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# THERMAL CONDUCTIVITY OF THE CURING CONCRETE

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Abstract

**Course of thermal interactions in the curing concrete, due to complex impact of internal and external factors, is not an entirely explained issue. Setting and hardening of concrete involved conjuncted and interlinked effects interacting between active particles of cement and other constituents of concrete mix. Their complexity is also tied with defining physical interactions related to emission of hydration heat. Due to simplifying assumptions that particular physicochemical processes in the curing concrete are independent and do not affect each other, description of thermal effects is a sort of approximation. Heat exchange between the curing concrete and environment as a result of variable activity of internal heat source considerably affects development of its properties. That is reflected by unstable temperature fields being present in the mass of tested material. Knowledge of physical properties of the curing concrete is required to define temperature distribution within it. Thermal conductivity of concrete is one of the essential parameters. Relevant literature points out to significant discrepancies in use of that quantity. The fact that in initial stage of curing thermal properties of concrete vary along with varied structure of concrete is most frequently left out. That is especially essential for defining distribution of temperature of the curing concrete using digital methods, in particular to identify gradients of temperature.**

Streszczenie

**Przebieg zjawisk termicznych zachodzących w dojrzewającym betonie, ze względu na złożony wpływ szeregu wewnętrznych i zewnętrznych czynników, pozostaje nie do końca wyjaśnionym zagadnieniem. Wiązanie i twardnienie betonu jest procesem skoniugowanych oraz sprzężonych ze sobą zjawisk zachodzących pomiędzy aktywnymi cząstkami cementu i pozostałymi składnikami mieszanki betonowej. Ich złożoność łączy się również z określeniem zjawisk fizycznych związanych z wydzielaniem się ciepła hydratacji. Ze względu na upraszczające założenia, iż poszczególne procesy fizykochemiczne zachodzące w dojrzewającym betonie przebiegają niezależnie i nie oddziaływają na siebie, opis zjawisk cieplnych jest pewnego rodzaju przybliżeniem. Wymiana ciepła pomiędzy dojrzewającym betonem a otoczeniem, spowodowana zmienną aktywnością wewnętrznego źródła ciepła, wpływa w sposób zasadniczy na kształtowanie się jego właściwości. Odzwierciedleniem tego zjawiska jest występowanie niestacjonarnych pól temperatur w masie badanego tworzywa. W celu określenia rozkładu temperatur w dojrzewającym betonie niezbędna jest znajomość jego właściwości termofizycznych. Jednym z istotniejszych parametrów jest przewodność cieplna betonu. Literatura tematu wskazuje na znaczne rozbieżności w przyjmowaniu tej wielkości. Najczęściej pomijany jest fakt, iż w początkowym okresie dojrzewania wraz ze zmianą struktury betonu zmieniają się także jego właściwości cieplne. Przyjmowane w większości obliczeń stałe wartości współczynnika przewodzenia ciepła dojrzewającego betonu wpływają na reprezentatywność uzyskiwanych wyników. Przedstawione w artykule propozycje przyjmowania przewodności cieplnej dojrzewającego betonu oraz ich analiza umożliwią otrzymywanie dokładniejszych wyników w symulacjach numerycznych.**

Keywords: **Thermal conductivity; Curing concrete; Heat exchange; Hydration heat; FEM simulation.**

## 1. INTRODUCTION

Concrete curing is a process of cross-linked effects interacting between active particles of cement and other constituents of concrete mix. Structure of concrete develops as a result of interaction of solid, liquid and gaseous phases with regard to temperature of reaction. Course of curing process is similar for all concretes involving Portland cement. Differences are related to sequence of physicochemical processes of liquefying cement minerals and they arise from diversified mineral composition of binding agent, use of admixtures and additives, if any, and ambient conditions. Properties of concrete are developed in effect of physicochemical and mechanical processes occurring during preparation, transport, placing, compacting, setting and hardening of concrete. Due to exothermic nature of interaction (thermal dissipation), cement hydration chemical processes are accelerated in specific curing conditions. In the curing concrete interior thermal and mass exchange is linked thermodynamically with chemical and physicochemical development of its structure. In concrete technology, structure and properties of cement products can be divided into the following arbitrary periods: pre-inductive (I), setting (II), hardening (III), use (IV). In period I heat is released very rapidly. That proceeds from mixing cement with water to a moment called beginning of setting. The main thermal effect in that period is related to absorption of water and initial hydration on the surface of cement grains. Period II is related to phase of induction, that is thermal calm, and continues from the beginning to the end of setting. It is marked by transition of cement slurry plastic state to solid state. Arbitrary periods related to characteristic phases of setting are called the beginning and the end of setting. Period III is related to post-inductive phase and is marked by releasing heat of variable intensity. It takes up to 28 days and can be divided into three stages: accelerated hydration (to 7 days), slowed hydration (7-14 days) and hydration end (14-28). Period IV marked by insignificant, but continuously weakening, release of heat. The course of thermal interactions in setting and hardening concrete is not entirely clarified due to complex influence of a series of factors As a result of exothermic interactions a temperature difference occurs between concrete and environment and heat exchange is generated. That is defined by variable activity of internal source and exchange of heat on the boundary of an element considerably affecting conditions of setting and hardening of concrete. Concrete curing is affected by variable groups of material and technological factors which are essential for development of shrink generating processes of material. Interior factors are related to components and composition of concrete, whereas exterior factors are related to conditions of curing and method of works.

## 2. HEAT EXCHANGE

Field of temperature in the curing concrete is defined using differential equation for thermal conductivity (also known as Fourier-Kirchoff or energy equation). It is vital for the considered thermal interactions related to concrete curing kinetics with interior heat source. For the spatial issue of undefined thermal conductivity with interior sources of heat the equation can be as follows:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial t}{\partial z}\right)+q_V=c_b\rho\frac{\partial t}{\partial \tau} \quad (1)$$

where,

$x, y, z$ – linear coordinates,
$t$ – temperature in any point in area and at any time $\tau$,
$q_v$ – hydration heat flux density,
$\lambda$ – concrete thermal conductivity coefficient,
$c_b$ – concrete specific heat,
$\rho$ – concrete mass density.

Differential equation for undefined thermal conductivity provides general relationship between temperature, time and spatial coordinates. In order to choose suitable solution for the considered phenomenon clear solution conditions need to be defined and those include,

- geometric conditions – to define geometry of a considered body (shape and dimension)
- physical conditions – to define physical properties of body
- distribution of interior heat source efficiency
- initial conditions – to define temperature distribution at initial time
- boundary conditions – to define thermal exchange conditions on outside surfaces of body.

Intensity and variability of curing concrete heat exchange with environment relative to exothermic processes of setting and hardening is revealed by variable thermo-physical properties of material. Due to complex nature of the course of physicochemical processes in concrete, its thermo-physical properties alter as curing proceeds. In many cases a simplification can be assumed that for the considered periods of variability of certain values thermal conductivity coefficient λ is constant and independent of direction. For calculations of temperature field of the curing concrete that cannot be assumed in all cases. Factors affecting development of physico-chemical properties of the curing concrete are related to thermochemical transitions of its structure. Those transitions are accompanied by generating cement hydration heat as interior heat source.

Apart from energy variations, development of thermophysical properties of concrete is related to phase transitions. Part of slurry water in concrete mix interacts chemically with active minerals of binder and part remains not chemically bound in developed material. Thermophysical coefficients in that period of time are subject to structure of centre, thermal conductivity of its phases, as well as their volumetric concentrations. An effort to describe course of variations of thermophysical properties of the curing concrete was made by means of numerous empirical formulae. However, background data indicate considerable discrepancies related to assuming thermophysical values of the curing concrete. Due to a small number of performed tests and analyses, relevant literature most frequently assumes permanent values of thermophysical coefficients.

## 3. THERMAL CONDUCTIVITY OF THE CURING CONCRETE

Factor of proportionality $\lambda$ in Fourier-Kirchoff equation is named thermal conductivity and it marks the curing concrete with respect to its capability of thermal conductivity. Thermal conductivity through concrete is performed by solid components (structure), water and air contained in material pores. Main factors affecting development of thermal conductivity of concrete related to its composition are the following: maximum density and structure of pores, moisture content and temperature. Change of thermophysical properties of concrete related to phase transitions is essentially relative to content of a particular phase (water, air, aggregate and binder). Movement of heat in the curing concrete can be by conduction, free convection, radiation and heat exchange by diffusing moisture. Mitzel states that thermal conductivity of concrete is relative to water and cement ratio to a lesser degree, whereas type of used aggregate is central. That is due to its volumetric content in concrete. Concrete thermal conductivity coefficients related to used aggregate were presented in A.M. Neville [7].

**Table 1.**
**Concrete thermal conductivity coefficients related to aggregate [7]**

| Aggregate | Apparent density of wet concrete [kg/m³] | λ [W/mK] |
|---|---|---|
| Quartzite | 2440 | 3.5 |
| Dolomite | 2500 | 3.3 |
| Limestone | 2450 | 3.2 |
| Sandstone | 2400 | 2.9 |
| Granite | 2420 | 2.6 |
| Basalt | 2520 | 2.0 |
| Barite | 3040 | 2.0 |

Development of thermal conductivity apart from sort and quantity of aggregate in concrete also is relative to quantity of water and less significantly to its temperature. Value of water thermal conductivity coefficient varies in temperatures 0°C – 40°C by some 10% – table 2.

**Table 2.**
**Water thermal conductivity coefficient subject to temperature [4]**

| Temperature of water [°C] | λ [W/mK] |
|---|---|
| 0 | 0.57 |
| 10 | 0.59 |
| 20 | 0.60 |
| 30 | 0.62 |
| 40 | 0.63 |

Mitzel's theory has been confirmed by K.-H. Kim et al. [5]. His research conducted at National Research Laboratory, Korea, involved testing of quantities of thermal conductivity coefficient for different age concrete (3-28 days) additionally dependent on aggregate overall volume, temperature of concrete, moisture content and *W/C* index, as well as fine aggregate volume. Modification coefficients were identified, relative to specific factors such as,

where:

$$\lambda_{AG} = 0.293 + 1.01AG \qquad (2)$$

$\lambda_{AG}$ – modification coefficient relative to aggregate volume in concrete,

$AG$ – volume of aggregate in concrete,

$$\lambda_t = 1.05 - 0.0025 t_b \tag{3}$$

where:

$\lambda_t$ – modification coefficient relative to temperature of concrete,

$t_b$ – temperature of concrete,

$$\lambda_R = 0.8\,[1.62 - 1.54(W/C)] + 0.2 w_{Rh} \tag{4}$$

where:

$\lambda_R$ – modification coefficient relative to w/c and relative moisture of concrete,

$W/C$ – water and cement index,

$w_{Rh}$ – relative moisture of concrete,

$$\lambda_{S/A} = 0.86 + 0.36(S/A) \tag{5}$$

where:

$\lambda_{S/A}$ – modification coefficient relative to fine aggregate volume in concrete,

$S/A$ – volume of fine aggregate in concrete.

Based on tested impact of particular factors concrete thermal conductivity coefficient was proposed

$$\lambda = \lambda_{ref}\,[0.293 + 1.01AG] \times [0.8\,(1.62 - 1.54(W/C)) + 0.2 w_{Rh}] \times [\,1.05 - 0.0025 t_b] \times [0.86 + 0.36(S/A)] \tag{6}$$

where:

$\lambda_{ref}$ – thermal conductivity coefficient measured for $AG = 0.70$, $W/C = 0.40$, $S/A = 0.40$, $t_b = 20$ °C, $w_{Rh} = 1.0$,

$AG$ – volume of aggregate in concrete,

$t$ – temperature of concrete,

$W/C$ – water and cement index,

$w_{Rh}$ – relative moisture of concrete,

$S/A$ – volume of fine aggregate in concrete.

However, the referred publication does not answer the question whether for different composition of concrete the modification coefficients as outlined in the formulae (2-5) would remain unchanged. Different dependency of thermal conductivity on concrete mix content defined by materials parameters has been outlined in [2]. The proposed method to identify thermal conductivity of concrete does not recognise phase transitions occurring in concrete curing process

$$\lambda = \Sigma G_i f_{1i} \tag{7}$$

where:

$G_i$ – % content of particular concrete components,

$f_{1i}$ – materials parameters for particular components.

In his publication, G. Kirchner argues that Cammerer made thermal conductivity of concrete dependent on water and cement content and introduced additional materials parameters [3]

$$\lambda = \lambda_N(1+12\,\Phi)/(1+12\,\Phi_r) \tag{8}$$

where:

$\lambda_N$ – standard hardened concrete thermal conductivity coefficient,

$\Phi$ = 0.05,

$\Phi_r$ = $(W$-$0.22C)/1000$,

$W$ – water content in m$^3$ concrete mix,

$C$ – cement content in m$^3$ concrete mix.

Setting out of thermal conductivity of solid components is most complex due to variable thermal properties of generated hydration products. An interesting description of curing concrete thermal conductivity coefficient relative hydration degree was proposed by Trinhztfy and Jongendijk [8]

$$\lambda(\alpha) = \lambda_{sb}(2 - \alpha) \tag{9}$$

where:

$\alpha$ – cement hydration degree,

$\lambda_{sb}$ – hardened concrete thermal conductivity coefficient,

J. Byfors, based on Hamfler's tests and analyses, presented thermal conductivity of concrete subject to degree of cement hydration and thermal conductivity of concrete mix when placed in mould (initial thermal conductivity) $\lambda_0$ [1]

$$\lambda(\alpha) = \lambda_0 - (\lambda_0 - \lambda_{sb})\,\alpha \tag{10}$$

where:

$\alpha$ – cement hydration degree,

$\lambda_{sb}$ – hard concrete thermal conductivity coefficient (1.5-2.1 W/mK).

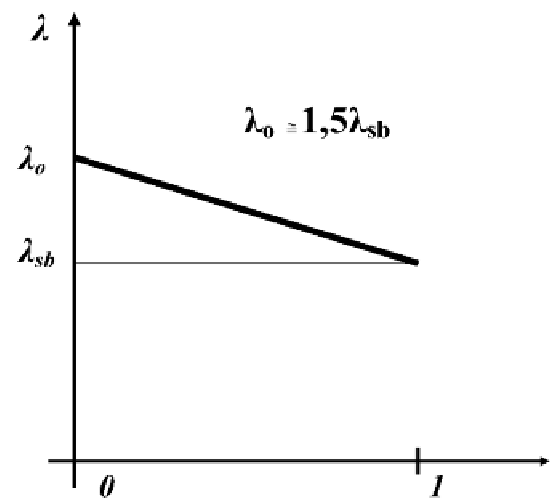


**Figure 1.**
**Dependency of concrete thermal conductivity on Hamfler's degree of cement hydration [1].**

Initial thermal conductivity of concrete mix ($\lambda_0$) is defined by the following formula

$$\lambda_0 = \lambda_{sb}\,(1+12\Phi)/1.6 \qquad (11)$$

where:

$W$ – water content in concrete mix,

$C$ – cement content in concrete mix,

$\Phi = (W\text{-}0.25C)/\rho_W,$

$\rho_w$ – water density.

Defining thermal conductivity of curing concrete is a complex issue related to presence of variable internal heat source as a result of exothermy of cement hydration. Exchange of heat by conduction of the curing concrete can be considered in two stages. In the first stage of emission of hydration heat (self-heating) a variable in time field of temperature is generated and it is relative to variable intensity of internal heat source. In the considered case temperature increases due to prevailing exothermic processes, next, cooling process occurs as far as to achieve thermal stability to accommodate concrete temperature to ambient temperature. Setting thermal characteristics of concrete during alterations of intensity of internal heat source, as a process related to unsteady thermal flow, is very difficult. Some authors points out to difficulties and problems with regard to setting out of thermal conductivity coefficient in unsteady thermal flow tests as is the case, among other things, with the curing concrete. Two phases of the process can be highlighted in terms of defining thermal conductivity of the curing concrete:

*I phase of concrete curing (dynamic curing)* – a problem to define concrete thermal conductivity coefficient is present in the first phase of curing. Standard definition of the λ coefficient under PN-EN ISO 7345 refers to unidirectional, steady thermal conductivity without internal thermal sources. In the considered curing phase we are dealing with internal diffusive thermal source and its movement towards all surfaces of the considered element. That is related to thermochemical transitions in the process of hydration – alteration of interior energy accompanying chemical reactions. Thermal conductivity of concrete can be considered at this stage from the point of view of: diffusive transport of thermal flux (prevalence of internal energy) and unidirectional transport of thermal flux (can be considered upon stabilising of concrete temperature field). Therefore, in phase 1 of curing apparent coefficient of thermal conductivity $\lambda_{pb}$ is the value marking thermal conductivity in concrete and it alters along with alteration of power of internal thermal source – dissipation of internal thermal source. In the I phase of curing thermal conductivity of concrete is essentially relative to moisture content (water) in material. Apparent thermal conductivity coefficient increases considerably as a result of increased convective heat transfer tied with flow of water through capillary pores. Together with decrease of liquid phase content heat exchange intensifies by conductivity resulting in decrease of $\lambda_{cm}$ coefficient.

*II phase of concrete curing (static curing)* – in view of thermodynamics, thermal conductivity coefficient $\lambda_c$ cannot be set out until temperature field gets stabilised (fixed state condition). It marks steady thermal conductivity in concrete, that is, quantity of heat flowing in unit of time across unit surface at unit temperature gradient at right angle to that surface.

## 4. FEM SIMULATION

FEM simulation was performed in order to determine impact of variability of heat conduction coefficient on distribution of curing concrete temperature. Besides determining temperatures distribution in massive elements, another important issue related to thermal phenomena is concrete curing in low outside temperatures. Further to the above the author found it legitimate to determine impact of variable value of heat conduction coefficient on temperature of curing concrete in heat-insulating casing Calculations were performer with the use of POLTEM program created by Barbara Klemczak, PhD, Eng. Program employed equation (1) in the context of finite elements method, with initial condition (12) and boundary condition (13)

$$T(x,y,z,0) = T_p \tag{12}$$

where:

$T_p$ – initial temperature of concrete mix

$$\lambda \frac{\partial T}{\partial x} n_x + \lambda \frac{\partial T}{\partial y} n_y + \lambda \frac{\partial T}{\partial z} n_z + q_b = 0 \tag{13}$$

where:

$n_x$, $n_y$, $n_z$, – direction cosines of normal outside n to the surface limiting area,

$q_b$ – heat led to or carried away from the element surface, W/m$^2$ .

Slender element of the cross-section 80 x 80 cm was employed as the subject of simulation. Heat exchange with surroundings only in horizontal plane was assumed. Value of coefficient λ was employed only as extreme, based on listed literature data [6] and additionally as standard value for hardened concrete based on standard PN-EN 12524 Building materials and products – Hydrothermal properties. Heat flux density of hydration in POLTEM program was employed based on Flaga function description.

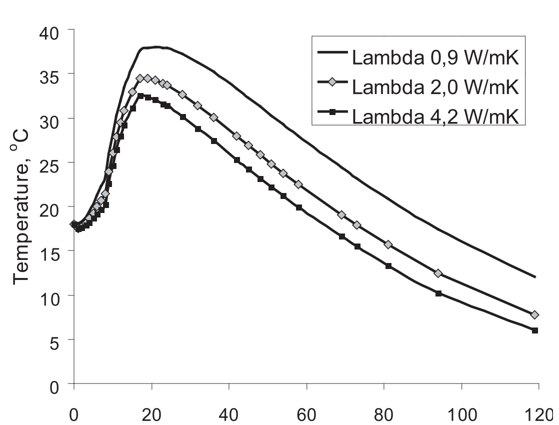


**Figure 2.**
**DComputational temperature (POLTEM) in curing concrete nucleus depending on employed heat conducting coefficient**

Cement hydration heat was determined based on manufacturer data. Constant value of specific $c_b$ = 0.84 J/(kg·K) heat was assumed. Calculations were made for concrete made of Portland cement CEM I 42.5R (390 kg/m$^3$), curing in temperature of –7$^o$C in heat insulating cover (T.cover) of thermal resistance R = 2.86 m$^2$ K/W. Calculation results have been presented in fig.1. Calculations showed significant impact of coefficient λ value on temperature distribution in curing concrete. For simulated medium-massive elements employing low λ values results in difference of calculation temperature for concrete nucleus on the level of 2.1-5.6 K, in relation to assumed maximal value λ = 4.2 W/mK.

In order to verify FEM simulation, comparison was carried out of selected calculations results with author's laboratory tests [6], for low massiveness elements (limited size of available freezing chambers) curing in low outside temperature. An attempt was made to determine optimal value of heat conduction coefficient in concrete. Carried out analyses showed best compliance of calculations with experience for heat conduction coefficient λ = 3,60 W/mK.

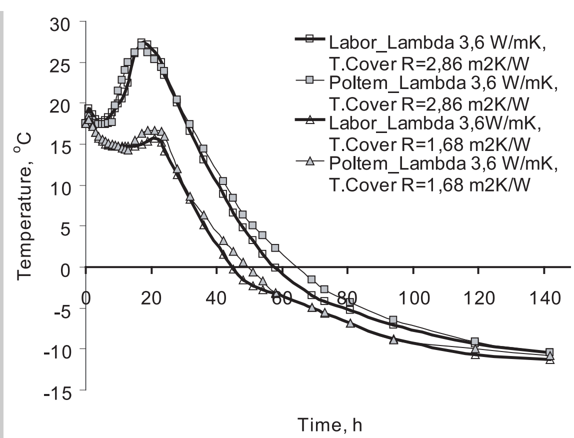


**Figure 3.**
**Comparison of surface and computational distribution of temperature for curing concrete in pole elements of small massiveness Mp=40$^{-1}$, depending on the employed heat conduction coefficient [POLTEM]**

## 5. SUMMARY

Modeling of thermal exchange in tje curing concrete providing overall relationship between temperature, time and spatial coordinates is significantly relative to employing clear solution conditions. That is related to difficulties in identifying distribution of efficiency of internal thermal source in concrete and boundary conditions, as well as thermophysical properties of concrete. Hitherto efforts to model concrete temperature distribution most frequently leave out the fact that the curing concrete is a material without defined thermophysical properties. Lack of possibility to directly test those quantities (not least thermal conductivity coefficient) and to clearly define heat transfer coefficient makes employing reliable values difficult. The outlined discrepancies arise from lack of complete theoretical solution to the problem. That is due to no uniform views on chemical processes involved with concrete curing despite long history of different theories. Complexity of transition processes in concrete with different method of tests and their interpretation considerably impedes development of a clear theory at the initial period of concrete curing. Difficulties related to correct identification of thermophysical properties of the curing concrete and thermal exchange conditions on boundaries of an area affect representativeness of achieved results. Proposals to use thermal conductivity coefficient based on defined dependencies as outlined in literature are more or less accurate effort to set them out. $\lambda$ for curing concrete seems significantly relative to sort of applied aggregate, as well as progress of phase transitions in concrete. It should be accepted that the majority of data related to thermal conductivity coefficient refer to second phase of heat movement leaving out the influence of internal thermal source. However, there is no possibility to clearly review the proposed use of thermophysical quantities of setting and hardening concrete. Significance of $\lambda$ coefficient value impact on temperature distribution of curing concrete increases together with element massiveness. Despite the fact that $\lambda$ is not the only parameter which, when employed appropriately, decides about calculations reliability, it is among this subject experts a parameter whose value is employed with significant differences. Use of the foregoing quantities has not been made standard and is essentially subject to expertise and experience of a researcher conducting the experiment.

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