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EARLY AGE THERMAL AND SHRINKAGE CRACKS IN CONCRETE STRUCTURES – INFLUENCE OF CURING CONDITIONS

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Abstract
The paper deals with issues related to often observed in practice cracks of concrete structures arising just at the stage of their construction. The main cause of these cracks are inhomogeneous volume changes associated with thermal and moisture gradients occurring in structures due to the hydration process. The paper discusses the influence of conditions during concreting such as initial temperature of concrete and ambient temperature on the distribution of temperature, moisture and induced stresses. Some methods of reducing the temperature gradients as use of insulation or pre-cooling are also considered. Two types of structures are analyzed: the massive foundation slab as the example of internally restrained structure and the reinforced concrete wall as the example of externally restrained structure.

Streszczenie
Zagadnienia prezentowane w artykule odnoszą się do zarysowań konstrukcji betonowych powstających już w fazie ich wznoszenia. Główną przyczyną powstawania tych rys są nierównomierne zmiany objętościowe twardniejącego betonu związane z powstającymi w procesie twardnienia betonu gradientami temperatur i wilgotności. W artykule analizowano wpływ warunków prowadzenia robót betonowych, takich jak temperatura początkowa betonu oraz temperatura otoczenia, na rozkład temperatur twardnienia betonu, zmian wilgotności i generowanych naprężeń. Rozpatrzono również niektóre metody ograniczania generowanych gradientów temperatur, takie jak stosowanie izolacji termicznej czy też wstępnego chłodzenia mieszanki betonowej. Analizowano dwa typy konstrukcji: masywne płyty fundamentowe jako przykład konstrukcji z więzami wewnętrznymi oraz ściany żelbetowe będące przykładem konstrukcji z więzami zewnętrznymi.

Keywords: **Early Age Concrete; Cracking; Initial Temperature; Insulation; Pre-cooling; Moisture; Stress; Massive foundation slab; RC walls.**

1. INTRODUCTION

The hydration of cement is a highly exothermic reaction and as a result concrete elements are subjected to temperature variations. In structural elements with thin sections the generated heat dissipates quickly and causes no problem. In thicker sections the internal temperature can reach a significant level. Furthermore, the internal temperature drops slowly while the surfaces in direct contact with environment cool rapidly. As a result, thermal gradients occur across the section of concrete elements. There are also moisture gradients due to the differences in loss of moisture from the surfaces and from the core of the element.

The volume changes due to the temperature and moisture variation have consequences in arising stresses in a concrete element. These stresses can be defined as self-induced stresses – they are related to internal restraints of the structure, resulting from non-uniform volume changes in a cross section. Additionally, the concrete element can be externally restrained. For example, such a restraint exists along the contact surface of mature concrete against which the new concrete element has been cast. In such case the forced stresses related to limitation of structure deformations freedom are also induced. The forced stresses are often observed in medium-thick elements such as a wall cast against an old set concrete. In this case a series of vertical cracks starting from the base are usually observed [1, 2, 3]. It should be also pointed that the stresses resulting from an external restraint of structure add to the effects of an internal restraint.

The risk of cracking in concrete structures increases with increasing temperature and increasing temperature difference between the interior and the surface of structural elements. A potential solution to reduce the cracking risk is to minimize the maximum temperature and temperature differences in concrete structures across a section. Specifications typically limit the maximum temperature to 65°C and the maximum temperature difference to 15÷20°C [4, 5]. This simple criterion based on engineering experience suggests that concrete can withstand the volume changes associated with such temperature difference. Accordingly, currently used methods include optimal concrete mix design, concrete cooling before or after placement, the use of smaller placements as well as insulation.

An important role is played by concreting and curing conditions related to the initial temperature of concrete mix, ambient temperature and mutual-couplings of these temperatures. Generally, favorable conditions for concreting of a massive concrete structure are considered as low but positive ambient temperature. The effective method of reducing the thermal effects can be also concrete cooling before placement [6, 7, 8]. Different methods depend on the local conditions, the willingness and experience of the concrete supplier can be applied to pre-cooling the concrete mix. The least costly way is using chilled water which pre-cools concrete by about 5°C. Shaved or chipped ice can substitute up to about 75 percent of the mix water to reduce the concrete temperature by up to 15 to 20°C [4]. In extreme pre-cooling liquid nitrogen is used to pre-cool the concrete mix and in this method the initial temperature can be reduced by about 35°C. However, the liquid nitrogen cooling requires highly specialized equipment and as a result it is the most expensive method.

Initial temperature of concrete mix can be estimated according to the formula [4]:

$$T_{initial} = \frac{0{,}22 \cdot (T_a \cdot W_a + T_c \cdot W_c) + T_w \cdot W_w}{0{,}22 \cdot (W_a + W_c) + W_w}, \qquad (1)$$

where:

$T_{i(i=k,c,w)}$ – temperature of ith component of concrete mix, °C,

$W_{i(i=k,c,w)}$ – mass of ith component of concrete mix related to 1m^3 of concrete mix, kg/m^3,

a, c, w – index related to aggregate, cement and water.

For example, for a concrete mix with components: cement 350 kg/m^3, water 175 l/m^3, aggregate 1814 kg/m^3 and assuming that the initial temperature of the components is equal to the ambient temperature $T_{ambient} = 20°C$ the following initial temperature of concrete mix can be obtained:

- without pre-cooling of concrete components $T_{initial} = 20°C$,
- with pre-cooling of water to temperature $T_w = 5°C \rightarrow T_{initial} = 16°C$,
- with pre-cooling of aggregate to temperature $T_k = 5°C \rightarrow T_{initial} = 11°C$,
- with simultaneous pre-cooling of water and aggregate to temperature $T_w = T_k = 5°C \rightarrow T_{initial} = 7°C$.

However, it should be remembered that the real initial temperature of concrete mix will be a little bit higher because of the mechanical work made during the process of concrete mix preparation.

The next method applied in the technology of massive concrete structures is the use of insulation. Insulation applied on surfaces of massive concrete elements slows down the cooling of the concrete surface and reduces the temperature difference [9]. In most cases, concrete insulating blankets are used, however, virtually any insulating material is often acceptable. The important issue is that insulation should be kept in place until the hottest portion of concrete cools to the temperature difference limit of the average air temperature. It should be noted that removing insulation cools only the surface, which increases the temperature difference and the likelihood of thermal cracking. Disadvantage of this method is the fact that insulation sometimes must be kept in place up to several weeks, especially on thicker placements.

The paper discusses the influence of conditions during concreting, such as initial temperature of concrete and ambient temperature, on the distribution of temperature, moisture and induced stresses. Some methods of reducing the temperature gradients as use of insulation or pre-cooling are also considered.

2. ASSUMPTIONS AND SCOPE OF ANALYSIS

Two types of structures are analyzed. One of them is a massive foundation slab as an example of internally restrained structure. The second one is a reinforced concrete wall cast against an old set foundation as an example of externally restrained structure.

The ambient temperature (Tz) was assumed to be 15°C, 20°C or 25°C. The initial temperature of concrete mix (Tp) was assumed as equal to the ambient temperature. Additionally, pre-cooling of the fresh concrete mix before casting by 5°C or 10°C has been investigated as well as the use of insulation. Insulation was applied on the upper surface of the massive foundation slab while for the wall the side surfaces were kept in insulation. For the massive slab two cases were considered: removing the insulation after 7 days as well as detaining the insulation for the whole time of cooling process. It was also assumed for the massive slab that wooden formwork made of 1.8 mm plywood remained on the bottom and side surfaces over the whole analyzed period. Detaining the wall in the formwork for the whole time of cooling process (either with or without insulation) in comparison to removing the formwork in the early construction stages (after 3 days) were investigated. First 20 days after concreting were observed in each case. In all cases it was investigated how the above potential solutions reducing the cracking risk would influence the early-age behavior of the analyzed structures.

Presented numerical results that illustrate the discussed problem were obtained with the computer codes TEMWIL, MAFEM_VEVP and MAFEM3D. The numerical model applied in the above mentioned programs can be classified as a phenomenological model. The influence of the mechanical fields on the temperature and moisture fields was neglected, but the thermal-moisture fields were modeled using the coupled equation of the thermodiffusion. Therefore, complex analysis of a structure consists of three steps. The first step is related to determination of temperature and moisture development, in the second one thermal-shrinkage strains are calculated and these results are used as an input for computation of stress in the last step. For the purpose of determination of the stress state in the early-age concrete structures the viscoelasto-viscoplastic model with a consistent conception was proposed. Full description of the model and computer programs: TEMWIL, MAFEM_VEVP and MAFEM3D is contained in [8, 10].

It was assumed that the analyzed slab was made of the following concrete mix: cement CEM II/BS 32.5R 350 kg/m^3, water 175 l/m^3, aggregate 1814 kg/m^3. In the wall cement type CEM I 32.5R was assumed. Thermal and moisture coefficients necessary for calculations were set in Table 1. The values of coeffi-

Table 1.
Thermal and moisture coefficients

Thermal fields		
Coefficient of thermal conductivity	λ ,W/mK	1.75
Specific heat	c_b, kJ/kgK	1.0
Density of concrete	ρ, kg/m^3	2340
Coefficient of thermal diffusion	α_{TT}, m^2/s	7.47·10^{-7}
Coefficient representing the influence of the moisture concentration on the heat transfer	α_{TW}, m^{2}K/s	9.375·10^{-5}
Thermal transfer coefficient	α_p, W/m^{2}K	6.00 (without protection) 3.58 (plywood) 0.66 (insulation) 0.81 (plywood+soil)
Heat of hydration	acc. to equation: $Q(T,t)=Q_\infty e^{\left[-at_e^{-0,5}\right]}$	for the slab: $Q_\infty = 350$ kJ/kg $a=200$ for the wall: $Q_\infty = 420$ kJ/kg $a=170$
Moisture fields		
Coefficient of the water-cement proportionality	K, m^3/s	0.3 10^{-9}
Coefficient of moisture diffusion	α_{WW}, m^2/s	0.6 10^{-9}
Thermal coefficient of moisture diffusion	α_{WT}, m^2/sK	2 10^{-11}
Moisture transfer coefficient	β_p, m/s	2.78 10^{-8} (without protection) 0.18 10^{-8} (plywood) 0.08 10^{-8} (insulation) 0.12 10^{-8} (plywood+soil)

cients were assumed according to suggestions given in literature [4, 5, 6, 7]. Additional layer on the concrete surface were considered by reducing thermal transfer coefficient according to the formula [6]:

$$\alpha_{pz} = \frac{\lambda_i \alpha_p}{\lambda_i + d_i \alpha_p} \tag{2}$$

where:

λ_i – coefficient of thermal conductivity of the additional layer, *W/(mK)*,

d_i – thickness of the additional layer, *m*.

The moisture transfer coefficient was reduced with the use of the same method [6, 10].

The foundation slab was assumed to be reinforced with a 20 cm x 20 cm mesh at the top, bottom and side surfaces. Steel class RB400 and Ø12 bars were assumed for calculations. The wall and the foundation of the wall were assumed to be reinforced with a near-surface reinforcing net of Ø16 bars. The wall was reinforced at both surfaces with horizontal spacing of 20 cm and vertical spacing of 15 cm. The foundation of the wall was reinforced with a 20 cm x 20 cm mesh at the top and bottom surface. Steel class RB400 was also assumed for the wall.

The development of mechanical properties in time was assumed according to CEB-FIP MC90 [11]. The final values for 28-day concrete were assumed as following: the compressive strength f_{cm} = 32.4 MPa, the tensile strength f_{ctm} = 3.0 MPa and the modulus of elasticity E_{cm} = 32 GPa.

3. MASSIVE FOUNDATION SLAB

The object of the conducted analyses was the massive foundation slab with the base dimension 10m x 10m and thickness 3m. The finite element mesh of the analyzed slab was shown in Figure 1. Because of the symmetry only the quarter of the slab was modeled. Essential elements of the slab that were used in presentation of calculation results were marked with black color in Figure 1.

Firstly, the temperature and moisture development were analyzed in slab with different curing conditions. The results are shown in Figure 2 and Figure 3.

It can be noticed that the character of temperature development and values of temperatures generated during the curing process strongly depend on the curing conditions. The results related to the temperature distribution can be summarized as follows:

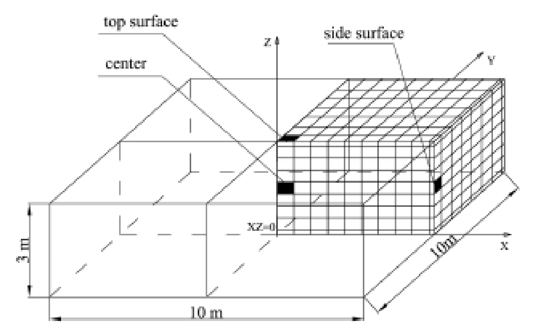

Figure 1.
Dimensions of massive foundation slab with the assumed finite element mesh

- in case of exposed upper surface of the slab and the lack of pre-cooling of concrete higher initial and external temperature (25°C) adversely affected the temperature of curing concrete. For such temperature the increment of temperature inside the slab (Tz25Tp25) was 13°C higher than in the slab with initial and external temperature equal to 15°C (Tz15Tp15),
- in all the analyzed cases the insulation layer on upper surface led to slight increase of maximum temperature inside the slab (only 1°C) and the maximum temperature was observed about 2 days later. The time of appearance of maximum difference in temperatures between the center and the upper surface of slabs was also significantly delayed (about 4 days). Additionally, the value of this difference was reduced to 6.7°C for slab ins.Tz15Tp15 (without insulation the difference is 23.1°C) and to 6.8°C for slab ins.Tz25Tp25 (without insulation the difference is 23.6°C). It can be also noticed that the maximum difference in temperatures between the center and the upper surface of the slab was similar, irrespective of different values of ambient and initial temperature. Similarly, the time of occurrence of the discussed differences was almost the same,
- removing insulation cools only the surface, which increases the temperature difference between the center and the upper surface of the slabs. In the slab denoted as ins.Tz25Tp25, after removal of insulation on the 7th day of concrete curing, the temperature difference between the center and the top surface rapidly increased from 6.8°C up to 23.1°C. In this case, as well as for the other slabs, the temperature difference after removal of insulation was close to the temperature differences obtained for the slab without any special methods (insulation or pre-cooling),

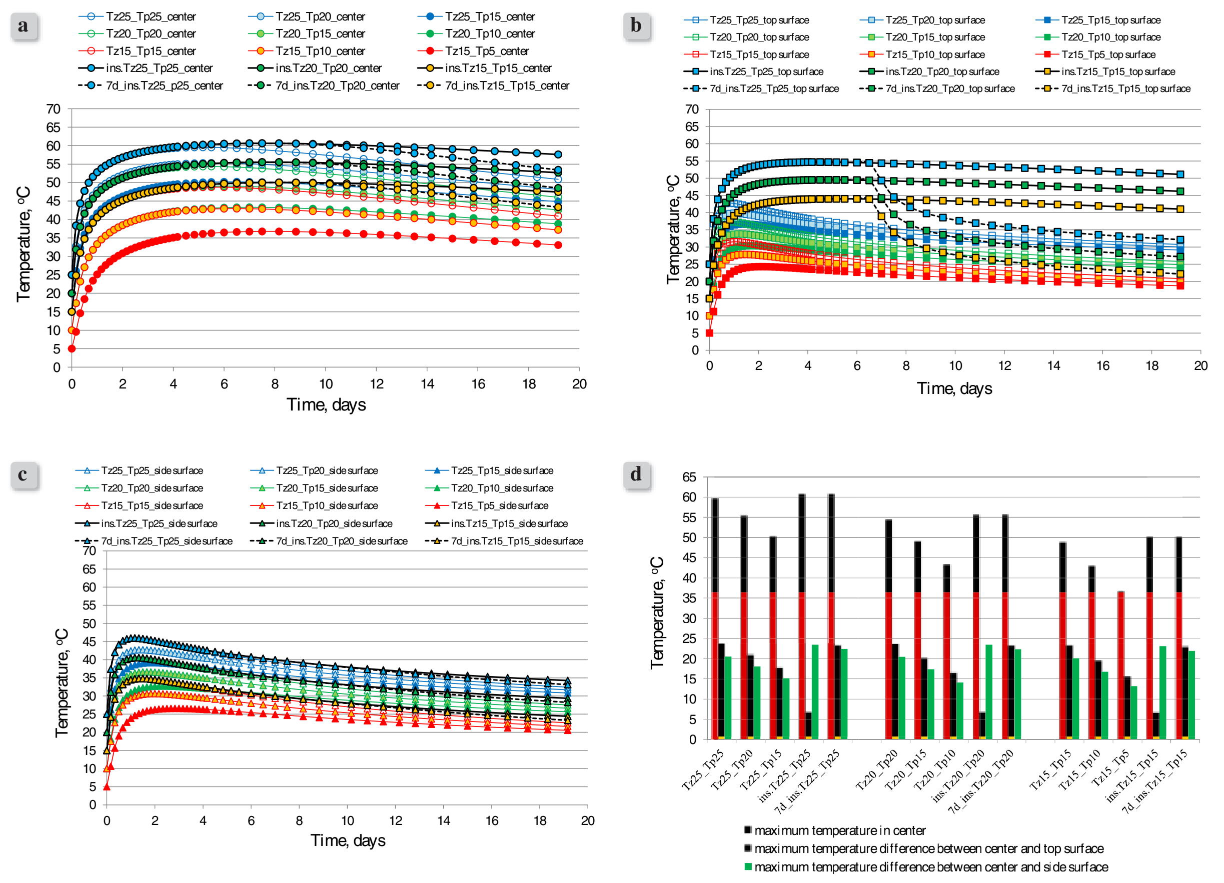

Figure 2.
Temperature development in essential elements of the analyzed slab: a) center, b) top surface, c) side surface, d) comparison of temperatures for different curing conditions

- particularly beneficial influence of pre-cooling of concrete can be seen in all presented examples. In case of pre-cooling, the maximum temperature inside the slabs as well as the temperature differences was reduced. The inside temperature in slab Tz15Tp5 reached the value of 36.8°C compared to the value of 48.8°C obtained for the slab Tz15Tp15 (slab without pre-cooling). Respectively, for the slab with the outside temperature of 25°C we obtained the values: 50.2°C in slab Tz25Tp15 and 59.6°C in slab Tz25Tp25,
- the initial temperature of concrete mix lower than the outside temperature about 10°C enabled to satisfy the condition of 20° difference of temperatures, which should not be exceeded in order to reduce the risk of cracking. The value of this difference was reduced to 15.4°C for slab Tz15Tp5 (without pre-cooling the difference was 23.1°C) and to 17.6°C for slab Tz25Tp15 (without pre-cooling the difference was 23.6°C). The time of occurrence of the discussed differences was also delayed (about 1.5 days).

The loss of moisture in the analyzed slabs is shown in Figure 3 for all the assumed curing conditions. The moisture development in the center and on the side surface (the surface with the formwork existing over the whole analyzed period) of the analyzed slabs has the same character and the similar amount of moisture was lost during the curing. The differences are observed on the top surface of the slab, where the highest loss of moisture is noticed for unprotected surface. The positive effect of insulation applied on the upper surface of the concrete slabs on moisture loss is visible in Figure 3. However, after removal of insulation on the 7th day of concrete curing the rapid loss of moisture from the upper surface was observed. No difference in moisture development was noticed for the slab with pre-cooling concrete mix and without pre-cooling.

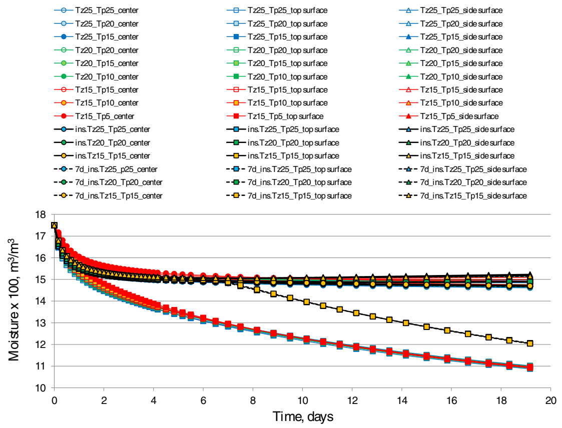

Figure 3.
Development of moisture content in essential elements of the analyzed slab for different curing conditions

The next step of the analysis was connected with determination of stress state and cracking area in the analyzed slab. Figure 4 presents development of stress σ_x in time for the massive foundation slab with different curing conditions. Additionally, the maximum values of the damage intensity factor obtained for different curing conditions are also presented in Figure 4. The damage intensity factor equal to 1 is equivalent to the stress path reaching the failure surface and signifies failure of the element (cracks). Three points of the slabs are considered: the point in the center of the slab, the central point on the top surface and the central point on the side surface (see Fig. 1). During the phase of temperature increase tensile stresses originate in surface layers of the element (top and side surface) and compressive stresses are observed inside the element. The results related to the stress distribution can be summarized as follows:

- in the center of the slab, regardless of the curing conditions, identical character and similar values of the generated compressive stresses were observed. The damage intensity factor also remained on a relatively low level and it did not exceed the value of 0.28 in relation to the value of 1.0 associated with the destruction. Only in case of insulation removal on the 7th day of concrete curing, increase in stresses was noticed,
- unprotected top surface of the slab is particularly vulnerable to cracking. Cracks on the top surface were observed in all slabs without pre-cooling and without insulation (Tz25Tp25, Tz20Tp20, Tz15Tp15). It is visible in Figure 4b where rapid decrease of stresses was observed in slabs: Tz25Tp25, Tz20Tp20, Tz15Tp15. The damage intensity factor for the top surface in these cases was equal to 1.0 (Fig. 4d). First cracks appeared relatively quickly: for the slab Tz25Tp25 it is 44 hours of concrete curing and respectively 56 hours and 72 hours for slab Tz20Tp20 and Tz15Tp15,
- insulation applied on the surfaces of massive concrete elements significantly reduced the tensile stresses on the top surface and the damage intensity factor (Fig. 4b, 4d). Removing insulation rapidly increased the tensile stresses and cracking was observed in such case (7d_ins.Tz25Tp25, 7d_ins.Tz20Tp20, 7d_ins.Tz15Tp15),
- pre-cooling of concrete mix can be considered as an efficient method of reducing the stress level and cracking risk. In all slabs where pre-cooling of concrete mix by 5°C or 10°C was applied the tensile stresses on the top surface were decreased and no cracks were observed,
- on the side surface of the slab, which was protected with formwork over the whole analyzed period, no cracking was observed. Relatively high values of damage intensity factor (Fig. 4d) was noted (about 0.8) for the slabs with insulation layer on the top surface (ins.Tz15Tp15, ins.Tz20Tp20, ins.Tz25Tp25). For these curing conditions the induced stresses also reached the highest level (Fig. 4c). The lowest stresses as well as the value of damage intensity factor on the side surface were obtained for the slab erected in the ambient temperature of 15°C and with pre-cooling of concrete mix by 10°C (Tz15Tp5).

The most advantageous curing condition for the analyzed slab is: ambient temperature equal to 15°C with simultaneous pre-cooling of concrete mix by 10°C (Tz15Tp5). The lowest stresses, both tensile and compressive, as well as the lowest values of damage intensity factor were obtained for such curing conditions.

4. MEDIUM-THICK STRUCTURES – RC WALL

The analyzed wall was assumed to have 20 m of length, 4 m of height and 70 cm of thickness, supported on a 4 m wide and 70 cm deep continuous foundation of the same length. The wall with the assumed mesh for finite element analysis is presented in Figure 5.

The results for two finite elements were analyzed and compared: in the middle of the wall for both internal and surface parts. The chosen elements are presented in Figure 5.

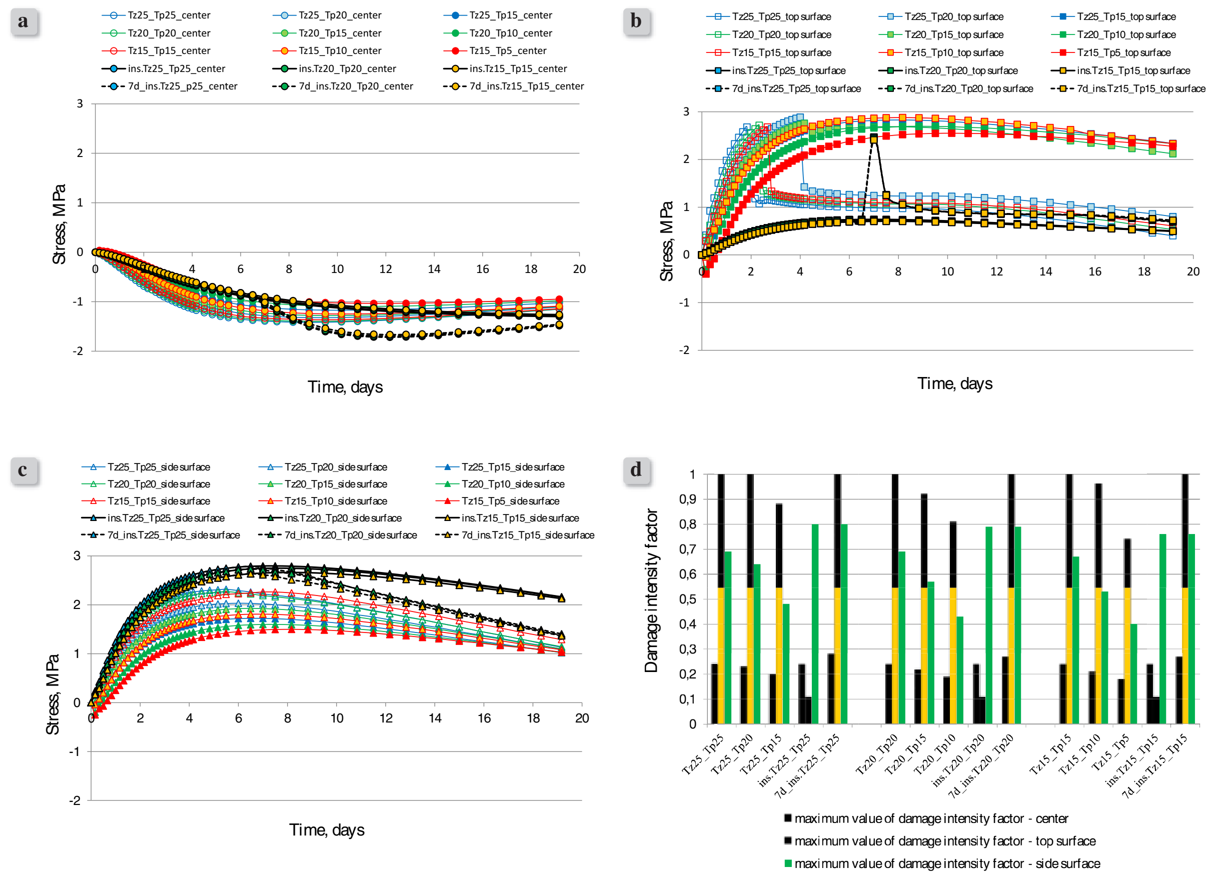

Figure 4.
Stress development in essential elements of the analyzed slab: a) center, b) top surface, c) side surface, d) comparison of damage intensity factor for different curing conditions

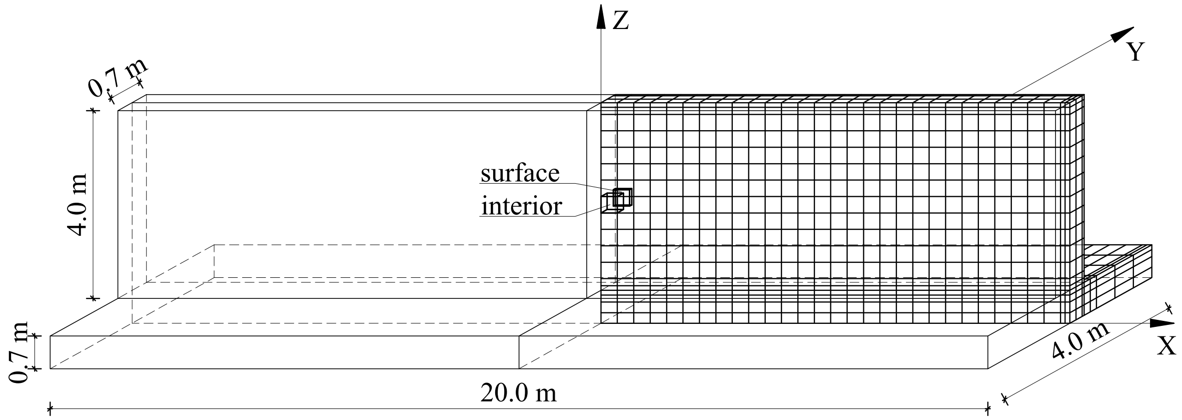

Figure 5.
Geometry of the analyzed reinforced concrete wall with the assumed finite element mesh

In the first step, the temperature and moisture developments were analyzed. Figure 6 and Figure 7 present the resultant diagrams. There is analogy in the character of temperature development in the structure in time independent of thermal conditions of concreting. The results can be summarized as follows:

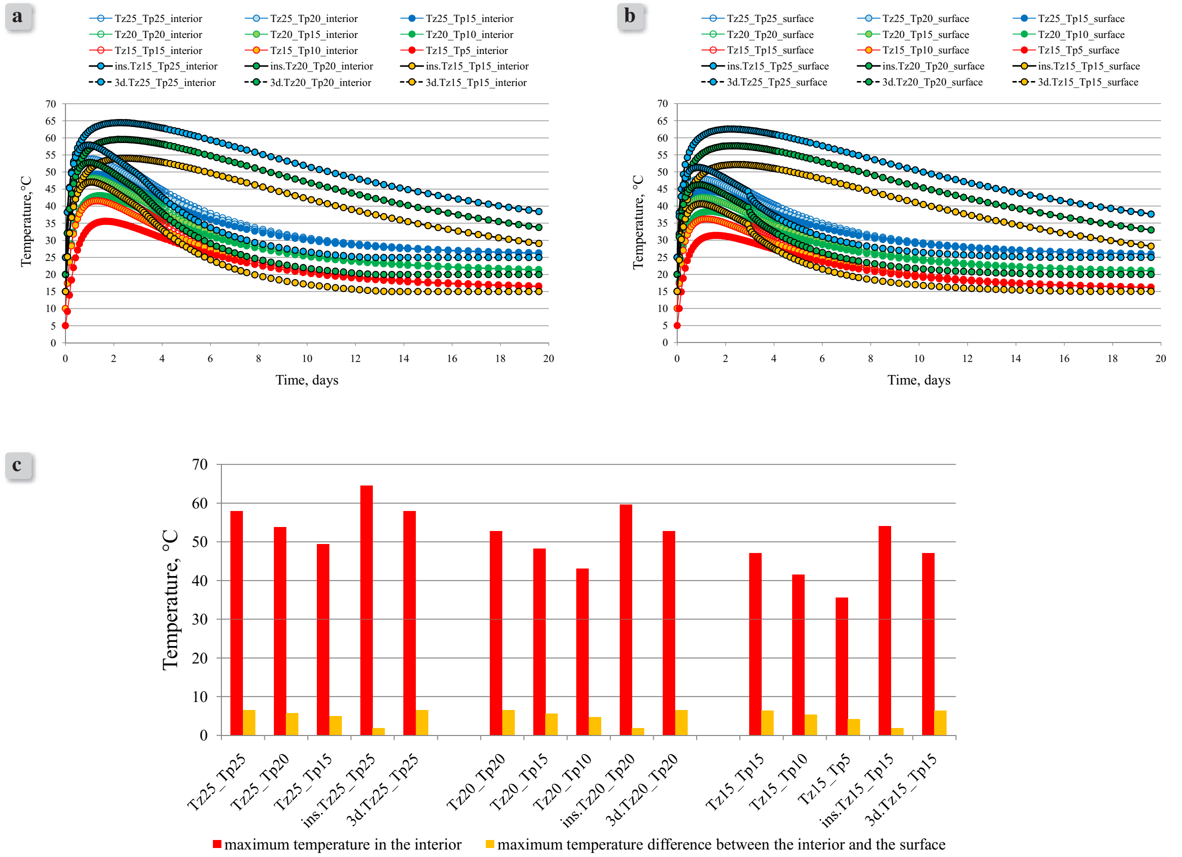

Figure 6.
Temperature development in essential elements of the analyzed wall: a) interior, b) surface, c) comparison of temperatures for different curing conditions

- in the walls kept in formwork for 28 days and with insulation (ins.Tz15Tp15, ins.Tz20Tp20, ins.Tz25Tp25) two characteristics were distinguished: one warmer in the central part of the wall and the other cooler at the edge. There was almost no difference at the thickness of the wall – the temperatures in the interior and on the surface of the wall differed by less than 2°C. It must be noted that in none of the analyzed cases the wall cooled down completely when the insulation was assumed,
- if there was no insulation used (Tz15Tp15, Tz20Tp20, Tz25Tp25), temperature development started to divert in different zones of the wall – the most heated part was in the interior of the wall in its mid-span while the least were the free-edge zones. The maximum temperature difference between the interior and the surface of the wall was observed at the moment when maximum hardening temperatures occurred and amounted to 6.5°C,
- removal of formwork in early phase of concrete curing (3d.Tz15Tp15, 3d.Tz20Tp20, 3d.Tz25Tp25) did not impact the value of the maximum hardening temperature – in all the analyzed cases it was reached not later than after 24 hours, so before the moment of removal. Nevertheless, a sudden temperature drop occurred once the formwork was removed, especially visible in the surface zones, which led to faster cooling of the wall,
- the highest temperatures were observed when there was formwork with insulation applied for the whole curing process and the highest external temperatures resulted in formation of the highest hydration temperatures: it was 54.1°C, 59.6°C and 64.5°C for ins.Tz15Tp15, ins.Tz20Tp20 and ins.Tz25Tp25 cases, respectively, in comparison to 47.1°C, 52.8°C and 57.9°C when no insulation was applied. Cooling process was then also the slowest, thus it may be concluded that it is advantageous to keep formwork to provide uniform cooling,

- this effect can be moderated by pre-cooling of concrete mix where positive impact was observed in all the cases. Lowering fresh concrete mix temperature by 5°C resulted in lowering the maximum hardening temperature by 5.7/5.5°C, 4.9/4.6°C and 4.3/4.1°C for the walls with/without insulation and the ambient temperatures 15°C, 20°C and 25°C, respectively. 10°C pre-cooling resulted in the analogical temperature decrease by 12.3/11.5°C, 10.5/9.7°C and 9.1/8.5°C,
- hence, there is a direct relationship between the value of pre-cooling temperature and the resultant lowering of the maximum temperature. The efficiency of this process is most significant in the insulated walls when the ambient temperature is low.

It must be noted that in case of externally restrained concrete structures the temperature gradients within the body of the structure are not a predominant cause of early age cracking. As presented in Fig. 6c the difference at the thickness of the wall is not much than 7°C which according to [4] should protect the wall from cracking. Nevertheless, it must be remembered that cracking of walls in early phases of concrete curing is caused by linear restraint generated by mature concrete of foundation and cracking depends more on the absolute value of maximum temperature than on the temperature difference [3].

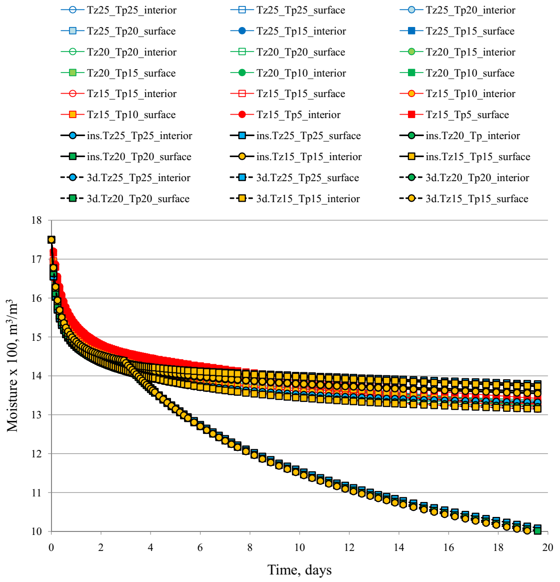

Figure 7.
Development of moisture content in essential elements of the analyzed wall for different curing conditions

The character of moisture migration is also similar regardless of the ambient and initial concrete mix temperatures for the same curing conditions. The following observations were made:

- application of the formwork with additional insulation for the whole analyzed time (ins.Tz15Tp15, ins.Tz20Tp20, ins.Tz25Tp25) guaranteed almost uniform water removal rate in the whole body of the wall,
- the most significant difference was noticed when the formwork was removed in the early phase of hardening process – in this particular case after 3 days. Migration rate accelerated instantaneously at the moment of removal, which was especially visible in the near-surface areas. Hence, the slowest water migration rate is ensured by keeping the wall in the formwork as long as possible. It is beneficial mainly for surface areas,
- pre-cooling had generally beneficial influence on limitation of water removal and its efficiency was increasing when the external temperature was decreasing. Pre-cooling by 5°C provided moisture content save by about $0.15{\cdot}10^{-2}$ m^3/m^3 when the ambient temperature was equal to 15°C, $0.05{\cdot}10^{-2}$ m^3/m^3 for 20°C but almost no saving was observed when concreting was proceeded in 25°C. Lowering the mix temperate by 10°C allowed greater saving which amounted to as much as 0.41, 0.19 and $0.06{\cdot}10^{-2}$ m^3/m^3, respectively. These results were observed for the non-insulated walls from which the formwork was removed in early days of curing (3d.Tz15Tp15, 3d.Tz20Tp20, 3d.Tz25Tp25).

For the known thermal-moisture fields, stress state was determined. The analogy in stress development in time was also observed. Figure 8 presents diagrams of stress σ_x development and the value of the maximum damage intensity factor for different curing techniques. The following observations we made:

- when formwork was applied for the whole cooling process (Tz15Tp15, ins.Tz15Tp15, Tz20Tp20, ins.Tz20Tp20, Tz25Tp25, ins.Tz25Tp25), the higher values of stresses were observed in the interior of the wall,
- if there was insulation used, the difference in stresses in the internal and surface parts of the wall was almost negligible and stress distribution was moderate in character. Although in this case compressive stresses reached the highest values (2.1, 2.2 and 2.3 MPa for ins.Tz15Tp15, ins.Tz20Tp20 and ins.Tz25Tp25, respectively), the moment of

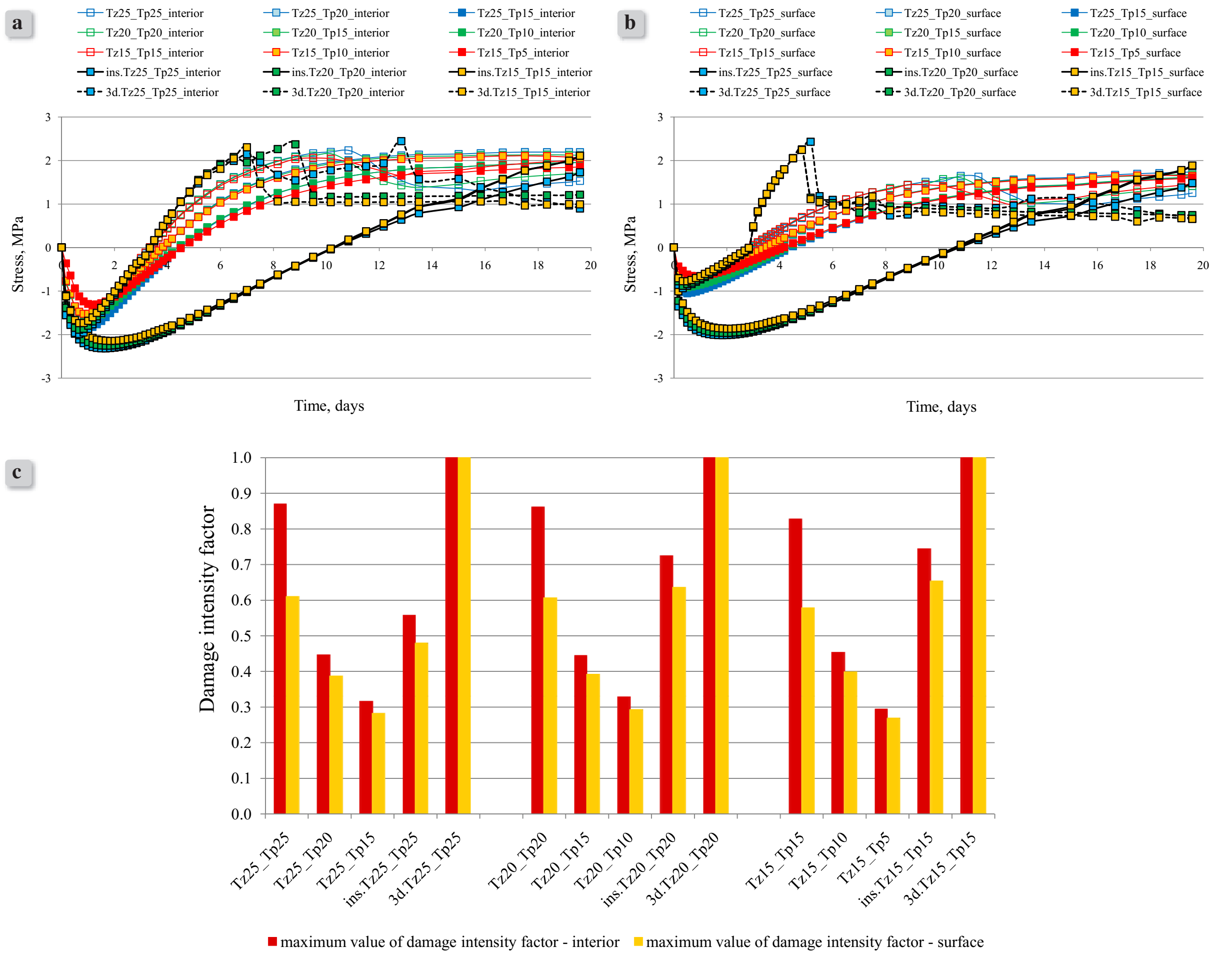

Figure 8.
Stress development in essential elements of the analyzed wall: a) interior, b) surface, c) comparison of damage intensity factor for different curing conditions

stress inversion occurred late (after 10.5 days) so originating tensile stresses could not expose the structure, whose tensile strength was already high at the time, to the risk of cracking. The maximum value of damage intensity factor for surface/internal part of the wall with insulation was 0.48/0.56, 0.29/0.33 and 0.27/0.29 in comparison to 0.61/0.87, 0.60/0.86 and 0.57/0.83 (wall without insulation) for 15°C, 20°C and 25°C temperatures, respectively,

- lack of insulation resulted in diversification of stress development in different wall zones. The greatest values of stresses – both compressive and tensile – occurred in its internal part,
- early formwork removal had significant impact on stress development in the wall. It was not observed in the first phase, as the stress inversion usually occurred about the moment the formwork was removed – in 3 days for the surface areas and 3.5 days for the interior. The procedure, however, accelerated development of tensile stresses (first cracks were observed after 5 days), which accompanied with relatively low tensile strength of the wall resulted in extensive cracking. In all the analyzed cases early formwork removal led to reaching damage intensity factor value equal to 1 in all the zones which is equivalent to cracking of the wall in its whole thickness (through cracks can be expected),
- the influence of pre-cooling was positive. In every case the values of stresses – compressive and tensile – were reduced and the moment of inversion was decelerated when fresh concrete mix was cooled,
- in the walls where no insulation was applied lowering the mix temperature even by 5°C provided

tensile stress reduction in the whole structure which resulted in a significant decrease in damage intensity factor in comparison to no pre-cooling applied,

- in case the formwork was removed early, pre-cooling ensured slight reduction of stresses, and consequently limitation of cracking, but this favorable influence was observed only when pre-cooling by 10°C was applied and only in the interior of the walls.

In conclusion, keeping the formwork during the whole curing process of the wall is advantageous because it ensures moderate progress of the process, especially by limiting moisture removal and cooling rate. Originating stresses also exhibit moderate values. As a consequence, it is possible to reduce or even eliminate cracking resulting from significant tensile stresses. Additional thermal insulation has generally positive influence on cracking risk in walls but its application must be thoroughly considered. On the one hand, stress inversion in the insulated walls occurs later and resulting tensile stresses do not pose the wall to the risk of cracking. On the other hand, though, originating temperatures reach significant values which leads to formation of high compressive stresses in the early phases of concrete curing.

It must be remembered that in the walls detained in the formwork the higher values of stresses were observed in the interior of the wall. Hence, the wall is prone to severe internal cracking which is extremely difficult to control.

It was observed that concrete curing should be performed under moderate environmental conditions (ambient temperature 15°C) with initial cooling of concrete mix additionally applied. In such case pre-cooling has the greatest efficiency: it allows for limitation of self-heating temperatures and moisture removal, reduction of compressive stresses, delaying inversion and consequently reduction of tensile stresses and cracking.

5. CONCLUSIONS

The problem with high temperatures arising during the hardening of concrete has been known since the 30s of last century when first dams were built in the United States. A lot of efforts of engineers and researchers are focused on creation of efficient methods for mitigation of the negative effects of concrete curing in massive structures. It is necessary to control temperature and moisture changes in the structure but earlier selection of optimum conditions for concreting should also be done. One of the recommended methods to reduce negative effects of self-heating of structures is the use of insulation layer in order to inhibit the rapid cooling of surfaces. The concrete mixture or its components can be cooled to the temperature lower than the surrounding temperature in order to reduce the temperature difference.

As a rule for massive concrete structures the maximum temperature difference between the interior and the exterior of a concrete structure should not exceed 20°C [3, 4, 5, 12, 13, 14]. Temperature difference condition is not that important in medium-thick but externally restrained structures where cracking results predominantly from the linear restraint of mature concrete of previous layers. In such structures the maximum temperature must be restricted and its allowable value (and consequent strain) depends on the degree of restraint.

This paper discusses the influence of different curing conditions on the distribution of temperature, moisture and induced stresses. Two types of structures were selected for the analysis: the massive foundation slab and the reinforced concrete wall. It should be pointed that presented results are related to the assumed concrete mix and cement type. In practical prediction of cracking risk in concrete structures the real concrete mix and cement parameters should be encountered.

Particularly beneficial influence of pre-cooling of concrete was showed in all the presented examples. In case of pre-cooling, the maximum temperature inside structures as well as the temperature differences was reduced. Consequently, the level of generated stresses and cracking risk were also reduced. The temperature differences were decreased, too, when insulation was applied on the surfaces of concrete elements. The crucial disadvantage of this method, however, is the fact that insulation must be kept in place up to several weeks because its removal cools only the surface which increases the temperature difference and the likelihood of thermal cracking.

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