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EARLY AGE THERMAL AND SHRINKAGE CRACKS IN CONCRETE STRUCTURES – DESCRIPTION OF THE PROBLEM

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Abstract
The issues related to often observed in practice scratches and cracks of concrete structures arising just at the stage of their construction are discussed in the paper. The main cause of these cracks are inhomogeneous volume changes associated with temperature rise caused by exothermic hydration process of cement as well as with moisture exchange with the environment. The paper discusses the origin of early cracks and their character in massive foundation slabs and concrete walls. The main technological and material factors contributing to increase of cracking risk in early age concrete as well as some methods of reducing this risk are also outlined in the paper.

Streszczenie
Zagadnienia prezentowane w artykule są związane z często obserwowanymi w praktyce zarysowaniami i spękaniami konstrukcji betonowych, powstającymi już w fazie ich wznoszenia. Główną przyczyną powstawania tych zarysowań są nierównomierne zmiany objętościowe twardniejącego betonu związane ze wzrostem temperatury betonu wywołanym egzotermicznym procesem hydratacji cementu oraz z wymianą wilgoci twardniejącego betonu z otoczeniem. W artykule omówiono przyczyny występowania wczesnych rys i spękań oraz ich charakter w masywnych płytach fundamentowych oraz w ścianach żelbetowych. Przedstawiono również główne czynniki technologiczno-materiałowe wpływające na zwiększenie ryzyka zarysowania we wczesnym okresie dojrzewania betonu jak również metody ograniczania tego ryzyka.

Keywords: **Early Age Concrete; Cracking; Thermal-shrinkage stresses; Massive foundation slabs; RC walls.**

1. INTRODUCTION

Cracks are commonly observed in concrete structures and it is important to understand that all cracks may have different causes and different effects on long-term performance of structures. The cracking of a concrete member is a problem when the crack width exceeds a critical value such that the durability, serviceability and appearance of the structure are impaired. Cracks may develop in concrete for a variety of reasons, but the main principle is the fact that concrete is a quasi-brittle material with a low capacity for deformation under tensile stress. Visible cracking occurs when the tensile stresses exceed the tensile strength of the material. The development of tensile stresses in concrete may be due to mechanical loading, some deleterious reactions and environment loading. Mechanical loading is commonly considered as being responsible for generating the majority of the tensile stresses in concrete structures while many of the cracks in concrete can be traced to intrinsic volumetric changes or the deleterious chemical reactions. The volume changes results in response to moisture, chemical, and thermal effects in concrete.

Test results and observations in nature indicate a different time of cracks formation and the difficulty with

Table 1.
Types of reasons for cracks in concrete structures

TYPES OF CRACKS					
CRACKS OCCURING BEFORE HARDENING		CRACKS OCCURING AFTER HARDENING			
FRESH CONCRETE		YOUNG CONCRETE (early age, immature concrete)		MATURE CONCRETE	
CONSTRUCTION MOVEMENT	FORMWORK MOVEMENT	VOLUME CHANGES	AUTOGENOUS AND DRYING SHRINKAGE	STRUCTURAL CRACKS	DESIGN LOAD/ /ACCIDENTAL OVERLOAD
	SUB-GRADE MOVEMENT				FATIGUE
PLASTIC	PLASTIC SHRINKAGE			VOLUME CHANGES	DRYING SHRINKAGE
	PLASTIC SETTLEMENT				EXTERNAL SEASONAL TEMPERATURE VARIATIONS
	AUTOGENOUS SHRINKAGE		TEMPERATURE VARIATIONS DUE TO HYDRATION PROCESS	PHYSIO-CHEMICAL	CORROSION OF REINFORCEMENT
FROST DAMAGE	PREMATURE FREEZING				FREEZE-THAW CYCLING
	SCALING, CRAZING				ALKALI-AGGREGATE REACTIONS
					CEMENT CARBONATION

determining one reason of cracking. In understanding why and when cracks develop in concrete it may be helpful to outline the classification of cracks [1, 2]. Table 1 provides some of the common types of cracks and distinguishes these cracks based upon when they appear in concrete.

Time of appearance of cracks before concrete hardening is from 10 minutes to 6 hours. These cracks appear primarily due to settlement, construction movements and excessive evaporation of water. The method of elimination of such cracks is the close attention to the mixture design, material placement, and curing conditions. Cracks that occur after the concrete has hardened may be due to a variety of reasons and the time of their appearance can be from 12 hours even up to many years. The additional, more precise subdivision is usually made here: into early age (immature) and mature concrete, mainly in order to specify the behavior of early age concrete. As the subject of the paper is cracking in early age concrete, therefore this issue will be discussed in next chapters.

2. CRACKS IN EARLY AGE CONCRETE

One of the major reasons of cracking in early age concrete is the volume changes due to the temperature and moisture variations during hardening process. The variations of the concrete temperature during curing are the result of exothermic nature of the chemical reaction between cement and water. When cement is mixed with water, heat is liberated - this heat is called the heat of hydration. This heat dissipates relatively quickly in thin concrete sections and causes no problems. In thicker sections, due to the poor thermal conductivity of concrete, high temperature gradients may occur between the interior and the surface of structural elements. Concrete curing is also accompanied with a moisture exchange with the environment in conditions of variable temperatures. The loss of water trough evaporation at the surface of element results in shrinkage, which is classified as an external drying shrinkage. There is also internal drying resulting from the reduction in material volume as water is consumed by hydration, which is classified as autogenous shrinkage. Additionally, the chemical shrinkage is also distinguished and it occurs because the volume of hydration products is less than original volume of cement and water.

The volume changes due to temperature and mois-

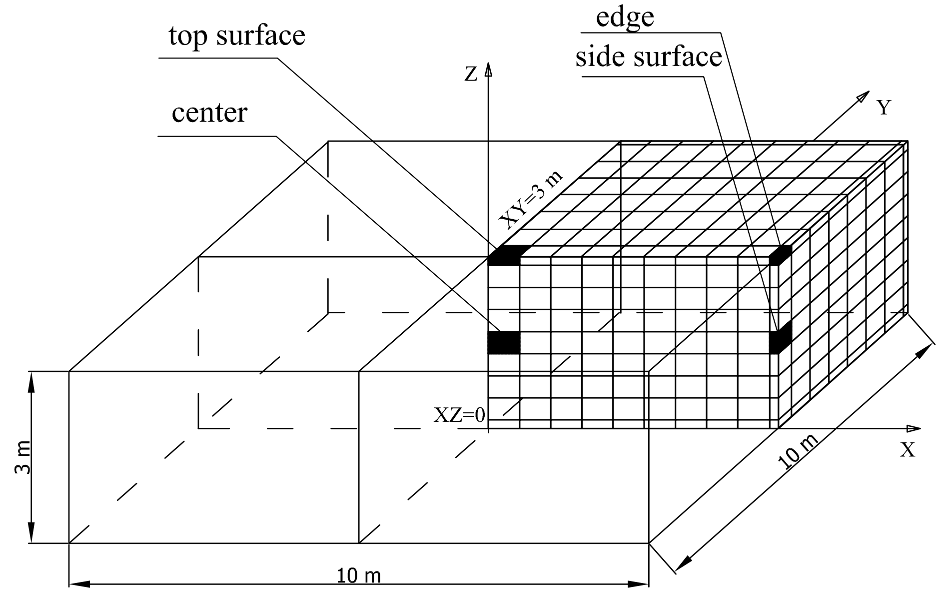


Figure 1.
Geometry of an exemplary massive foundation slab with the assumed finite element mesh

ture variation have consequences in arising stresses in the concrete element. When the tensile stress exceeds the tensile strength of the concrete cracks can be observed in structural element. Early age cracking of thermal and shrinkage origin is usually considered as a durability issue because it can initiate corrosion of reinforcement. Additionally, induced stresses can reach significant level in some cases and the cracking may affect the structural capacity of the concrete. Early age cracking takes many forms in structural elements. Generally, two kinds of early age cracking can be distinguished:

- in massive foundation slabs the significant temperature generated during the hydration process is generally different in each point of structure. The tensile stresses are induced by temperature and moisture differences developing between the interior and the surface. In such elements random crack maps on surfaces can be usually observed,
- in medium thick structures (mainly walls) usually thermal and shrinkage deformation is prevented by restraint e.g. if a wall is cast against an old set concrete. The cracking may develop due to restraint stresses generated by shrinkage and thermal effects. In such elements a series of vertical cracks starting from the base are usually observed.

2.1. Massive foundation slabs

The volume changes due to temperature and moisture variation have consequences in arising stresses even if the concrete member is externally unrestrained. In such case some internal restraint is induced and it is caused by a temperature and moisture difference within the section. The internal restraints usually occur in thick sections, such as massive foundation slabs, with a significant temperature and moisture gradient that can be built up through the section. To illustrate the discussed phenomena some results of numerical analysis are presented.

The object of the conducted analyses was the massive foundation slab of base dimensions 10 m x 10 m and thickness 3 m. It was assumed that the analyzed slab was made of the following concrete mix: cement CEMII/BS 32.5R 350 kg/m^3, water 175 l/m^3, aggregate 1814 kg/m^3. The foundation was assumed to be reinforced with a 20 cm x 20 cm mesh at the top, bottom and side surfaces. Steel class RB400 and ϕ 12 bars were assumed for calculations. The finite element mesh of the analyzed slab was shown in Figure 1. Because of symmetry only the quarter of the slab is modeled. Essential elements of the slab that were used in presentation of calculation results were marked with black color in Figure 1.

Presented numerical results that illustrate the discussed problem were obtained with the programs TEMWIL, MAFEM_VEVP and MAFEM3D. The

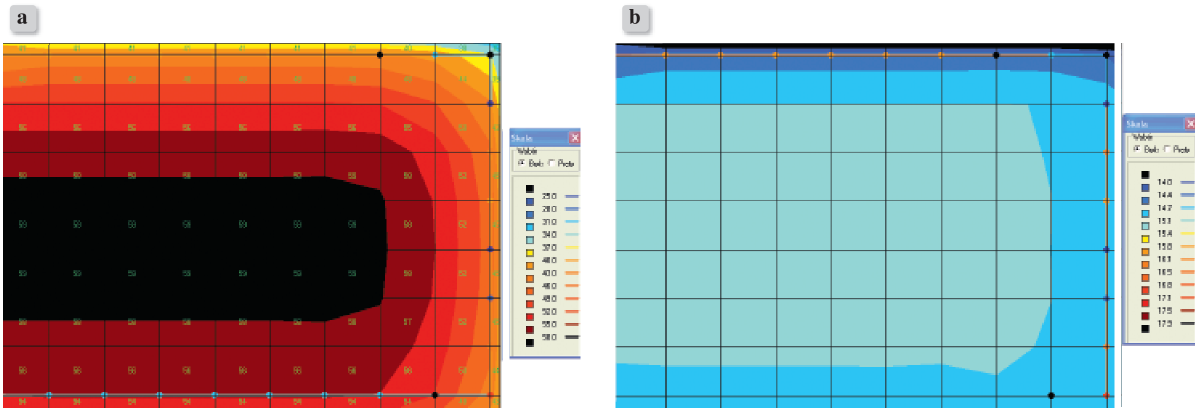


Figure 2.
a) Exemplary temperature distribution: XZ=0, 6.5 day of curing, b) Exemplary moisture distribution (x100): XZ=0, 6.5 day of curing

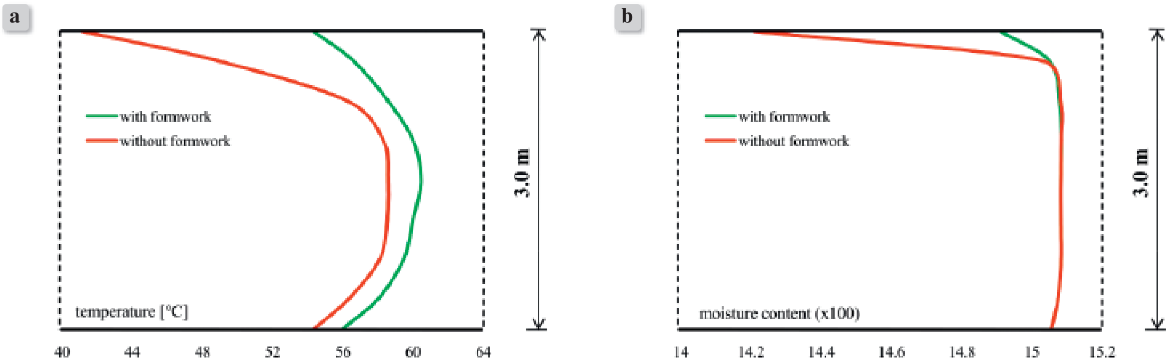


Figure 3.
Exemplary diagram of temperature and moisture distribution at the thickness of the slab

numerical model applied in 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, the 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 [3, 4].

Figure 2a shows the nonlinear temperature distribution on the 6.5 day of curing in the midspan cross-section of the concrete slab, while Figure 3a presents the temperature along the vertical axis of the slab. These temperatures are not symmetrical because the boundary conditions existing at the upper and lower surfaces are different. A significant difference in temperatures of the interior and the surface of the slab is observed, for the assumed curing conditions it is nearly 25°C (Fig. 2a). Possible application of insulation on the top surface may reduce the temperature difference in the cross-section of the massive foundation slab (Fig. 3a). Unlike heat dissipation of massive concrete elements, moisture loss from mass concrete occurs very slowly and comprises mainly the surface zones of the slab (Fig. 2b, Fig. 3b). In cases of insulation application the significant reduction in moisture loss in surface zones can be observed. Moisture content inside the slabs despite the use of insulation is maintained at the similar level (Fig. 3b).

The originating non-linear and non-stationary coupled thermal-humidity fields generate self-induced stresses in the slab, related to the internal constraints of the structure resulting from inhomogeneous distribution of thermal-humidity fields. During the phase

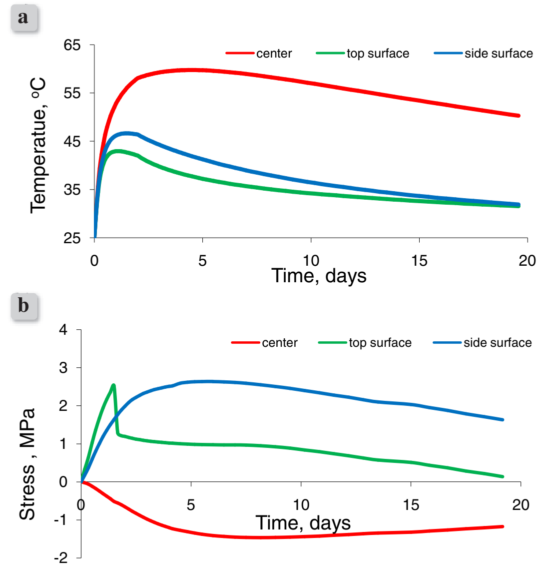


Figure 4.
Exemplary temperature and stresses development in massive foundation slab

of temperature increase the tensile stresses are induced in surface layers of the slab and compressive stresses inside the element. The induced stresses compared to the temperature development in the curing time are shown in Figure 4. The distribution of stresses in heating phase and cooling phase can be seen in Figure 5. It should be mentioned that during the cooling phase an inversion of the stress body may occur. In such case the tensile stresses are observed inside and compressive stresses in the surface layers (Fig. 5b).

In massive concrete elements such as foundation blocks and slabs the cracks are usually observed on the upper surface of the member, especially when it is unprotected with insulation. According to the stress development shown in Figure 4 and Figure 5, such cracks appeared in the heating stage of concrete, when the tensile stresses existed in surface zones of structures. The cracks can occur at the surface of a massive concrete member within the first few days after placement. The possible crack area and its development on the upper surface of the mas-

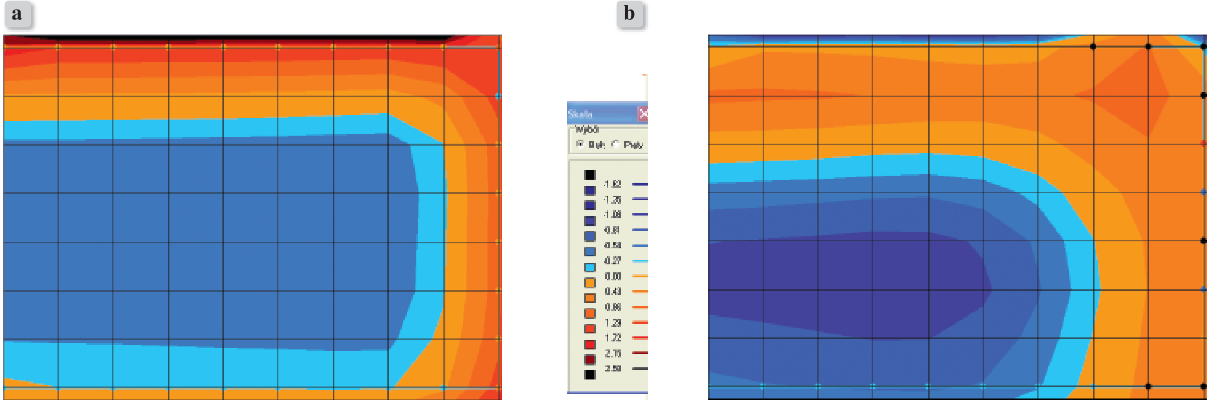


Figure 5.
Distribution of stresses in the midspan cross-section of the slab (XZ=0): a) the heating phase, b) the cooling phase

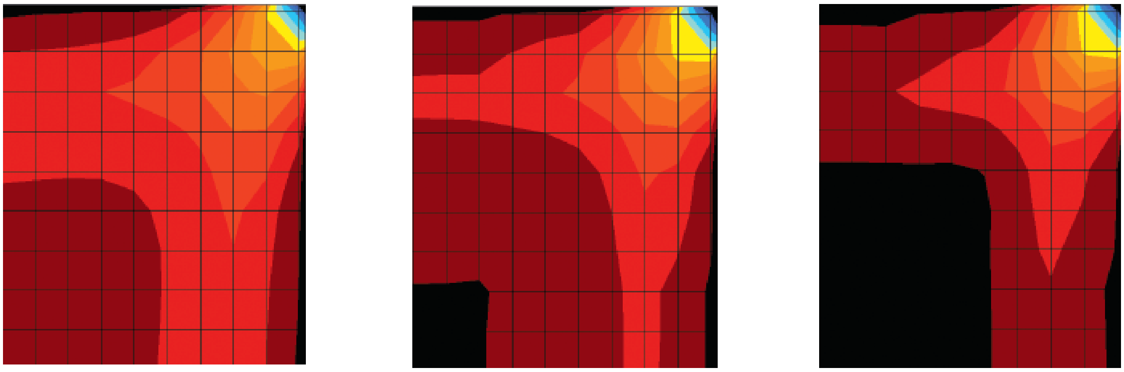


Figure 6.
Propagation of cracking area (black color) on the top surface of the slab in time

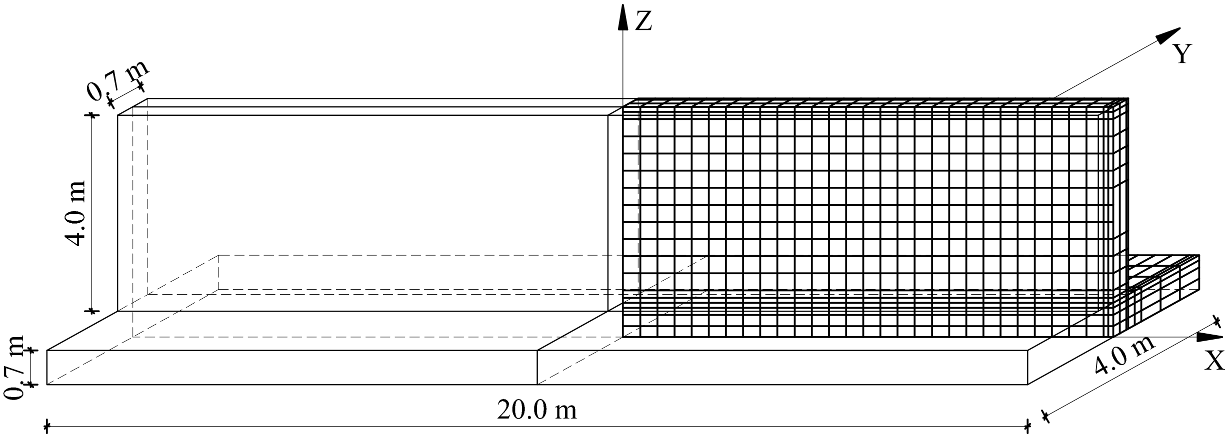
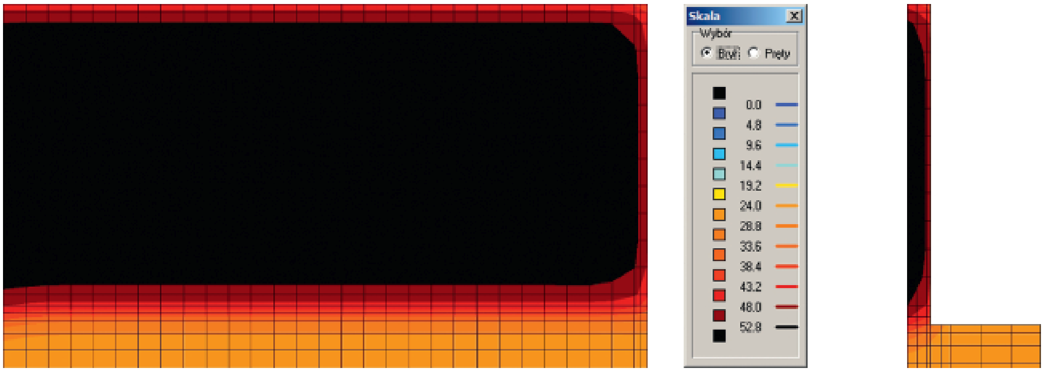


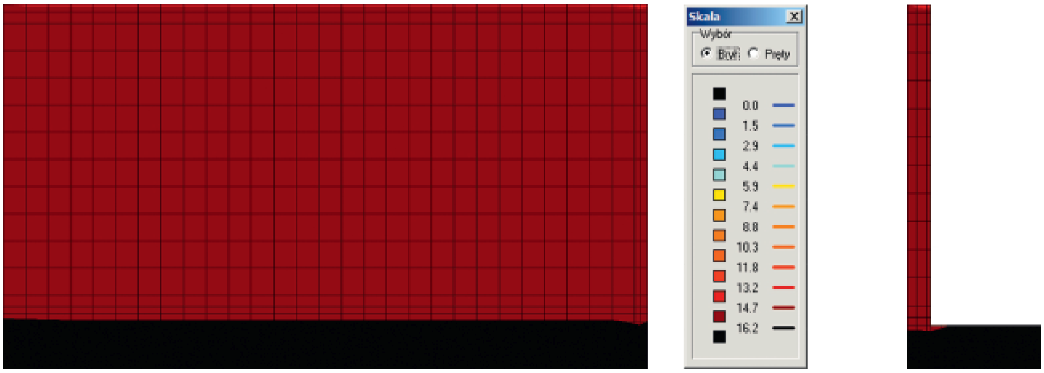
Figure 7.
Geometry of an exemplary reinforced concrete wall with the assumed finite element mesh



a) longitudinal section XZ = 0

b) cross-section YZ = 0

Figure 8.
Exemplary map of temperature distribution in a reinforced concrete wall



a) longitudinal section XZ = 0

b) cross-section YZ = 0

Figure 9.
Exemplary map of moisture distribution in a reinforced concrete wall

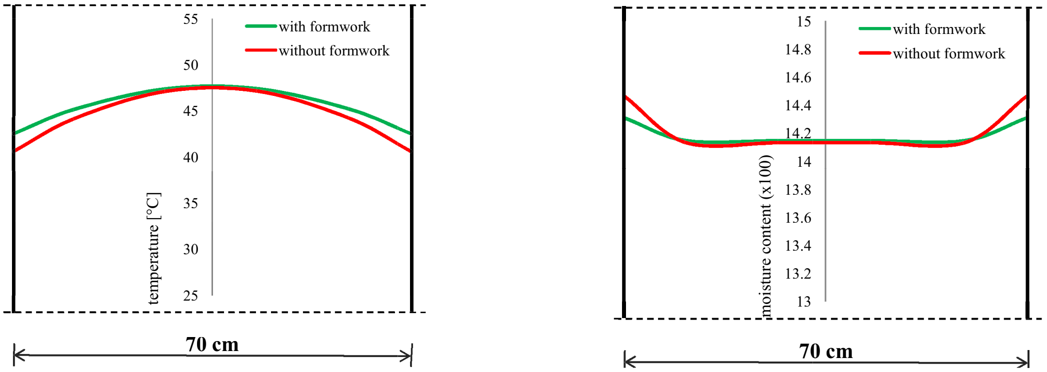


Figure 10.
Exemplary diagram of temperature and moisture distribution at the thickness of the wall

sive concrete slab are presented in Figure 6. First cracks are expected in the edge area of the top surface, later the cracking area expands to the central part of the top surface. It should be also pointed that the cracks can appear also inside a massive member due to inversion of stresses and the tensile stresses induced there in the cooling stage [5].

2.2. Medium thick structures – walls

In case of medium-massive structures deprived of the possibility of deformation, such as a reinforced concrete wall cast against an old set foundation, the cracking mechanism is different. Stresses developing in the wall result mainly from restraint stresses, connected with restraint of deformation of the wall. There are also self-induced stresses resulting from non-uniform temperature and moisture distribution in the wall. However, in massive slabs and foundation blocks the self-induced stresses reach comparatively higher values and, as a consequence, are predominant impacts, their influence in walls is much lower. This is mainly the result of the hardening temperatures distribution within the wall. Even though a difference in temperatures of the interior and the surface of the wall is observed, the difference is small in magnitude. Only early formwork removal may lead to greater temperature difference in the cross-section. A similar situation can be observed in moisture distribution in a cross-section of the wall. Due to a relatively small thickness of the element, water migration is almost uniform.

Similarly as in previous subchapter some numerical analysis was performed for RC wall to illustrate the discussed issues. 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. An exemplary wall with the assumed mesh for finite element analysis of thermal-moisture effects is presented in Figure 7.

The wall and the foundation were assumed to be reinforced with a near-surface reinforcing net of ϕ 16 bars. The wall was reinforced at both surfaces with horizontal spacing of 20 cm and vertical spacing of 15 cm. The foundation was reinforced with a 20 cm x 20 cm mesh at the top and bottom surface. Detailed material properties, environmental and technological conditions were taken as: cement type CEM I 32.5R, 450 kg/m^3, concreting proceeded in summer – ambient temperature 25°C, initial temperature of fresh concrete mixture 25°C (no initial cooling applied), wooden formwork of 1.8 mm plywood; no insulation; no protection of top surface.

Exemplary maps of temperature and moisture distribution in a reinforced concrete wall are presented in Figures 8 and 9.

Figure 10a presents temperature distribution in a midspan cross-section of the wall while Figure 10b is related to the moisture distribution in the same cross section. As it was mentioned earlier a difference in temperatures of the interior and the surface of the wall is small compared to the massive foundation slab. Also, the moisture loss from wall occurs very slowly especially when the surfaces are protected with formwork.

Two main phases can be distinguished observing a temperature change in time during the concrete curing process (Fig. 11a): a phase of concrete temperature increase (self-heating) and a phase of cooling of the element down to the temperature of the surrounding air. In the first phase the wall extends being opposed by the weakly bonded foundation, which results in occurrence of compressive stresses (Fig. 11b, Fig. 12). These are usually the first 1-3 days. As soon as the maximum self-heating temperature is reached, the wall starts to cool down, which takes another few days, restrained by a cooled foundation. This leads to development of tensile stresses in the wall (Fig. 11b, Fig. 13).

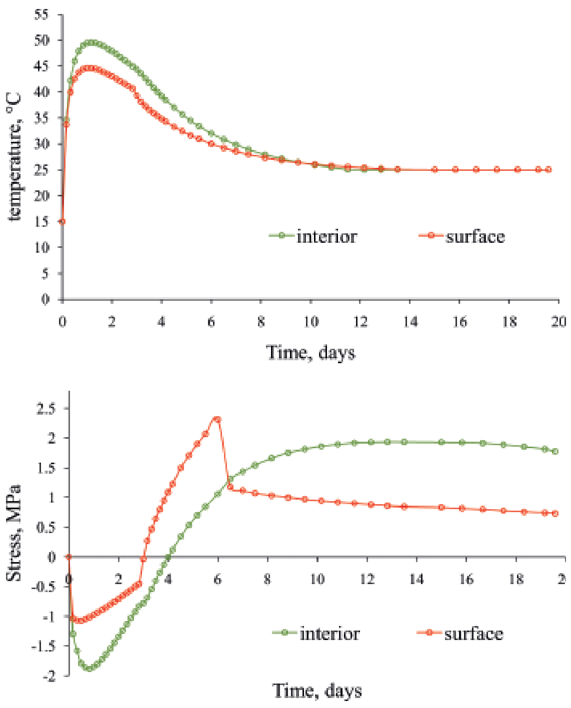
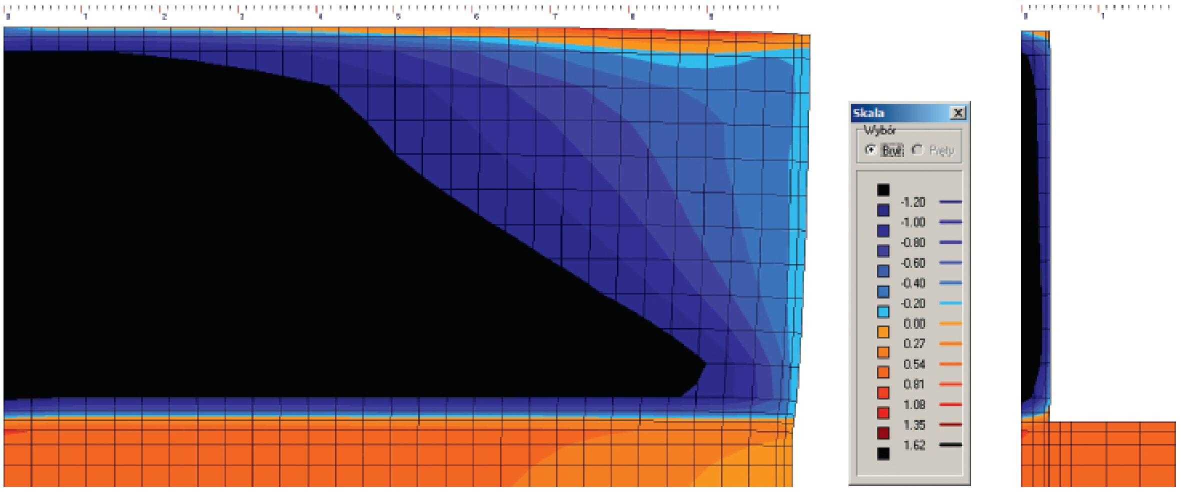


Figure 11.
Temperature and stresses development in the externally restrained concrete wall

In the cooling phase a stress decrease is observed, disproportionately huge with respect to the concrete cooling rate. It is connected with an influence of rheological processes and higher – in comparison to the temperature increase phase – value of the elasticity modulus of hardened concrete. These stresses often reach considerable magnitudes leading to cracking of the walls. Figure 14a presents the direction of principal tensile stresses. Cracks location is perpendicular to these directions (Fig. 14b, c).

A typical pattern of cracking due to edge restraint of a wall is shown in Figure 14b, assuming that the base is rigid. Without restraint the section would contract along the line of the base, and so with restraint a horizontal force develops along the construction joint. This leads to vertical cracking at midspan but splayed cracking towards the ends of the section where a vertical tensile force is required to balance the tendency of the horizontal force to warp the wall. In addition, a horizontal crack may occur at the construction joint at the ends of the walls due to this warping restraint. Figure 14c presents the cracking image observed in a real RC wall [7].

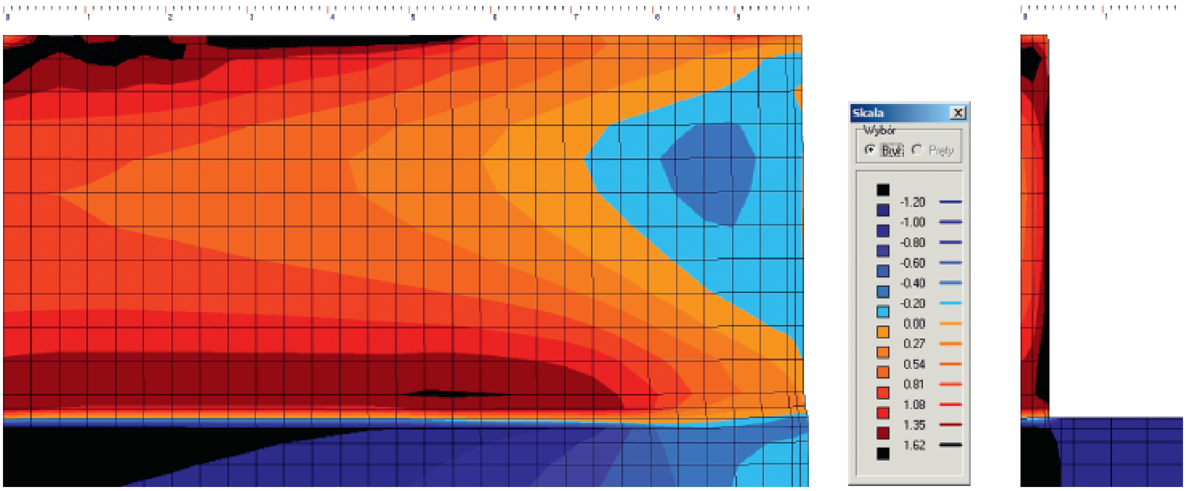
Generally, it is considered that a basic pattern of cracking is independent of the amount of reinforcement provided [8, 9, 10, 11]. When sufficient reinforcement is provided to achieve the critical reinforcement ratio the widths of these primary cracks are controlled, although secondary cracks may be induced. The extent and size of cracking will then depend on the amount and distribution of reinforce-



a) longitudinal section XZ = 0

b) cross-section YZ = 3 m

Figure 12.
Compressive stresses in the first phase of reinforced concrete wall curing process (8 hours)



a) longitudinal section XZ = 0

b) cross-section YZ = 3 m

Figure 13.
Tensile stresses in the second phase of reinforced concrete wall curing process (~4.5 days)

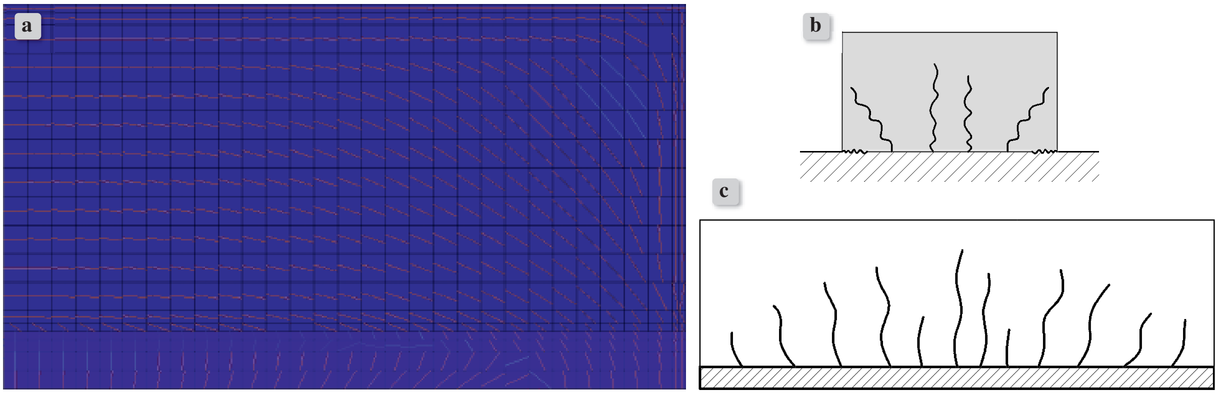
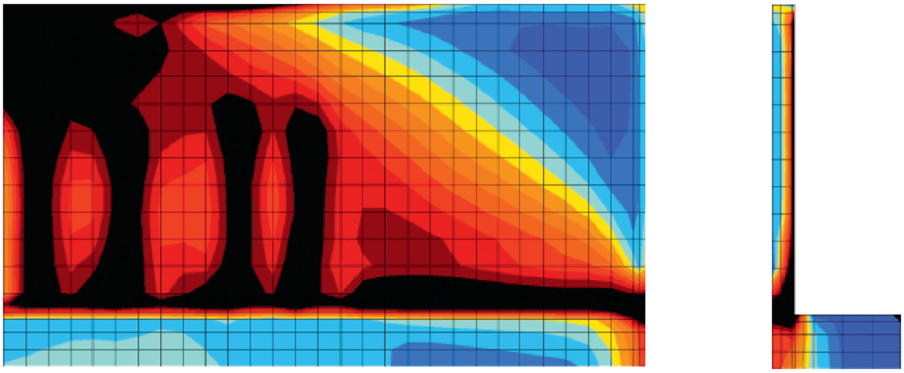


Figure 14.
a) Direction of principal tensile stresses, b) typical crack pattern, c) real cracks observed in RC wall [6, 7]



a) XZ=0.35, surface

b) YZ=3m

Figure 15.
Initiation of cracking area (black color) in the wall with formwork removed after 3 days

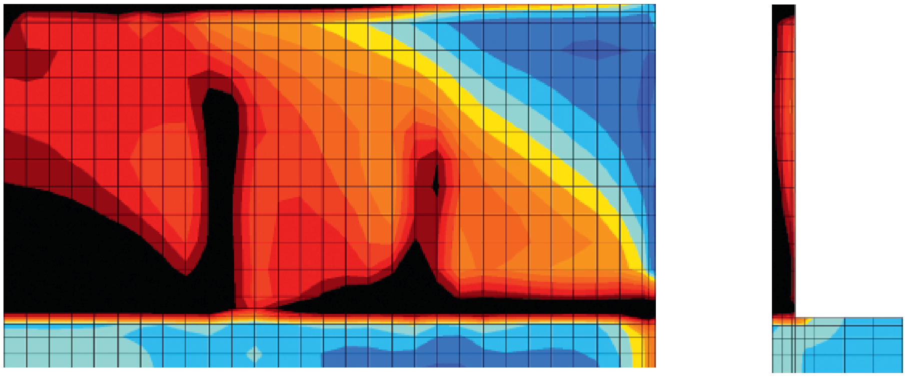

a) XZ = 0, midspan cross-section b) YZ = 3 m

Figure 16.
Initiation of cracking area (black color) in the wall with formwork removed after 25 days

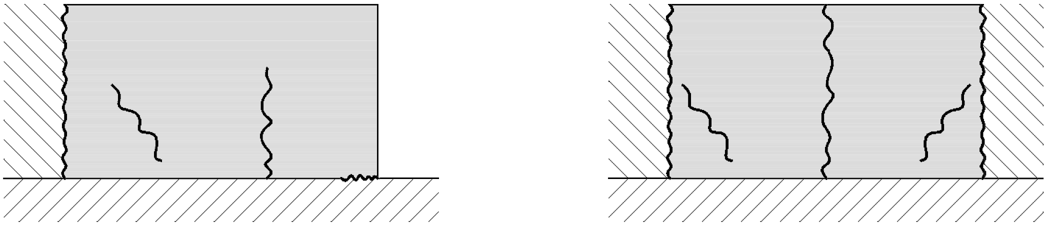


Figure 17.
Cracking due to combined end and edge restraint

ment provided. The occurring cracks have vertical alignment, reach $^{1}/_{3}$, $^{1}/_{2}$ or even $^{2}/_{3}$ of the height of the wall, depending on the length and height of the wall, and are spaced every 1.5-3.0 m. The maximum width of the crack $w_{k,max}$ is about 0.3÷0.5 mm (in walls with low horizontal reinforcement ratio) in $^{1}/_{3}$ of the height of the cracks. The cracks start at the wall-foundation interface, widen up to the $w_{k,max}$ value and then decrease in width [6]. Another interesting property of the cracks is their distribution: the greatest height of the crack can be observed in the middle of the wall and it declines towards the beginning and the end of the wall or towards the expansion joints, as presented in Figure 14.

When formwork is removed relatively early (e.g. after 3 days, which is a common practice), rapid cooling of the wall surface leads to first crack formation in the near-surface areas (Fig. 15). If the wall is kept in the formwork long enough for the concrete to cool down completely, the heat concentration in the interior of the wall leads to first cracks development in the internal parts of the wall (Fig. 16). It should be noted that in both cases, cracks may extend to the entire wall thickness.

Sometimes the external restraint is a combination of the end restraint and continuous edge restraint (Fig. 17). Usually the first crack will occur at a construction joint as the strength of the bond between new and mature concrete is generally less than the tensile strength of the member. Such a crack is therefore less likely to be fully developed. If the overall contraction of the wall can be satisfied by fully developed cracks at one or both construction joints then the intermediate cracks shown in Figure 17 may not occur. This explains why the worst cracks are usually seen at construction joints or at changes of section which cause stress concentrations.

3. FACTORS AFFECTING THE RISK OF EARLY AGE CRACKING AND METHODS APPLIED TO REDUCE THEM

The most important factor when analyzing early age thermal-shrinkage stresses is the temperature development in concrete member. The complex variables that affect the rate of temperature rise, the maximum temperature and the temperature difference between sections are:

- thermal properties of early age concrete, such as the rate of heat evolution, the total amount of heat, specific heat, thermal conductivity – these properties are strongly dependent on the amount and properties of concrete components, especially the amount and kind of cement,
- conditions during concreting and curing of concrete, such as initial temperature of concrete, kind of formwork, the use of insulation or pipe cooling,
- technology of concreting, such as segmental concreting,
- environmental conditions, such as ambient temperature, temperature of neighboring elements, wind, humidity,
- dimension and geometry of concrete structure.

Potential solutions to minimize high temperature and temperature differences in massive concrete are referred to factors listed above. Accordingly, currently used methods include optimal concrete mix design, concrete cooling before or after placement, the use of smaller placements as well as insulation. Design of optimal concrete mix is often considered as the easiest way to minimize negative thermal effects in massive concrete. The optimal concrete mix is usually related to using low-heat cement and minimization of the total amount of cement in concrete. It is also suggested to use aggregate such as granite or basalt which reduces the thermal expansion of concrete and potential for thermal cracking.

The effective method of reducing the thermal effects can be concrete cooling before placement [1, 5, 12]. Different methods depend on the local conditions, the willingness and experience of the concrete supplier can be applied to precooling the concrete mix. The least costly way is using chilled water which precools 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 [13]. In extreme precooling liquid nitrogen is used to precool 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. After placement, cooling pipes installed prior to concrete placement can be used to remove heat from the interior of the concrete [9, 14]. Cooling pipes typically consist of a uniformly distributed array plastic pipes embedded in the concrete. Undoubtedly, this method increases the cost of construction, but limits the maximum temperature and greatly reduces temperature differences in massive concrete.

The next method applied in technology of massive concrete structures is the use of smaller placements – in such case large elements can be divided up into several smaller placements. It was confirmed during the concreting of thick foundation slabs that placing of concrete in multiple lifts with smaller thicknesses can be an effective method to minimize the potential for thermal problems [15, 16].

Insulation applied on surfaces of massive concrete elements slows the warming of the concrete surface and reduces the temperature difference [16]. 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 the 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.

To summarize the method of thermal control two main concerns about massive concrete placements must be emphasized: the maximum temperature and the maximum temperature difference across a section. Specifications typically limit the maximum temperature to 65°C and the maximum temperature difference to 15÷20°C [13]. This simple criterion based on engineering experience suggests that concrete can withstand the volume changes associated with such temperature difference. However, it is important to point out that this method may not be a safe criterion and it has limitations. The limitations are mainly related to externally restrained structures, where the lower temperature difference can induce cracks.

Early age cracking sensitivity is also associated with moisture evaporation through exposed surfaces of concrete element. Although the loss of water is a slow process compared to heat dissipation of early age concrete structures, it should also be considered in evaluation of possible cracks. This loss of water, while the concrete is still in plastic stage, results in plastic shrinkage and later in drying shrinkage. Both plastic and drying shrinkage are highly dependent upon environmental conditions, such as wind, relative humidity and temperature. Additionally, the chemical and autogenous shrinkage can reach significant level, especially in concrete with low w/c ratio. The chemical shrinkage is defined as the internal-microscopic volume reduction which results from the fact that the absolute volume of the hydration products is smaller than the reacting constituents – cement and water [11]. Autogenous shrinkage is considered as the external-macroscopic volume reduction of hydration cement paste, it is driven by chemical shrinkage.

The plastic and drying shrinkage is usually limited by application of proper curing conditions such as providing water to the exposed surfaces of concrete or sealing surfaces to prevent any evaporation. Some extra insurance is also provided by incorporation of polymer fibers into concrete mix. Autogenous deformation can be reduced by internal curing of concrete provided by addition of pre-saturated light weight aggregates or super absorbent polymers to concrete mixture [17].

The next properties with great importance on development of early age stresses are related to the mechanical behavior of maturing concrete:

- strength development of concrete,
- elasticity and viscous behavior of concrete subjected to high stress and elevated temperature.

Additionally, in case of restrained structures the degree of restraint also influences the distribution of stresses. It should be pointed that a high percentage of reinforcement restrains the concrete. Furthermore, the provision of too much reinforcement can cause undue restraint as the surrounding concrete cools after casting.

4. CONCLUSIONS

Control of thermal and shrinkage cracking in early age concrete is of great importance to ensure a desired service life and function of structures. Although early age cracking has been documented since the early 20th century, it is continually subject of extensive research, mainly due to complex nature of interacting phenomena and large number of contributing factors. What is more, the factors producing early age cracking can not be examined independently of one another. It has recently become a major concern because of increasing demands referred to durability of structures. Additionally, some structures such as dams or tanks require a solid concrete preventing water from leaking through and then cracks are undesirable.

This paper briefly reviews causes and character of the early age cracking in structural elements. The discussed problems will be further investigated in next papers that will be focused on the influence of structural, materials and technological factors on development of temperature, moisture and finally induced stresses.

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