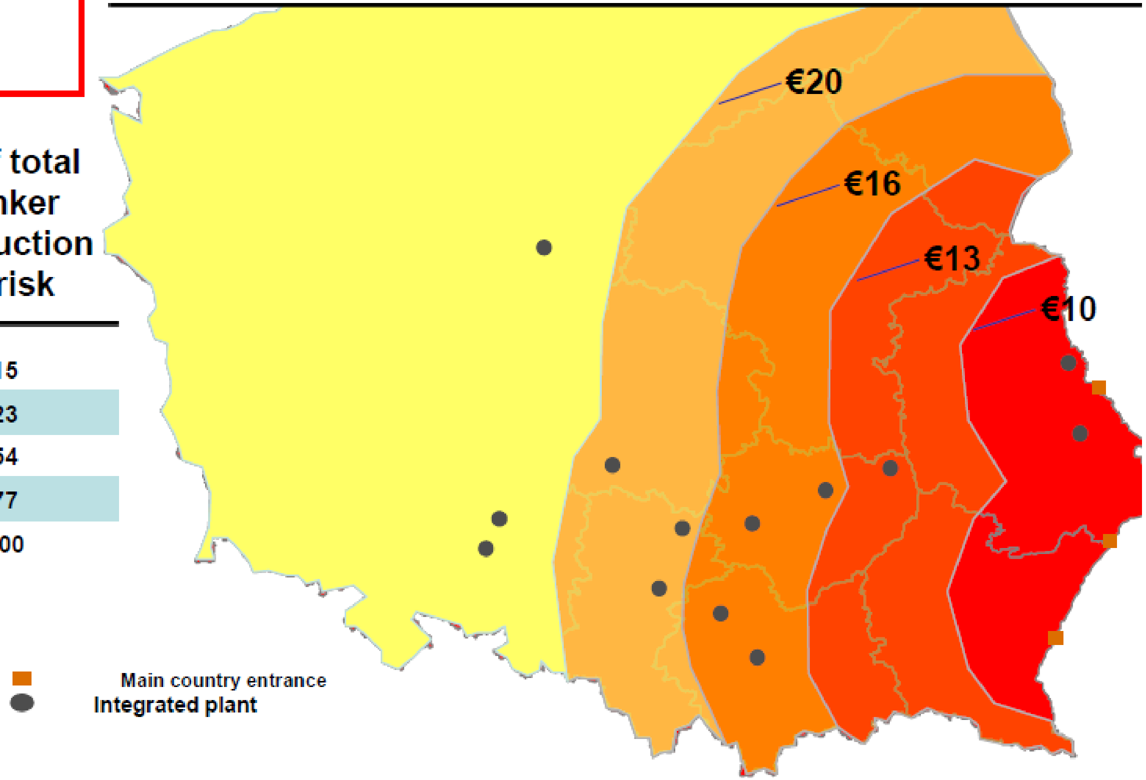
**Threat =** European Union Emissions Trading System (EU ETS)
→ lack of about 4.5 million ton of $CO_2$ allowances annualy

# Clinker production at risk in Poland due to high price of carbon emissions in EU ETS

**~100% of clinker production at risk with a $CO_2$ price of €23/t**
0% free allowances allocated

| $CO_2$ prices (€/t) | Distance (km) from border to isoline | % of total clinker production at risk |
|---|---|---|
| 10 | 150 | 15 |
| 13 | 250 | 23 |
| 16 | 350 | 54 |
| 20 | 450 | 77 |
| 23 | 550 | 100 |

**Isolines[1] of production at risk for different $CO_2$ prices based on inland transportation costs in Poland from Ukraine**




1. For clinker from Ukraine
Note: Clinker production by plant estimated as average being a confidential information; Distance from the plant in Ukraine to main entrances is 50 km
Source: Cembureau; Polish Cement Association

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The thermal properties of concrete, whether the concrete is massive or in thin sections, are the properties that are most ignored and the least understood by the general concrete engineering and construction industry …

Stephen B.Tatro

in: Significance of tests and properties of concrete and concrete making materials, J.F.Lamond and J.H.Pielert, eds., ASTM STP 169D, 2006

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# OBJECTIVES OF INVESTIGATION

- ❑ to develop numerical tools for determination of transient temperature field in concrete during hardening
- ❑ to establish the range of possible applications of concrete containing new blended cements

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# Heat transfer equation to describe the transient temperature field in hardening concrete

$$c\rho \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = Q$$

where: $T$ – temperature, $t$ – time,
$x$, $y$, $z$ space coordinates,
$\rho$ – density, $c$ – heat capacity,
$k_x$, $k_y$, $k_z$ thermal conductivity in direction $x$, $y$, $z$ respectively.
$Q$ - internal heat source

**the coefficients are time, space and temperature dependent**

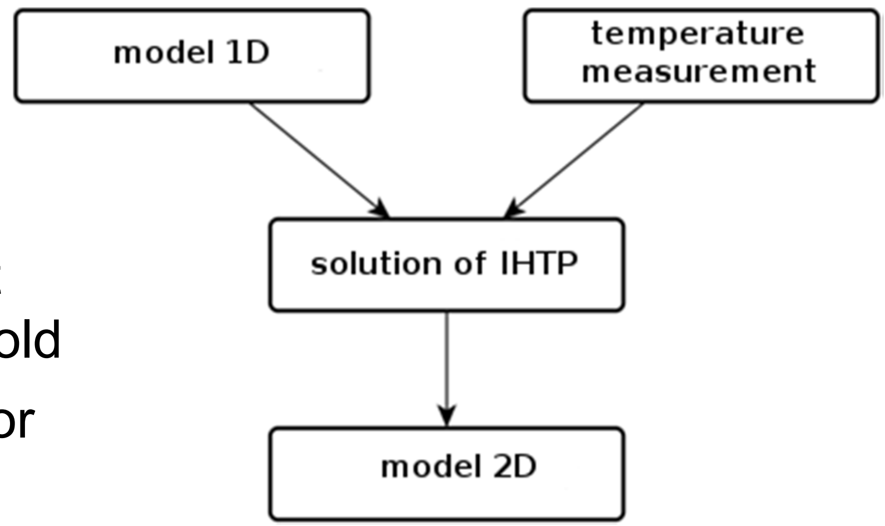
# Solution of heat transfer equation:

## →direct solution

requires fine identification of material parameters,
fails when less known (unconventional) components are used

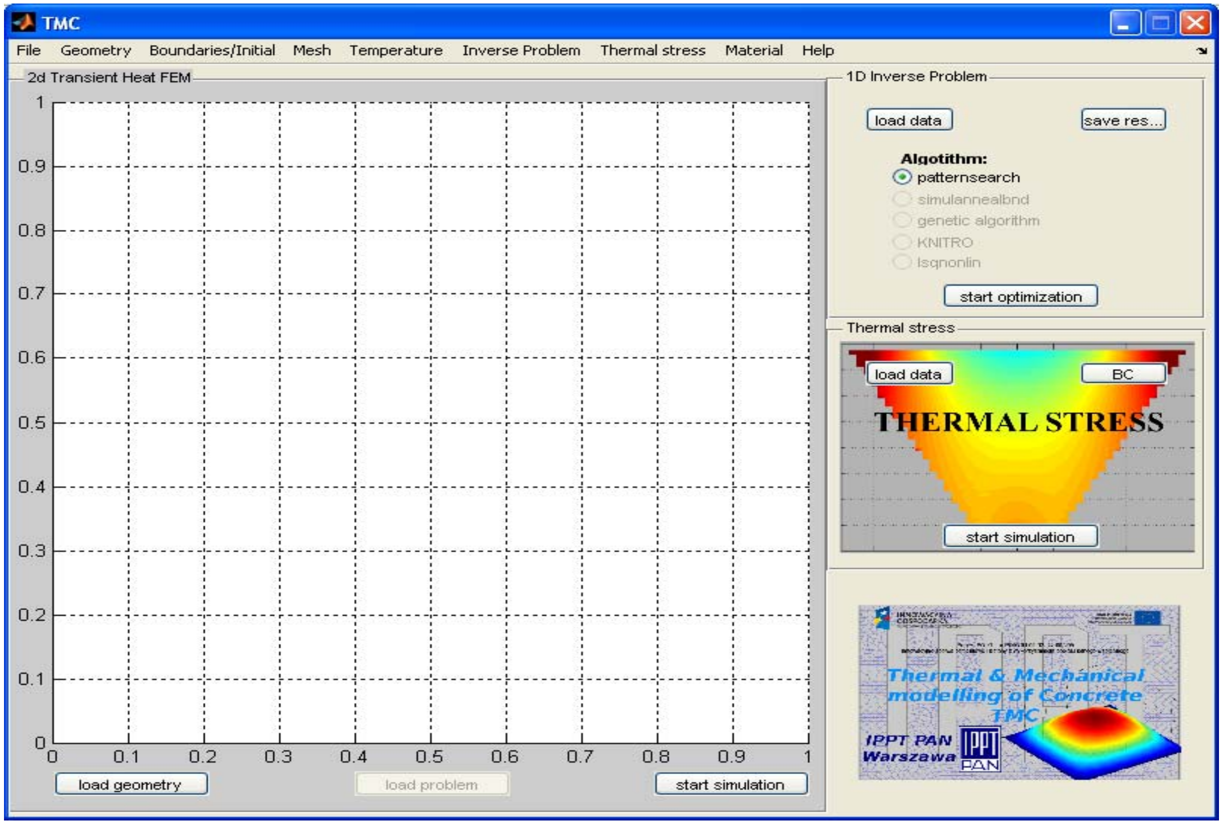
## → inverse solution

- one dimensional heat flow equation
- the temperature field is estimated on the basis of temperature measurement in several points in one dimensional mold
- solution of the optimization problem for given initial and boundary conditions



# Thermal & Mechanical modelling of Concrete

# TMC software



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# Solution of inverse heat transfer problem

functions *k*, *c* and *Q* are parameterized:

$$k_x = k_y = k_z = k(t_e) = \begin{cases} a_k t_e + b_k, & 0 \le t_e < 72h \\ 72a_k + b_k, & t_e \ge 72h \end{cases}$$

$$Q = Q(t, t_e) = \frac{t_e}{t}\sum_{i=1}^{n} q_i N_i(t_e)$$

$$c = c(t_e) = \begin{cases} a_c t_e + b_c, & 0 \le t_e < 72h \\ 72a_c + b_c, & t_e \ge 72h \end{cases}$$

$t_e$ is the equivalent time:

$$t_e = \int_0^t \beta(T)dt' = \int_o^t exp\left(\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+T}\right)\right)dt'$$

*E* is the activation energy and *R* is the universal gas constant

$N_i$ are linear shape functions for a one dimensional finite element

$a_k$, $b_k$, $a_c$, $b_c$, $q_i$ are unknown coefficients to be determined the calculated temperature $T^n$ is compared with the measured temperature $T^e$ to define the objective function to be minimized:

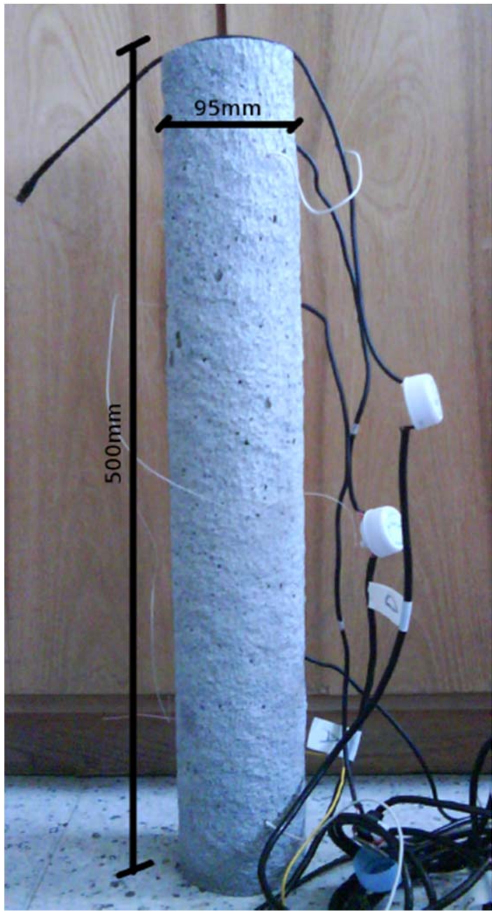
$$E(\boldsymbol{a}) = (T^e - T^n)^T (T^e - T^n) + \gamma \sum_{p=1}^{P} a_p^2$$

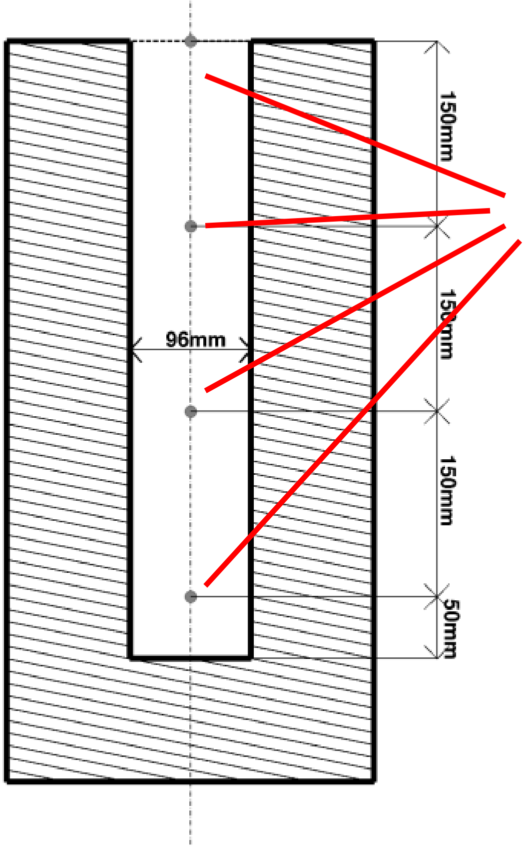
where $\gamma$ is a regularization parameter,
$a_p$ unknown parameters ($a_p=\{a_k, b_k, a_c, b_c, q_i\}$),
$P$ is a number of unknown parameters.

the objective function $E$ is minimized by non-gradient direct search algorithm

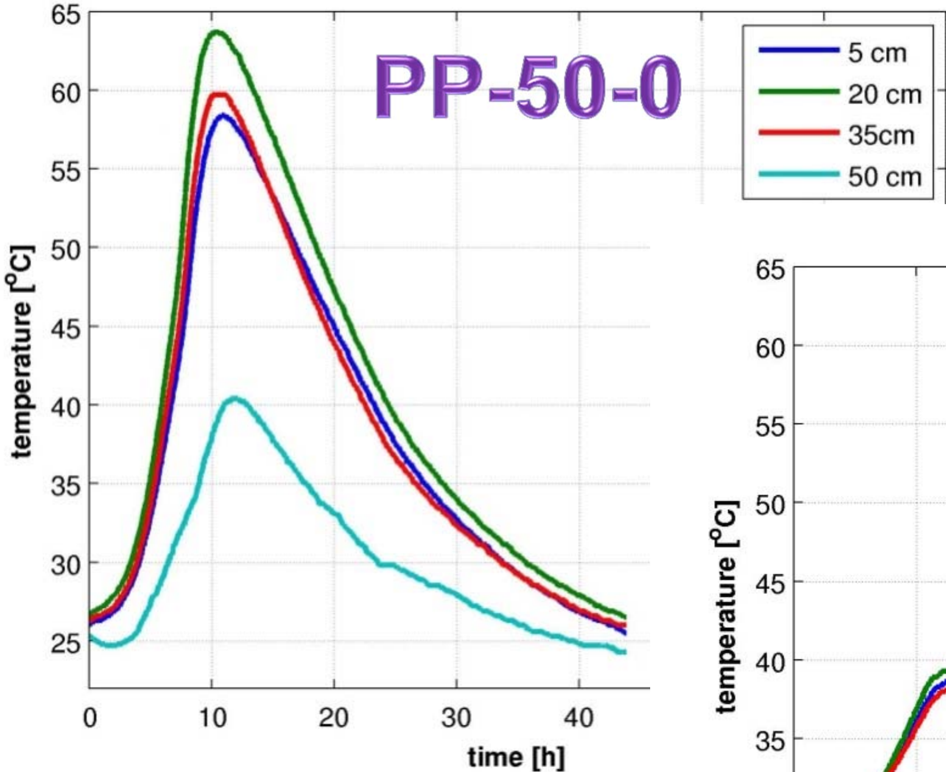
to avoid non-uniqueness of solution the IHTP is solved twice

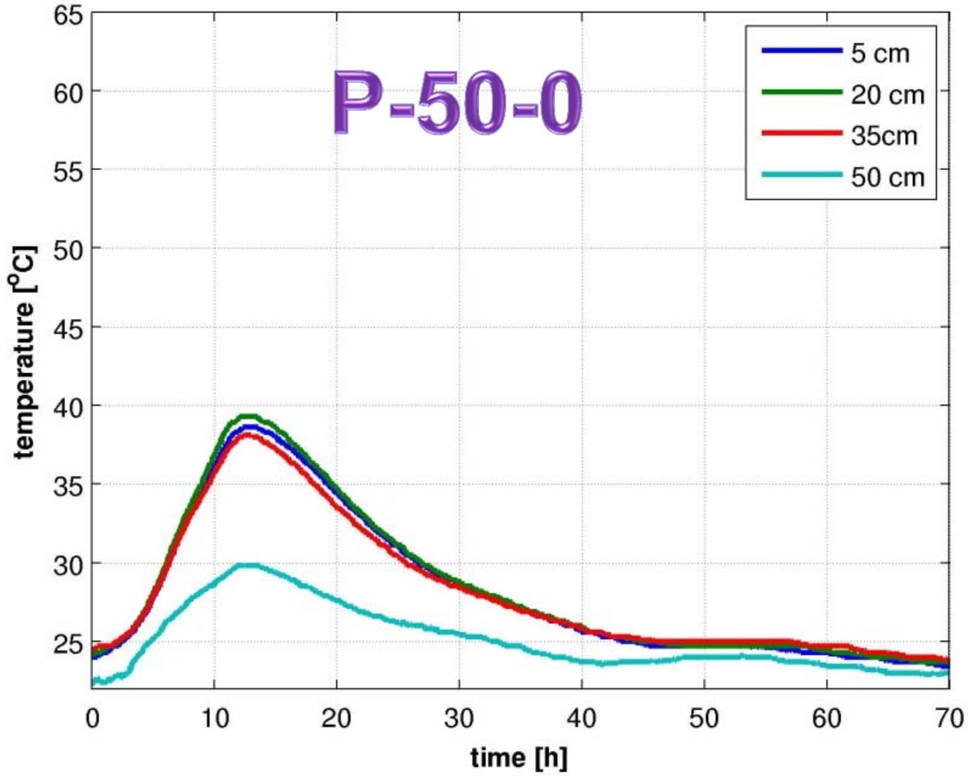
# Experimental data input: one dimensional mould



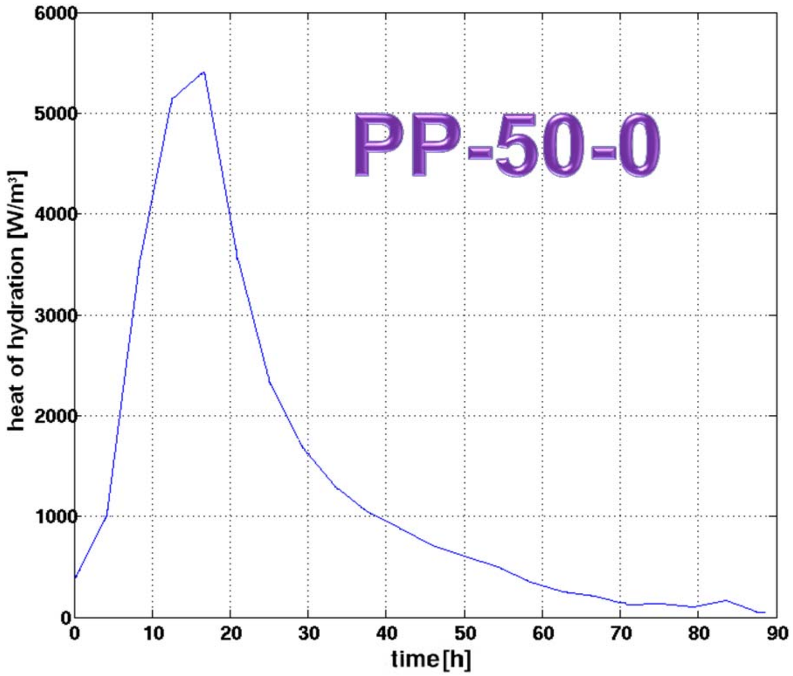



# Results of 1D measurements



# Results of inverse heat transfer solution in 1D




$c(t_e)$

| $a_c$ [J/kgKh] | $b_c$ [J/kgK] | Mixture |
|---|---|---|
| 0.0578 | 915.77 | PP-50-0 |
| 0.1928 | 910.1 | P-50-0 |
| 0.0729 | 912.1 | P-50-60 WS |

$k(t_e)$

| $a_k$ [W/mKh] | $b_k$ [W/mK] | Mixture |
|---|---|---|
| -0.0021 | 1.628 | PP-50-0 |
| -0.0037 | 1.592 | P-50-0 |
| -0.0018 | 1.398 | P-50-60 WS |

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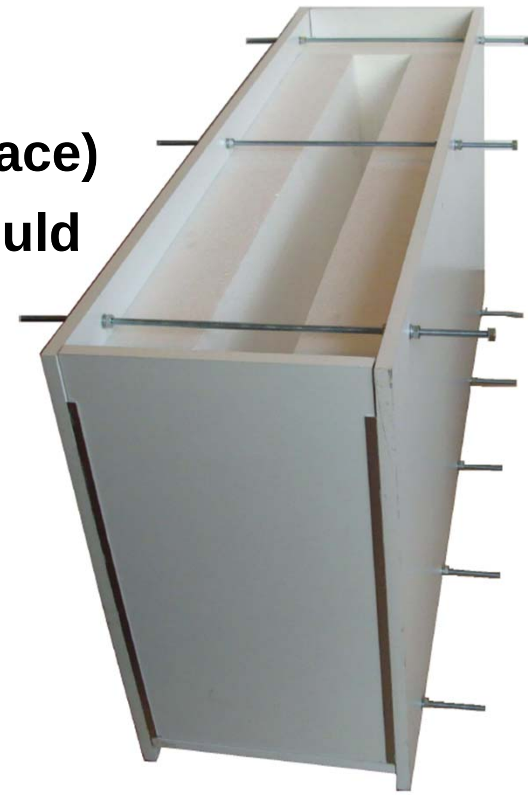
# VERIFICATION
# 2D calculations and measurements

**Trapeziodal shape element**

**Thermally isolated mould (except the upper surface)**

**Set of temperature sensors positioned in the mould**



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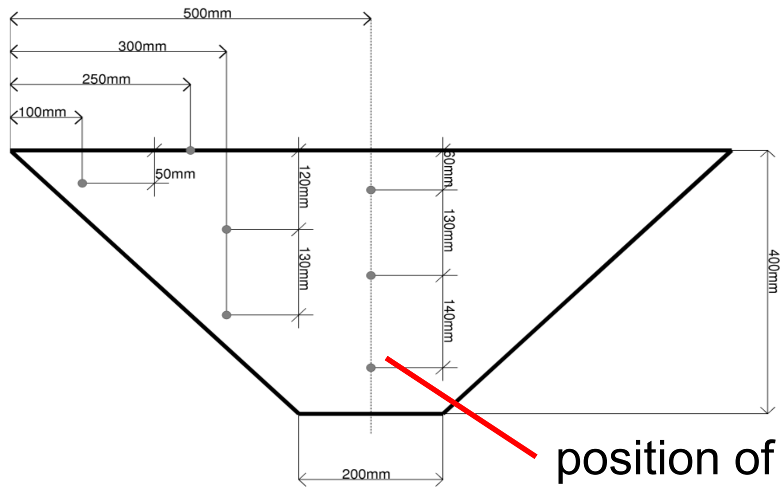
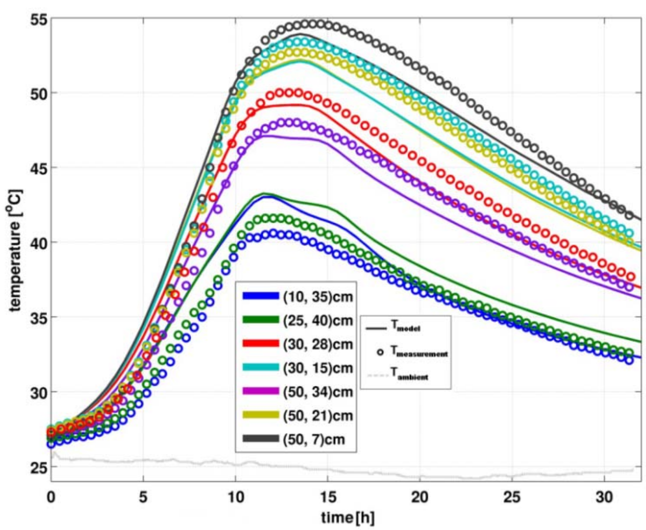
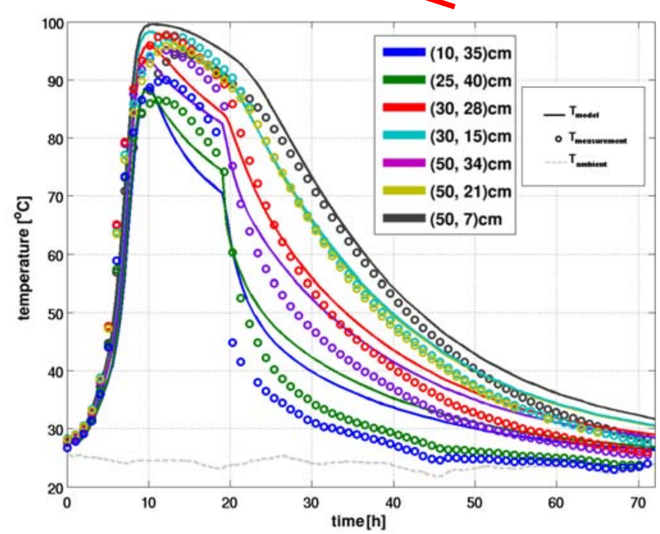
# Predicted and measured temperature in 2D element




position of temperature sensors




P-50-0

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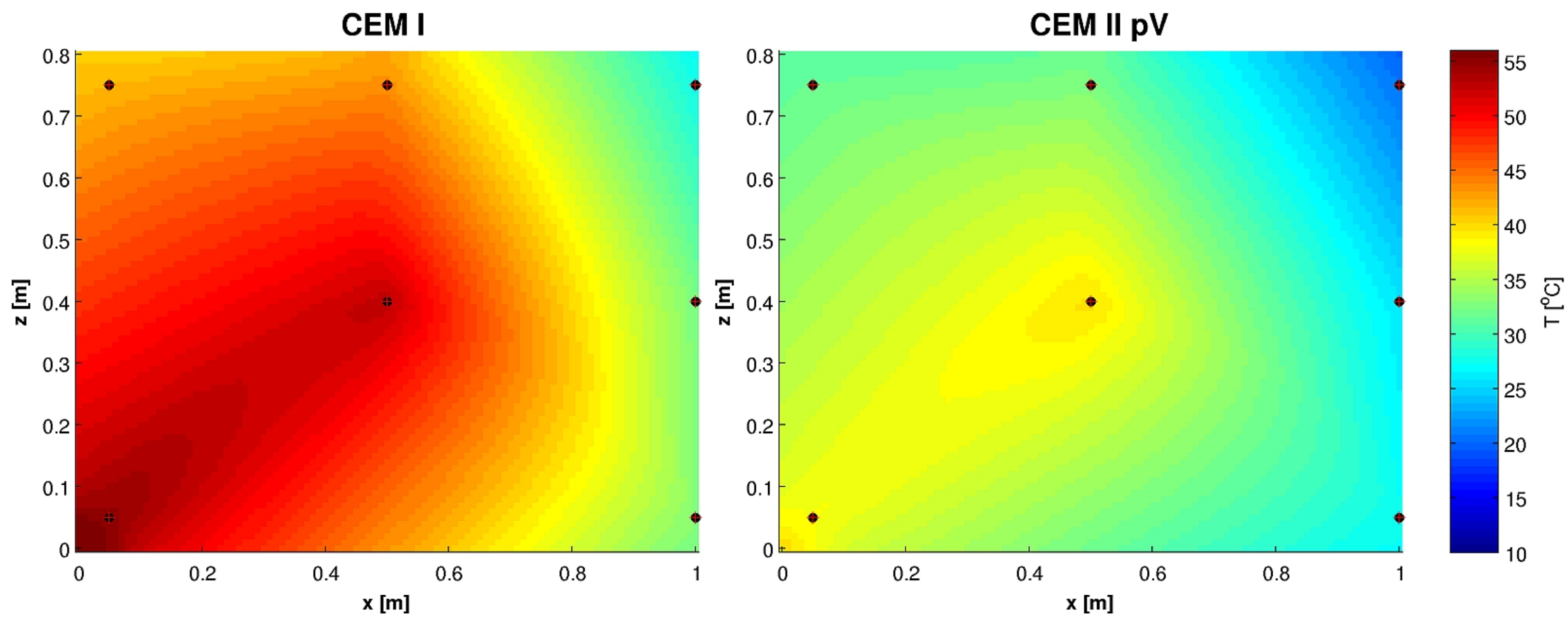
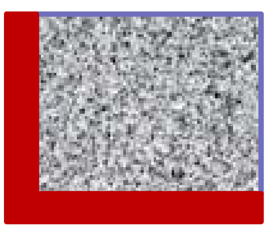
# Predicted and measured temperature in large concrete blocks

**Thermally isolated mould (~0.8 $m^3$)**

**Set of positioned temperature sensors**

# Temperature field in concrete block



**no thermal isolation at 1 side**

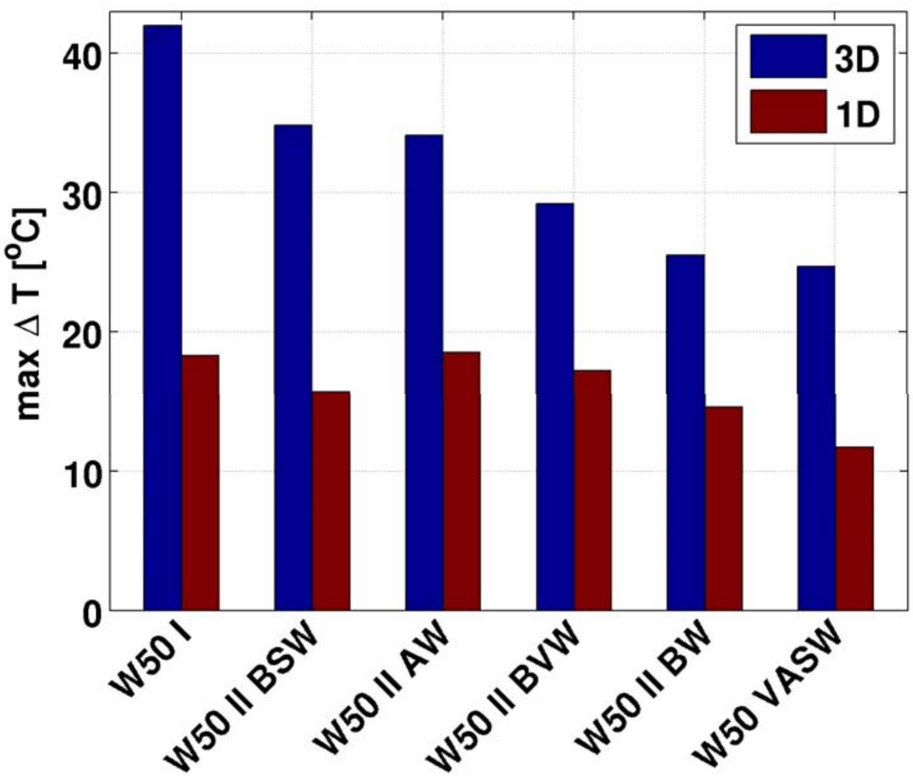
**Equal binder content:**

- **CEM I portland cement**
- **CEM II B-S + HCFA**

# Effect of cement composition on temperature field in concrete block

**Composition of new blended cements**

| Cement type | Clinker | HCFA | Fly ash | Slag | Gypsum |
|---|---|---|---|---|---|
| CEM I | 94.5 | - | - | - | 5.5 |
| CEM II/A-W | 80.9 | 14.3 | - | - | 4.8 |
| CEM II/B-W | 67.4 | 28.9 | - | - | 3.7 |
| CEM II/B-M (V-W) | 66.6 | 14.3 | 14.3 | - | 4.8 |
| CEM II/B-M (S-W) | 66.6 | 14.3 | - | 14.3 | 4.8 |
| CEM V/A (S-W) | 47.9 | 23.9 | - | 23.9 | 4.2 |



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# CONCLUSIONS

- Thermal properties of hardening concrete were effectively determined using unconventional approach- the **inverse heat transfer problem solution** using 1D temperature measurements and optimization by non-gradient direct search algorithm
- Determination of transient temperature field in hardening concrete is possible for unknown mix composition


## ACKNOWLEDGEMENT

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