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HARDENING CONCRETE EFFECTS IN MASSIVE STRUCTURES

Jan Ślusarek

Silesian University of Technology, Civil Engineering Faculty, Gliwice, Poland

ABSTRACT

Although cement materials have had more than one hundred years history, they are still building material of great importance. Positive and negative experiences with their application were used in subsequent realizations. Significant development of material engineering, especially in the last few years, has created new possibilities also in the cement materials technology. This has contributed to the considerable increase the durability of cement materials and the firmness of their structure as well. Those effects were possible to attain by dint of the modifications of the cement materials` structure that rested mainly on usage of specific chemical admixtures (super plasticizers) and mineral supplements (silica fume). The modifications of the cement materials structure allowed to reduce remarkably water-cement ratio and porosity. As a result one can obtain a mixture with much more active particles that are able to make structural bonds and much less capillary pores, which create main structural defects. It may appear that modelling problems have already been solved. In literature one can find many different hardening models. In this research the structural model of cement materials hardening is presented.

Formulas, shown on the basis of established model assumptions, make possible to observe the development of concrete's strength under compression in wide range of changes of its structure, defined by porosity coefficient. This coefficient, giving the ratios between molecular (gel) pores capacity and total pores capacity in hardening concrete, is a proper description of structures – formed processes character, integrally connected with structure of porosity of hardening cement paste. It means that there is an influence of mineral additives and physical and chemical active admixtures on development of hardening concrete strength. In the established model the fundamental influence on concrete's strength, in the period of its structural changes, exerts the cement gel with dissipated, molecular, capillary and air pores. The distinction of porosities and equivalent influence on the development of concrete's strength under compression fixing makes the identifying of significant model difference in scope of concretes characterized by dissimilar composition of matrix possible.

The setting and hardening of concrete are accompanied by no stationary, heterogeneous temperature and moisture distributions caused by the hydration heat development. In this paper theoretical and experimental studies of temperature distributions induced in large High Performance Concrete (HPC) and Ordinary Concrete (OC) blocks during the hardening process are discussed. Two concrete mixes with water to binder ratios 0.52 (OC) and 0.32 (HPC) are used in the experimental blocks to identify the temperature fields and thermal stresses during their hardening.

Concrete structures treated by outer load are exposed to loads resultant from material properties and technology of structure. These loads are mainly caused by unsteady, coupled fields of temperature and humidity. They come into being during truss and hardening of concrete under the influence of action of inner heat sources and inner dry up as a result of hydration process in binder and also as a result of mass (humidity) and energy (heat) exchange with environment. These processes, causing irregular changes of volume in hardening concrete, are often the reason of forming the first scratches and cracks in structure, even in stage of its realization. Thermal and humidity distortions are essential in massive structures. The increasing of massive structure temperature evokes distortion and stress in this structure. Maximal values of thermal stresses are being noticed in initial period of concrete truss and hardening. Cracks can be made in zones of tensioned concrete on the surface of solid. In the consequence of later, natural cooling of structure of the influence of plastic and rheological distortions and changes of material features in hardening concrete, there is a phenomenon of inversion in solid's distortion, causing tension of inner zones.

Key words: cement matrix, gel products, gel pores, capillary pores, air pores, porosity coefficients, setting and hardening process of concrete, large concrete column, nonlinear temperature distributions, temperature gradients, setting and hardening process of concrete, large concrete blocks, nonlinear temperature distributions, temperature gradients, exertion of early ages concrete.

INTRODUCTION

Cement and water blending generates chemical reaction that is usually called hydration. Reaction of cement with water is in fact a set of chemical reactions and physical processes. After blending cement with water, the reactions take place in the surface of the grains of cement and its components and some other products in the reaction dissolve in liquid phase [5,13,15,20,24]. Some components of cement dissolve congruently and fall into hydration. Other components dissolve incongruently – with disintegration, falling into hydrolysis [5,13,15,20,24]. In the analyzed process, there are also reactions of synthesis between compounds created as the result of hydration or hydrolysis of separate cement components.

There is also a phenomenon of hardening of newly made products. Reaction of cement with water is a very complicated process. Mutual influences of different cement components reacting with water are often complicated by the activity of various supplements [5,13,15,20,24].The analyzed process is not only hydration. Much more complicated one, often called the hardening [11,14,15], seems to be adequate and well-founded. Despite the long-term research, it has not been possible to unequivocally define the sort and character of chemical reactions taking place during the time of the cement materials hardening process [5,13,15,20,24].

The setting and hardening of concrete is accompanied by nonlinear temperature distributions caused by the heat of hydration [3,6,7,8,12,15,33,37]. High temperature gradients associated with the exothermic chemical reactions of cement hydration may occur between the interior and the surface of structural elements at early ages [7,15,33], [35,37]. Cracks occur when these temperature gradients lead to tensile stresses that exceed the tensile strength of the young concrete, influencing the durability of the structure [15,26,29,37]. This problem is especially accentuated in massive concrete structures [3,6,7,8,12,15,26], [29,35,37]. In the case of High-Performance-Concrete structures, such effects can also be significant, due to the higher cement and silica-fume contents [7,8,15].

In this paper, a theoretical and experimental studies about temperature and stress distributions induced in ordinary and high-performance concrete structures during the hardening process are presented. Heat of hydration effects were studied for the two large concrete blocks. One of them was made of ordinary concrete with water to binder ratios 0.52. The second block was made of high – performance concrete with water to binder rations 0.32. Composition and properties of the used in the experimental tests are presented in Table 1. The concrete blocks had a cylindrical form 100 cm in diameter. They were waterproof and thermally insulated from above and below.

NUMERICAL MODEL OF HARDENING CONCRETE

Modelling of concrete hardening process

It may appear that modelling problems have already been solved. In literature one can find many different hardening models: technological, time-dependent, structural and thermo dynamical [13,15,17,20]. The notion of hardening concrete temperature function and the ripeness of concrete are also discussed in these dissertations.

The problem of mechanical properties development in concrete hardening process has a large bibliography. The results of considerations are systematized in form of functional or correlation relationships. It is possible to point out two fundamental methods of hardening process modelling. In one of them the problems concerning the modelling of hardening process have been presented with distinction of technological and time-dependent models. In these models changes of hardening concrete strength are described by time-dependent function and parameters of binding material that had been used [2,4,14,15,16,19,20,21,34], CEB-FIP Model Code MC 90 [38].
The second method of concrete hardening process modelling may be called the structural modelling. In this case mechanical properties of hardening concrete are described by relationships of structural parameters depending on binding materials hydration degree [1,11,14,15,19,20,22,27].

The process of hardening of new generation concretes (with addition of superplasticizer and micro-silica) leads to forming up qualitatively different structure than in ordinary concretes. Mineral admixtures and chemical additives also affect the kinetics of structural processes. In present paper the structural model which enables to predict compressive strength of concrete, especially in early time of its hardening, is presented. Two different concrete mixtures there are presented in Table 1, are considered. There are Ordinary Concrete (OC) and High Performance Concrete (HPC).

General model assumption

Comprehensive specification of mechanical characteristics of hardening concrete, especially of high performance, creates necessity to adopt specific physical model. In this paper it is established that the concrete can be treated as a composite material, where the dissipate phase – aggregate and grain of non-hydrated cement is joined by gel with dissipate pores, which makes a matrix. Assumptions which are established here can be a basis for description of destruction process, which, in the broad scope of structure's development, proceed in the matrix area. Mechanical characteristic are given by following factors [5,13,14,15,19,20]: total porosity, pores size distribution, defect's existence, diversity of structure's level.

Fig. 1. The microscopic picture (magnification ×500) of Bridge Cement 42.5 (own research)

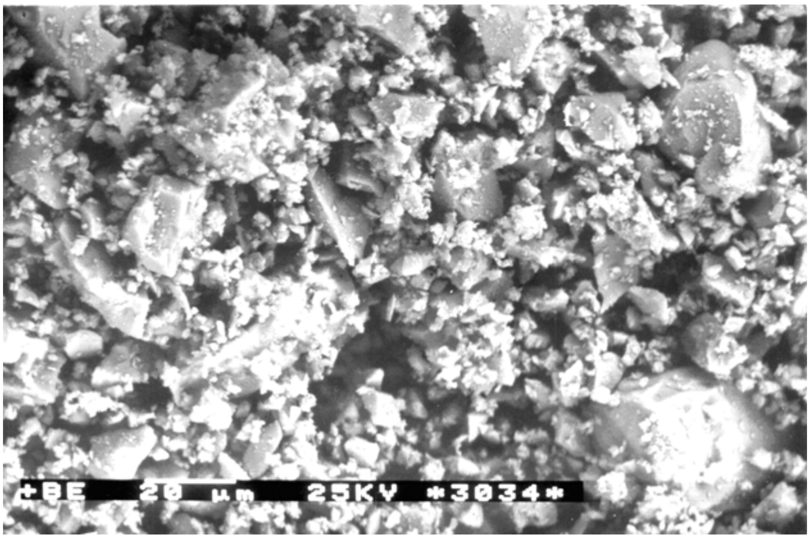
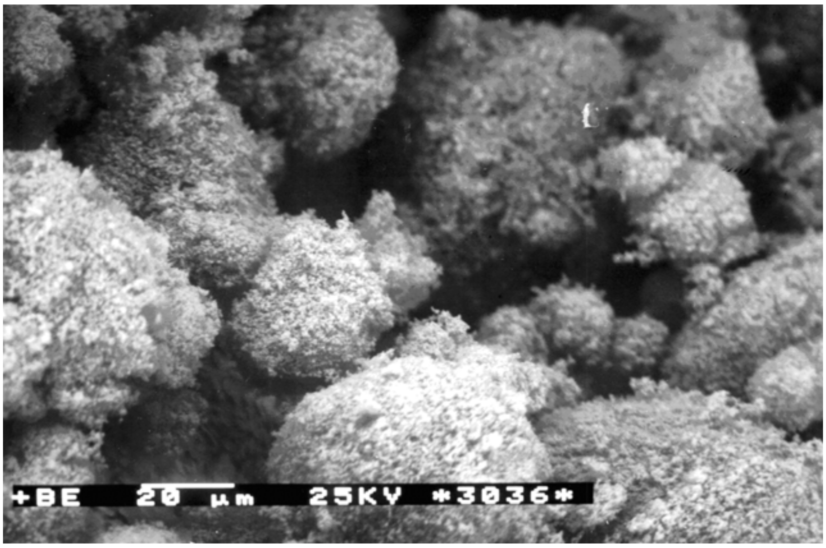


Fig. 2. The microscopic picture (magnification ×500) of Silica Fume (own research)



On Fig. 1 the microscopic picture of Bridge Cement 42,5 is presented and on the next one – Fig. 2 the microscopic picture of Silica Fume is presented as well. The different microstructure of these materials can be clearly seen. Cement grains are irregular but Silica Fume grains are fundamentally spherical.

Table 1. Composition and physical properties of the concretes mixes

	Component name, physical properties		O C	HPC
1.	Water to binder ratio	$\omega = \frac{W}{C + SF}$	0.52	0.32
2.	Cement	C [$kg \cdot m^{-3}$]	340	388
3.	Silica fume	SF [$kg \cdot m^{-3}$]	-	43
4.	Superplasticizer	SP [$kg \cdot m^{-3}$]	-	10.781
5.	Sand	S [$kg \cdot m^{-3}$]	989.0	988.0
6.	Basalt coarse aggregate	[$kg \cdot m^{-3}$]	989.0	988.0
7.	Water	W [$dm^3 \cdot m^{-3}$]	177.0	132.0
8.	Apparent density of concrete mix	ρ_a [$kg \cdot m^{-3}$]	2495.0	2555.0
9.	Density of concrete mix	ρ [$kg \cdot m^{-3}$]	2519.0	2577.0
10.	Tightness of concrete mix	S [-]	0.990	0.990
11.	Air pores volume	V_a [$m^3 \cdot m^{-3}$]	0.010	0.010
12.	Concrete mix consistence	$V_e - b_e$ [s]	10.5	9.0
13.	Cube strength of hydroisolated concrete after 28 days	$f_{c\ cube}$ [MPa]	50.4	93.5

Parameters of concrete microstructure

Concrete materials, because of character of physical and chemical processes, occurred in cement grout included in them, and on the point of contact of filler's grains with a cement paste, have a porous structure.

In the hardening process of cement grout, next to capillary pores, molecular (gel) pores, directly connected with gel products, are created. Capacity of capillary pores with reference to the unit of binder's mass can be calculated from the formula [31]:

$$\omega_{cap} = \frac{w}{s} - \left(\omega_H + \omega_p\right), \tag{1}$$

where w is initial capacity of water in the unit of cement grout's capacity [dm^3], ω_H is chemically tied water in the unit of binder's mass [$dm^3 \cdot kg^{-1}$], ω_p is out of network water which stays in binding gel's structure with reference to the unit of binder's mass [$dm^3 \cdot kg^{-1}$], α is degree of binder's hydration, S is binder's mass, w / s = ω is water – binder ratio.

Capacity of molecular (gel) pores with reference to the unit of binder's mass amounts [31]:

$$\omega_{gel} = 0.28 \cdot \alpha \cdot \left(\frac{1}{\rho_s} + \omega_H + \omega_p - V_s\right), \tag{2}$$

where: ρ_s is binder's density, V_S is a change of system's volume: water – cement with reference to the unit of cement's mass (contraction).

Structures parameters and thermo-physical characteristics of binders that compose the analyzed concretes: OC and HPC are presented in Table 2. Value of degree of binder's hydration in the process of its hardening is approximated on the basis of own calorimetric research of hardening's heat by the equation [31]:

$$\alpha = \exp\left[-c \cdot \left(\ln t_a\right)^{-d}\right] \cdot \frac{Q_{max}}{Q_o}, \tag{3}$$

where: c, d are empirically appointed parameters, t_a is reduced time [h], Q_{max}, Q_o are maximum and theoretical value of heat in binder's hardening.

Table 2. Parameters of structure and thermo-physical characteristics of binder

No	Concrete's mixture	$\omega_t = \omega_H + \omega_p$ [cm³·g⁻¹]	ω_H [cm³·g⁻¹]	ω_p [cm³·g⁻¹]	V_s [cm³·g⁻¹]	ρ_s [g·cm⁻³]
1.	OC	0.439	0.252	0.187	0.04690	3.125
2.	HPC	0.395	0.278	0.117	0.04221	2.973

In Table 3 equation's parameters (3), assigned to individual type of researched concretes, are presented. Equivalent time is described by the equation:

$$t_a = \int_0^t \exp\left[\frac{E_k}{R}\left(\frac{T_{(t)} - T_a}{T_{(t)}T_a}\right)\right]dt\ , \tag{4}$$

where: E_k is an energy of chemical process activation, R is universal gas constant [$J\cdot mol^{-1}\cdot K^{-1}$], $T_{(t)}$ is an absolute temperature of course of reaction [K], T_a is temperature of reference [K], t is time [h].

Energy of activation E_k is an important parameter which characterizes influence of temperature on kinetics of structural transformation of binders process. Raised temperatures of hardening activate structural transformations process in various degrees, depending on binder's composition. In author's own researches there was possible to obtain the higher level of activation energy comes out in HPC (26 $kJ\cdot mol^{-1}$) which include micro silica in comparison with OC (23 $kJ\cdot mol^{-1}$) without it.

Table 3. Parameters of (3) equation

No	Concrete	c	d	Q_{max} [$kJ\cdot kg^{-1}$]	Q_o [$kJ\cdot kg^{-1}$]
1.	OC	13.448	2.135	430	430
2.	HPC	132.679	4.025	313.47	387

The measure of cement materials structure's condition during their hardening determines, put by [19], porosity coefficient, given by an equation:

$$x = \frac{\omega_{gel}}{\omega_{gel} + \omega_{cap} + \omega_a}\ , \tag{5}$$

where: ω_{gel}, ω_{cap}, ω_a are adequately stand for gel, capillary and air pores capacity with reference to unit of binder's mass [$dm^3\cdot kg^{-1}$].

Taking into consideration equations (1) as well as (2) and providing $\omega = w / s$, one will get

$$x = \frac{0.28\cdot\alpha\cdot\left(\frac{1}{\rho_s} + \omega_H + \omega_p - V_s\right)}{0.28\cdot\alpha\cdot\left(\frac{1}{\rho_s} + \omega_H + \omega_p - V_s\right) + \omega - (\omega_H + \omega_p)\cdot\alpha + \omega_a}\ , \tag{6}$$

Porosity coefficient x assumes values of <0,1> range. For $\alpha = 1$, $\omega_a = 0$ and $\omega = \omega_H + \omega_p$, porosity coefficient $x = 1$, which means that hardened binder grout consists of hardened gel only.

Proprietary research on OC and HPC (compare Table 1) concrete made also possible to identify the influence of the modification of cement matrix on its microstructure. The results of the analysis indicate that there is a close relationship between the properties of cement matrix and the porosity coefficient x. Superplasticizer`s molecules adsorb on the surface of cement grains and lead to their deflocculating and in this way the use of cement is better that in the mixes without it [5,11,13,17,22,24]. The effect of a combined action of a superplasticizer and micro silica in HPC was observed. The effects of a cement matrix modification are especially visible in the analysis of inner microstructure. The research made by means of a scan microscope showed that microstructure of hardened cement paste in HPC is very consistent, well packed and definitely less porous in comparison to the OC.

The essential differences are presented in the structure of phase C – S – H of these types of concrete as well. These microstructures of OC and HPC cement matrix after one year of hardening process are shown on the Fig. 3 and 4 respectively.

Fig. 3. The microscopic picture (magnification ×500) of a hardened OC cement paste (own research)

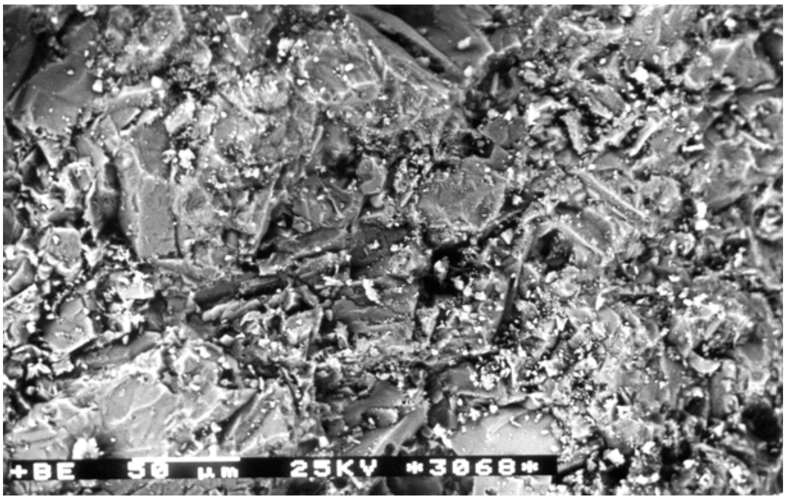
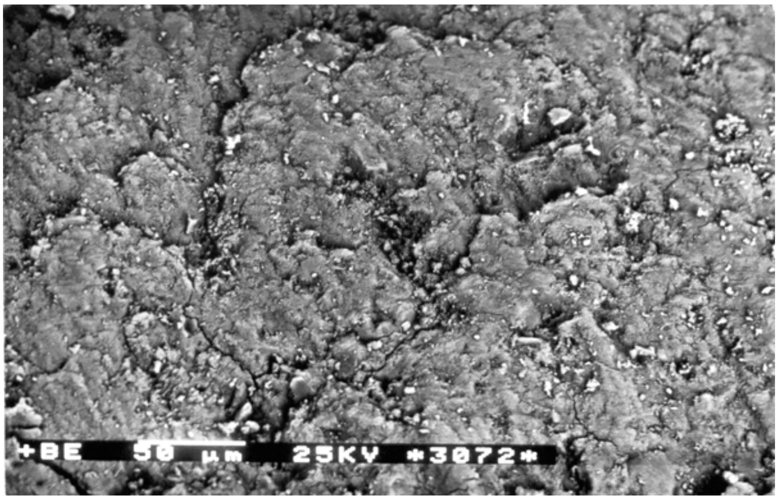


Fig. 4. The microscopic picture (magnification ×500) of a hardened HPC cement paste (own research)



Structure parameters in connection with compression strength

Mathematical model showing the dependence between concrete compressive strength and porosity coefficient of its structure (given by 6 formula), assumed in this paper, is depicted by general equation:

$$R_c = R_o \cdot x^a \cdot \exp[b(1-x)], \quad (7)$$

where: R_c is current compression strength of concretes in a given stage of structure's development, R_o is theoretical compression strength of concrete's, when x = 1, a, b are empirically characterized parameters, dependent on the type of concrete's mix.

General structure of formula (7) refers to the conception of specification of concrete strength in porosity coefficient's function [19] and ceramic material's model given by [30] as well. Exponential part of formula (7) expresses influence of grain's size, thus pores structure, on material's strength. A and b parameters of equation (7) for an individual groups of concrete's blends are given by the method of multiple regression with simultaneous definition of correlation coefficient. The results of computations for individual groups of concrete are depicted on Fig. 3 and 4.

Fig. 5. Graph of formula (7) for OC

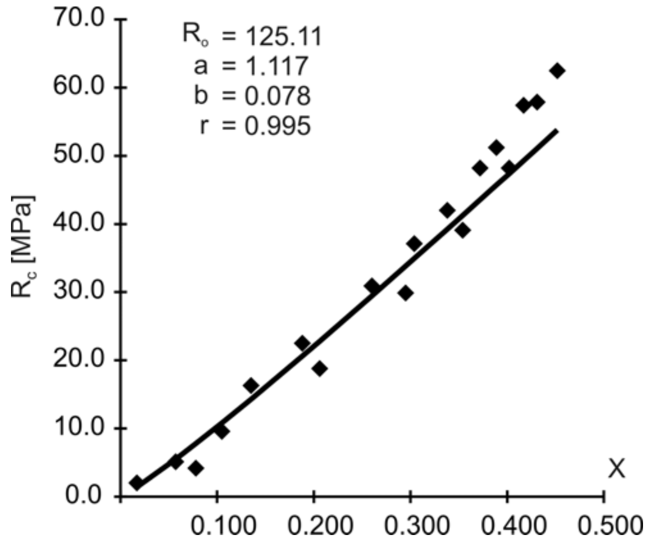
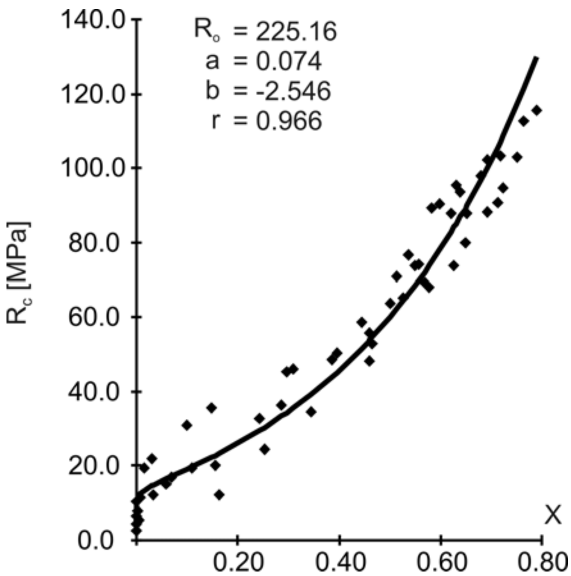


Fig. 6. Graph of formula (7) for HPC



TEMPERATURE FIELDS IN EXPERIMENTAL BLOCKS

General model assumption

Assuming that concrete verifies several hypotheses – continuum, isotropy and homogeneity – the well-known differential equation that governs the heat transfer problem in these cases is:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial T}{\partial r}=\frac{c\cdot\rho}{\lambda}\cdot\frac{\partial T}{\partial r}-\frac{q_v}{\lambda}, \tag{8}$$

in which λ is the thermal conductivity [$W\cdot m^{-1}\cdot K^{-1}$]; c is the specific heat [$J\cdot kg^{-1}\cdot K^{-1}$]; ρ is the density [$kg\cdot m^{-3}$]; q_v is the rate of heat generated per volume unit [$W\cdot m^{-3}$]; r is the radius of the cylinders [m]; T is the temperature [K] and t means time [s]. Replacing the partial derivatives with the differential quotients and making some transformations we can obtain an well-known equation:

$$T_{i,k+1} = T_{i,k} \frac{\lambda}{c\rho} \cdot \frac{\Delta t}{\Delta r^2} \left[\left(2 + \frac{1}{i}\right) T_{i,k} - \left(1 + \frac{1}{i}\right) T_{i+1,k} - T_{i-1,k} \right] + c\rho \Delta t \cdot qv_{i,k} , \tag{9}$$

Basing on an equation (9) one can calculate the temperature fields in time (k+1)Δt, assuming that the temperature fields in time kΔt are known. The energy transferred between the boundary and the environment may be expressed by Newton's law:

$$\alpha_p [T_n - T_f] = -\lambda \frac{\partial T}{\partial r} \bigg| n , \tag{10}$$

in which α_p is the boundary heat transfer coefficient [W·m^{-2} · K]; T_n is the boundary temperature [K]; T_f is the environment temperature [K].

Replacing the partial derivative $\frac{\partial T}{\partial r}$ with the differential quotient and making some transformations one may express the boundary temperature of the analyzed cylinders by the following formula:

$$T_n = \frac{\alpha_p \cdot \Delta r \cdot T_f + \lambda \cdot T_{n-1}}{\alpha_p \cdot \Delta r + \lambda} . \tag{11}$$

Internal heat sources function

To obtain the nonlinear temperature fields in large concrete columns, it was necessary to determine the internal heat sources function W(t) connected with the heat of concrete hardening Q_t which can be expressed by the equation:

$$Q_t = \int_0^t W(t) dt . \tag{12}$$

In literature there are many formulas making identifying the internal heat sources of hardening concrete possible. There are estimated on the bases of isothermal or adiabatic hardening process results [15,18,31]. It is possible to find the exponential function for the isothermal conditions [23,35], the form of parabola fragment [35] and in the form of polynomial [18]. For the adiabatic conditions of hardening concrete the internal heat sources may be approximated by exponential function [12] as well. In work [36] one can find the heat sources equation in the form of difference of two exponential functions. Commonly used in practice, interesting algorithm was carried out in work [37]. The internal heat sources function may be appointed on the bases of known isothermal functions series. It is possible to obtain this function on the bases of isothermal researches [37]. Influence of temperature on power of internal heat sources was carried out in work [9]. It is possible to define of this influence on the bases of temperature function, which may be given for example in the form of exponential function [9].

In this article heat of hydration effects in OC and HPC mixes were studied by means of BMR differential micro calorimeter. Based on experimental research, realized in temperatures 283 K, 298 K, 313 K, the internal heat sources function W(t) can be determined by the following formula [3]:

$$W(t) = Q_{max} \frac{p \cdot q \cdot \exp\left[-p (\ln t\alpha)^{-q} \right]}{t (\ln t\alpha)^{q+1}} , \tag{13}$$

where: Q_{max} is the maximum value of binder hydration heat [kJ·kg^{-1}]; p, q are the parameters described in Table 4; the variable ta is an equivalent time of the process [15,36] obtained by:

$$T_a = \int_0^t \exp\left[\frac{E_k}{R} \left(\frac{T_{(t)} - T_a}{T_{(t)} \cdot T_a} \right) \right] dt , \tag{14}$$

where: E_k is an activation energy of the chemical process presented in Table 4 [kJ·mol^{-1}]; T_a is a reference uniform temperature [K] and R is an universal gas constant [kJ·mol^{-1}·K^{-1}]; t means time [h].

The function described by formula (13) is monotonically decreasing and at the beginning of concrete hardening process is not good approximating of reality. Independently of this fact on the bases of experience of Authors of the work [3] this formula was accepted arbitrarily for the next investigations.

Table 4. Thermo physical properties of concretes

Type of concrete[1)]	Parameters							
	$c^{2)}$	p	q	Q_{max}	Q_o	$\lambda^{2)}$	E_k	α_p
OC	0.971	13.448	2.135	430	430	2.195	23	5
HSC	0.908	132.679	4.025	313.47	387	2.184	26	5

1) Composition and physical properties of the mixes are given in Table 1
2) Parameters calculated on basis of work [18]

Temperature distributions in the experimental blocks

Concrete hardening temperatures of the tested columns were estimated on basis of equations (9) and (11):

$$q_{vi} = W_i(t) \cdot B, \tag{15}$$

where: B is binders content [$kg \cdot m^{-3}$].

Examinations of concrete hardening temperatures were realized in two experimental blocks. In the researches supervisory measuring equipments with continually recording system of temperature fields were used. Locations of measuring points in analyzed experimental blocks are shown on Fig. 7. Registered temperature distributions in the OC and HPC blocks are presented in Fig. 8 and 9. Theoretical and experimental surface temperature distributions in the analyzed blocks are presented in Fig. 10 and Fig. 11.

Fig. 7. Location of measuring points in analyzed experimental blocks

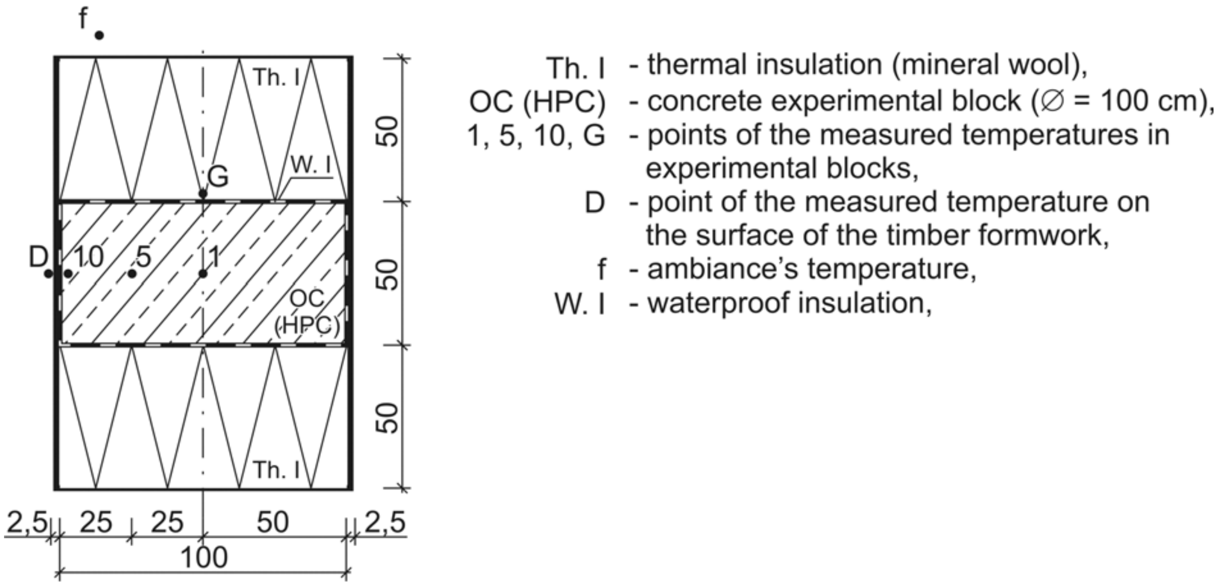


Fig. 8. Registered temperature distributions in the OC block

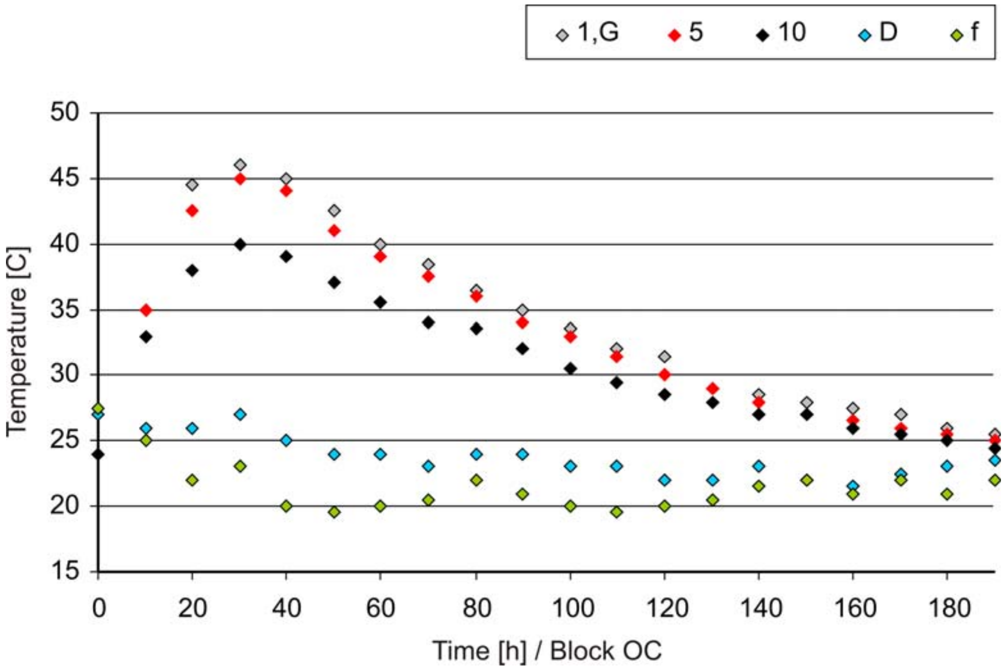


Fig. 9. Registered temperature distributions in the HPC block

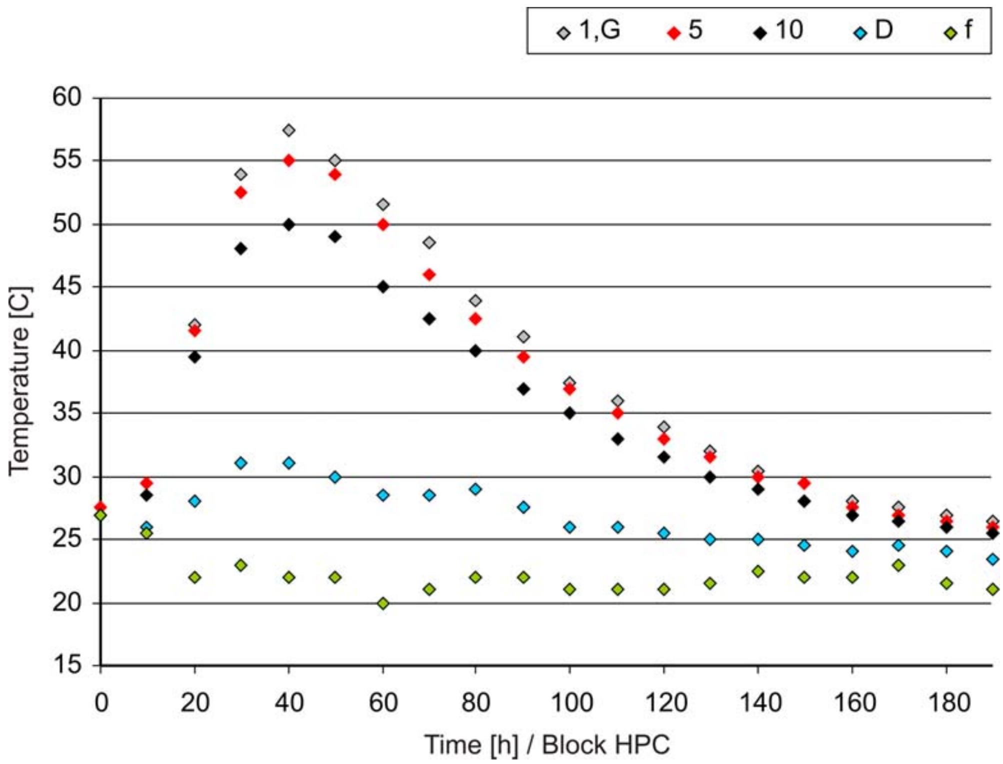


Fig. 10. Surface temperature of hardening OC block, T_{max} after 25 h

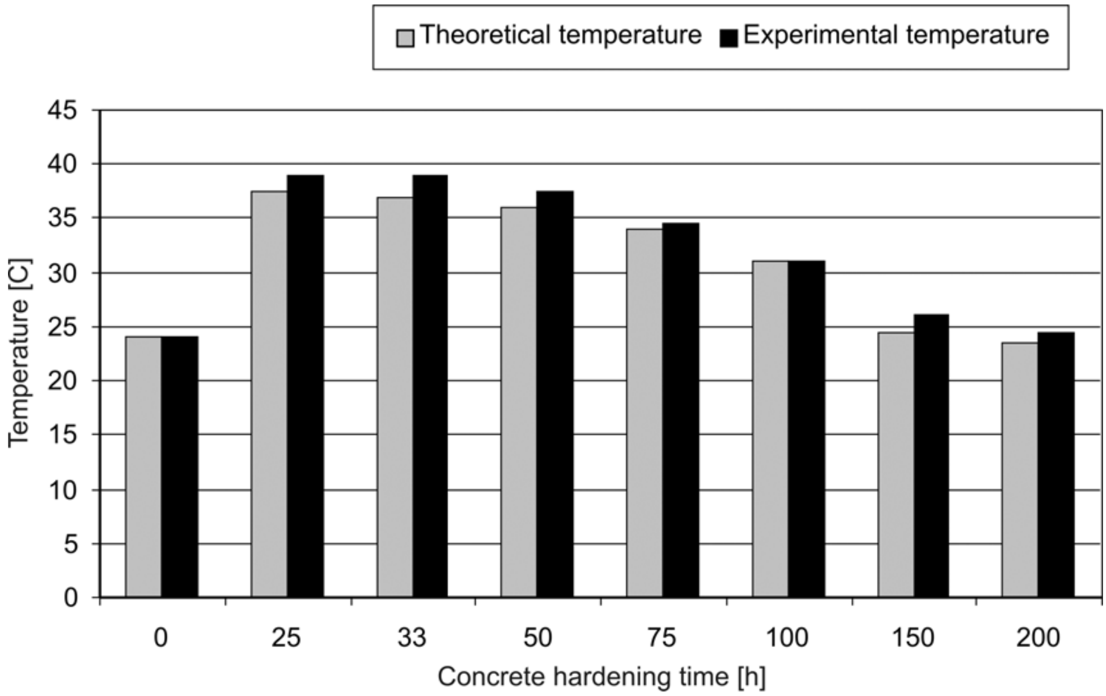
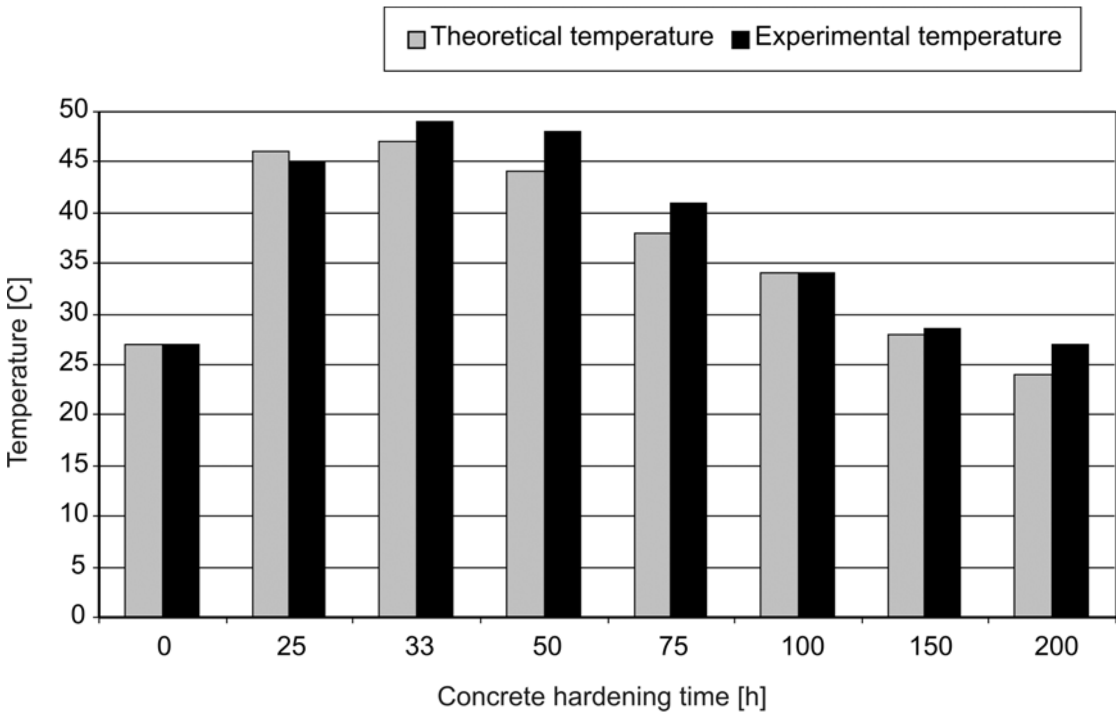


Fig 11. Surface temperature of hardening HPC block, T_{max} after 33 h



EXERTION OF EXPERIMENTAL CONCRETE BLOCKS CAUSED BY HEAT OF HYDRATION

Thermal stresses in the experimental cylindrical blocks-basic equations

In the paper the examples of numerical analysis of concrete blocks thermal stresses are presented. The stresses of external surface of endless cylinder were observed. Thermal stresses in the cylindrical experimental blocks can be expressed by equations [32]:

$$\sigma_r = \frac{\alpha_T E}{1-\nu}\left(\frac{1}{b^2}\int_0^b Trdr - \frac{1}{r^2}\int_0^r Trdr\right), \tag{16}$$

$$\sigma_\theta = \frac{\alpha_T E}{1-\nu}\left(\frac{1}{b^2}\int_0^b Trdr + \frac{1}{r^2}\int_0^r Trdr - T\right), \tag{17}$$

$$\sigma_z = \frac{\alpha_T E}{1-\nu}\left(\frac{2}{b^2}\int_0^b Trdr - T\right). \tag{18}$$

In this case we are analyzing thermal stresses on the external surface of the cylinders, therefore $\sigma_r = 0$ and $\sigma_\theta = \sigma_z$.

In these analyses it is impossible to observed an inversion of stresses effects. This effect, of course, need not take place in the point of cylinder external surface.

Analyses of the tested blocks exertion can be made on the grounds of Zandel`s hypothesis described in [10]:

$$\sigma_1 + \left(1 - \frac{R_r}{R_c}\right)\frac{\sigma_2}{2} - \frac{R_r}{R_c}\sigma_3 = R_r, \tag{19}$$

where: $\sigma_1 \geq \sigma_2 \geq \sigma_3$ - the main stresses [MPa], R_r, R_c - the tensile and compressive strength of concrete, respectively [MPa].

Based on formula (19), the exertion function can be expressed as follows:

$$W = \frac{\sigma_1}{R_r} + \left(1 + \frac{R_r}{R_c}\right)\frac{\sigma_2}{2 \cdot R_r} - \frac{1}{R_c}\sigma_3, \tag{20}$$

For the external cylinder surface, when $\sigma_1 = \sigma_2 = \sigma$ and $\sigma_3 = 0$, the exertion function can be described by the equation:

$$W = \frac{\sigma}{R_r}\left(1.5 - 0.5\frac{R_r}{R_c}\right). \tag{21}$$

Analysis of thermal stresses caused by exothermic of set-up process requires taking into account rheology phenomenon in hardening concrete inside massive structure. Euro code 2 [39] estimating after effects of rheology distortions, recommends the usage of equation of concrete state (shape) in algebraic form:

$$\varepsilon_{tot}(t,t_0) = \varepsilon_n(t) + \sigma(t_0)\cdot J(t,t_0) + \Delta\sigma(t,t_0)\cdot\left[\frac{1}{E_c(t_0)} + k\frac{\Phi(t,t_0)}{E_{c28}}\right], \tag{22}$$

where: $\varepsilon_{tot}(t,t_0)$ - total deformation of concrete; $\varepsilon_n(t)$ - independent on stresses, forced deformation; t_0 – time of initial load of concrete; t – time of calculations; $J(t,t_0)$ – the creep function after time t; $E_c(t_0)$ – the modulus of elasticity for concrete after time to; E_{c28} – the modulus of elasticity for concrete after 28 days; $\Phi(t,t_0)$ – the creep coefficient; k – the ageing coefficient; $\sigma(t_0)$ – stress at time to; $\Delta\sigma(t,t_0)$ – change of stress at $(t - t_0)$.

Equation (22) in case where solid value of deformation of producing concrete at to is kept, stress $\sigma(t_0)$, enables fixing of stress changing in relaxation process:

$$\Delta\sigma = \sigma(t_0) - \sigma(t) = \sigma(t_0) \cdot \frac{\Phi(t,t_0)\frac{E_c(t_0)}{E_{c28}}}{1 + k \cdot \Phi(t,t_0)\frac{E_c(t_0)}{E_{c28}}} . \tag{23}$$

Relational change of stress with time is defined by relaxation coefficient:

$$\Psi(t,t_0) = \frac{\Phi(t,t_0)\frac{E_c(t_0)}{E_{c28}}}{1 + k \cdot \Phi(t,t_0)\frac{E_c(t_0)}{E_{c28}}} . \tag{24}$$

Thermal stress, with regard to rheological deformation can be expressed by the equation:

$$\sigma(t) = \sigma(t_0) \cdot [1 - \Psi(t,t_0)], \tag{25}$$

where: $\Psi(t,t_0)$ is the relaxation factor.

Algorithm of calculations of temperature fields and exertion of hardening concrete

Application of superposition rule of influence, occurring in the various age of concrete in consecution of temperature changing in particular steps of time at use of equation (25), enables to estimate total thermal stresses in the point given at massive construction. Temperature distribution of hardening concrete in experimental blocks obtained earlier as well as structural and thermo physical parameters of applied building compounds defined before at usage of derived mathematical dependence let to estimate the exertion of hardening concrete according to algorithm given in Fig. 12.

In this paper examples of numerical analyses of concrete blocks exertion are presented. The exertion of external surface of endless cylinder $W_{10}(t)$ was observed. In presented algorithm material performances were taken into consideration on the bases of proper and literature investigations. The relationship between strength of concrete and modulus of concrete elasticity can be calculated on the basis of work [25]:

$$E = 4274 \cdot \rho_b \cdot (R_c)^{\frac{1}{3}}, \tag{26}$$

where ρ_b is the apparent density of concrete.

Using proper researches on the basis of equation (26) we obtain:

- for OC:

$$E = 10664 \cdot (R_c)^{\frac{1}{3}}, \tag{27}$$

- for HPC:

$$E = 10889 \cdot (R_c)^{\frac{1}{3}} . \tag{28}$$

The dependence of concrete tension strength on its compression strength can be calculated, using proper researches, on the basis of the following equation:

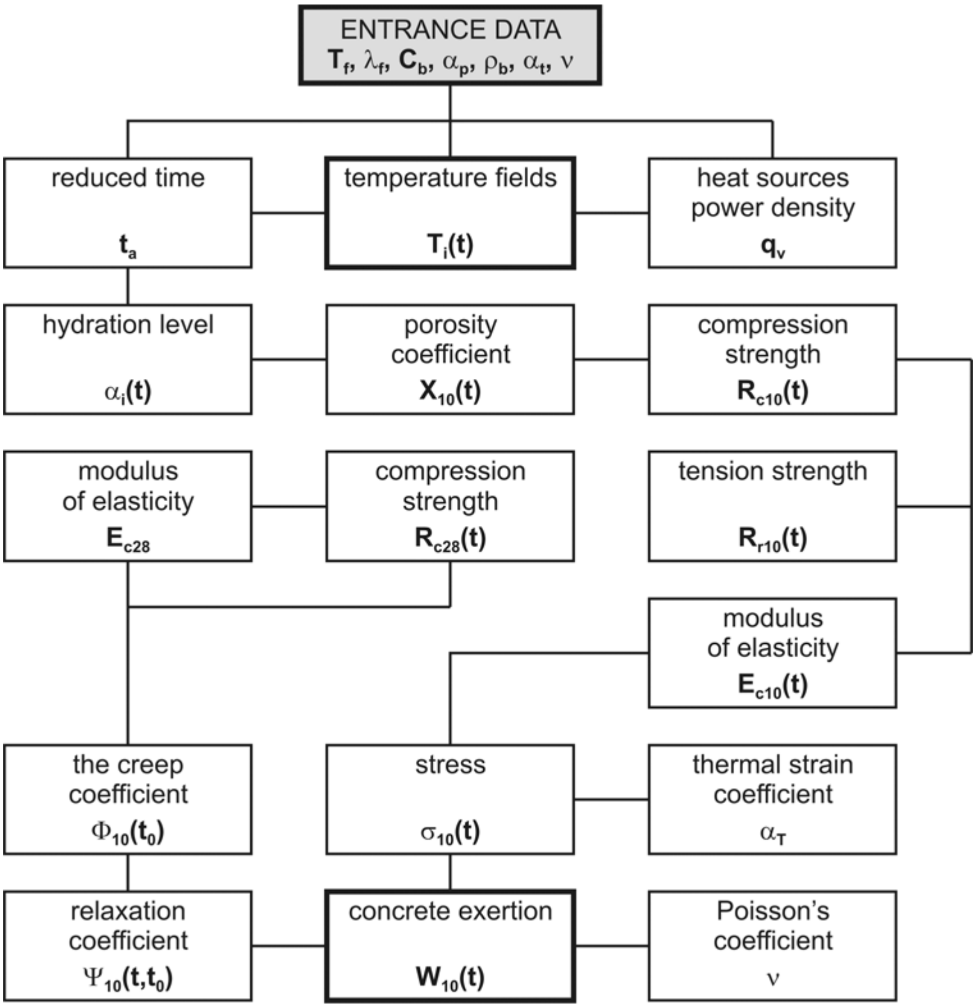
- for OC:

$$E = 0.070 \cdot (R_C)^{1{,}095}, \tag{29}$$

- for HPC:

$$E = 0.197 \cdot (R_C)^{0{,}748} . \tag{30}$$

Fig. 12. The algorithm of calculations of temperature field and exertion of hardening concrete



Analysis of test results of experimental blocks exertion

On the base of the equations and parameters described earlier, distribution of exertion function for OC and HPC hardening process can be calculated. The results given by PC – program are presented in Figs. 13 and 14.

Numerical analysis of exertion of hardening concrete in experimental blocks (OC, HPC) showed dissimilar process of exertion function. Maximum value of concrete exertion in blocks OC occurred after passage of 17 hours from the moment of its mould. In (particular) case of hardening concrete in block HPC analogous time amounts to 32 hours. Level of maximal exertion of hardening concrete in analyzed experimental blocks can be recognize as comparable. At this moment it has to be marked out that initial temperature of concrete compound placed in those blocks was different and for OC concrete was T_p = 24°C, however for HPC concrete T_p = 27°C.

Fig. 14. Graph of the exertion on the external cylinder surface – function for HPC

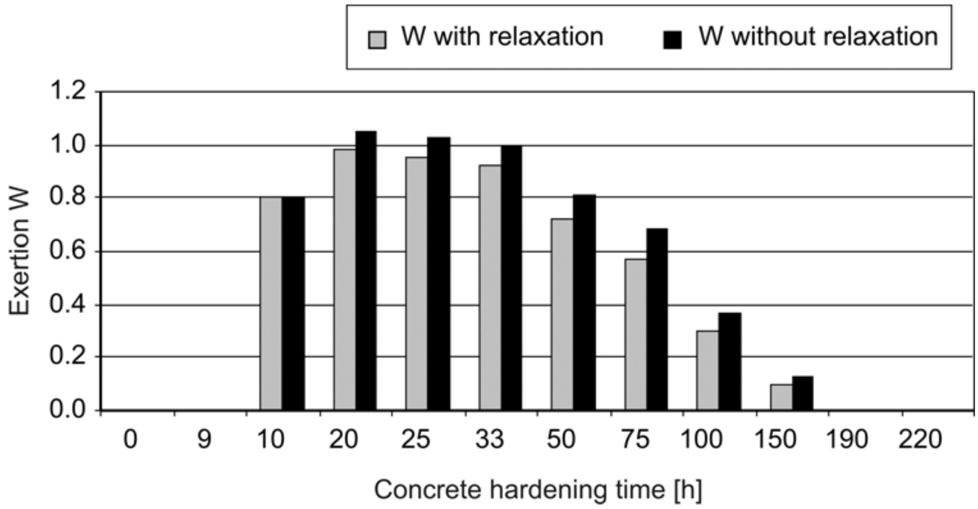
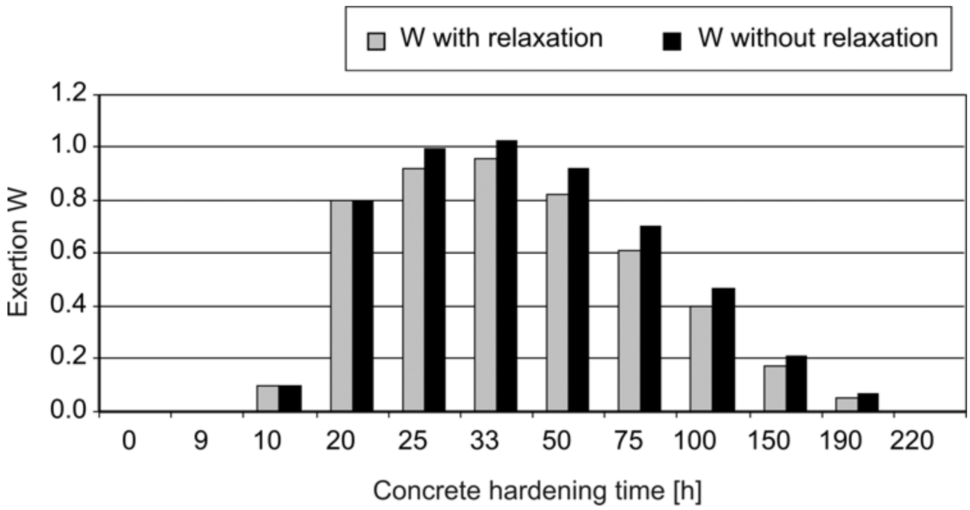


Fig. 13. Graph of the exertion on the external cylinder surface – function for OC



In Table 5 the results of numerical analysis made for tested concrete with usage of cylinder model where diameter equals 1.0 m were showed. T_{max} is maximal temperature reached by hardening concrete as a result of exothermic of structure-construction process with time $t_{\Delta T}$, after which maximal self warm-up of concrete ΔT. W_{max} indicates maximal power of exertion reached by concrete in t_{Wmax} time. Calculation were made with assumption that external ambient temperature T_f is even during whole process of hardening and equals initial temperature of concrete blend $T_p = 20°C$. Coefficient of taking over heat from outer cylinder surface is assumed as $\alpha_p = 5$ [W·m^{-2}·K].

Table 5. The results of numerical calculations for various concretes

Initial temperature of concrete blend T_p [°C]	Type of concrete	Water binder indicator W/S [-]	Self warm-up of concrete (inside solid)			Exertion (solid surface)	
			T_{max} [°C]	ΔT [°C]	$t_{\Delta T}$ [h]	W_{max} [-]	$t_{w,max}$ [h]
$T_p = T_f = 20°C$	OC	0.52	44.8	24.8	65.5	0.51	25.0
	HPC	0.32	50.3	30.3	62.8	0.54	42.3

On the basis of Table 5 it can be said that exertion of ordinary concrete (OC) and high-performance-concrete (HPC) is comparable. In each of tested concrete that maximal value of exertion (on the solid surface) appears sooner than maximal value of self warm-up inside solid. Maximal exertion of concrete is only slight size depends on relation between water and binder (W/S). The results of calculations made on that field for different concretes were showed in Table 6.

Table 6. Dependence of ordinary concretes exertion on water-cement ratio

Water-cement relation	Temperature		Exertion (solid surface) W_{max} [-]
	initial of concrete mix T_p [°C]	ambient T_f [°C]	
0.52	20	20	0.51
0.57			0.51
0.62			0.50
0.67			0.49

Profitable effects, revealed by lowering maximal level of concrete exertion hardening inside solid construction, can be reached by initial lowering of initial temperature of concrete blend to ambient temperature. The results of these calculations made for OC and HPC are showed in Table 7.

Table 7. Dependence OC and HPC exertion on cooling (down) concrete mix

Initial temperature of concrete compound T_p [°C]	Ambient temperature T_f [°C]	Exertion solid surface W_{max} [-]	
		OC	HPC
10	10	0.66	0.67
	15	0.63	0.66
	20	0.60	0.65
	25	0.58	0.64
	30	0.56	0.63
	35	0.55	0.62

In Figs. 15 and 16 cylinder (diameter 1.0 m) exertion function charts were showed. Cylinders were made of OC and HPC hardening at ambient temperature of $T_f = 20°C$. Initial temperature of concrete compounds both OC and HPC was equal to ambient temperature. On the basis of analysis of Fig. 13 and 14 it can be said that OC and BWW reach comparable value of maximal exertion, however in different time. Lag (delay) regarding to OC observed in HPC to gain maximal exertion, is caused by lagging effect (influence) of superplasticizer, present in HPC composition. On the basis of analysis of calculations result, slight influence of rheological distortion of hardening concrete in massive construction was stated on the level of its maximal exertion. Cutback (reduction) of maximal exertion on account of action of rheological distortion is similar in case OC and HPC and it's about 10%. Influence of rheological distortion on exertion of hardening concrete is tested and it was proved that massive construction is disclosed more intensively with time. Results of calculations brought through in this range for OC and HPC are showed in Table 8.

Table 8. Influence of observation time in rheological distortion action intensity in concrete exertion

W = exertion with relaxation / W = exertion without relaxation								$T_p = T_f$
For OC after time [hour]				for HPC after time [hour]				
100	150	200	250	100	150	200	250	
0.83	0.77	0.73	0.65	0.86	0.79	0.75	0.67	20°C

Fig. 15. Graph of the exertion function for OC block ($T_p = T_f = 20°C$), W_{max} after 25 hours

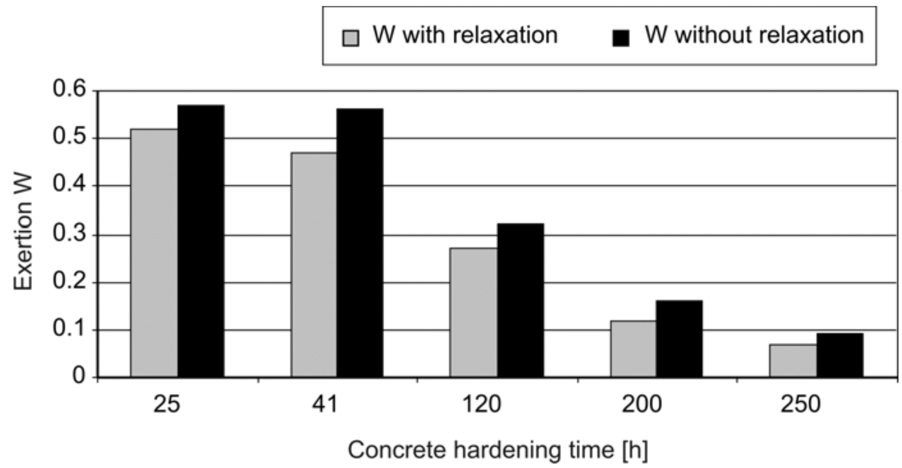
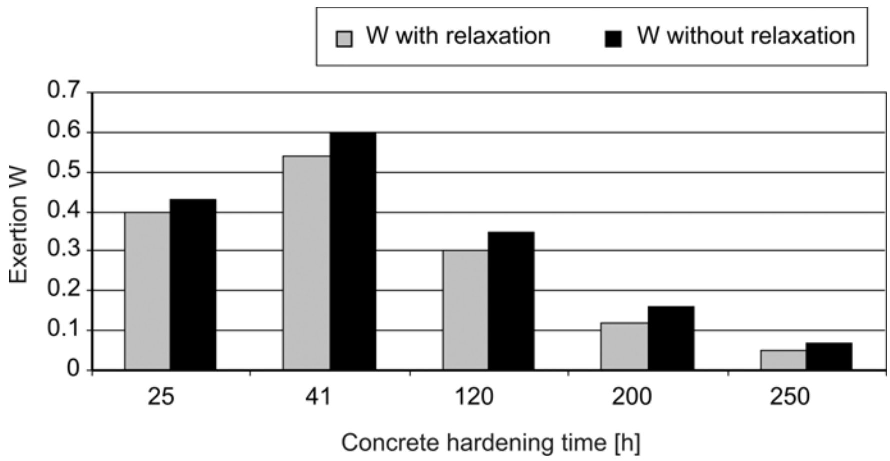


Fig. 16. Graph of the exertion function for HPC block ($T_p = T_f = 20°C$), W_{max} after 41 hours



CONCLUSIONS

Formulas, shown on the basis of established model assumptions, allow for expectations of development of concrete's strength under compression in wide range of changes of its structure, defined by porosity coefficient. This coefficient, giving the ratios between molecular (gel) pores capacity and total pores capacity in hardening concrete, is good description of structures – formed processes character, integrally connected with structure of porosity of hardening binding gel. The analyze shown permit statement that various concretes show various characteristics at the same value of porosity coefficient. It means that there is an influence of mineral additives and physical and chemical active admixtures on development of strength of hardening concrete. In the established model the fundamental influence on concrete's strength, in the period of its structural changes, exerts the cement gel with dissipated, molecular, capillary and air pores.

The setting and hardening of concrete is accompanied by nonlinear temperature distributions caused by the hydration heat development. Heat of hydration effects in large OC and HPC blocks where it was tested by experimental way. On the bases of Finite Difference Method the simulation model for development of temperature distributions of the investigated large concrete blocks was carried out. Results of the theoretical way were tested as well. The results obtained by experimental and theoretical way are comparable.

The simulation model of early age concrete is presented for prediction of development of the degree of hydration and structure formation in cement and chemical and mineral admixtures bared materials. The general idea of the modelling is to predict early age strength and static modulus of elasticity growth of ordinary and high strength concretes.

Simulation model of hardening concrete, based on the porosity factor, was used for the prediction of concrete strength. Simulation models for development of temperature distributions and development of mechanical properties are used for the thermal stresses analysis method of the investigated large concrete columns. The HPC and OC columns had comparable maximum exertion values. The difference concerned only the time needed to achieve the maximum exertion values, which was 17 hours for OC and 32 hours for HPC. Initial temperatures of OC and HPC mixes were 24°C and 27°C, respectively. Influence of relaxation on concrete exertion during the hardening process was minimal. No cracking was observed on the surface of the two investigated columns.

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Jan Ślusarek
Silesian University of Technology
Civil Engineering Faculty
Akademicka Str. No. 5, 44-100 Gliwice, Poland
E-mail: Jan.Slusarek@polsl.pl

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