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Procedia Engineering 193 (2017) 226 – 233

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures AMCM'2017

Numerical study on restraints effects in massive foundation slabs

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Abstract

The aim of the presented study is to simulate the restrained stresses in early age massive foundation slabs. The character of self-induced stresses related to internal restraints resulting from inhomogeneous distribution of thermal-humidity fields as well as restraint stresses related to limitation of structure deformations freedom are described in the article. The combined thermal and both autogenous and drying shrinkage effects are considered. The presented numerical study on the above mentioned effects are conducted with the use of original numerical model. The distribution and the magnitude of stresses induced by hydration temperature and shrinkage are computed, both in heating and curing phase of concrete curing. The special attention is paid to the externally restraint stresses depending strongly on contact layer between the slab and subsoil. Finally, the total restraint stresses are computed for slabs with different thickness.

Peer-review under responsibility of the scientific committee of the International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures

Keywords: early age concrete; foundation slabs; temperature, shrinkage; self-induced stresses; restraint stresses

1. Introduction

The concrete temperature increases as a result of heat released in hydration process. 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 because conditions are close to adiabatic and maximum temperature can

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Peer-review under responsibility of the scientific committee of the International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures
doi:10.1016/j.proeng.2017.06.208

reach even 50÷70°C [1÷6]. Furthermore, the internal temperature drops slowly while the surfaces with direct contact with environment cool rapidly. As a result, thermal gradients occur across the section of concrete members. One of the causes that affect high temperature increase and its non-uniform distribution between surface layers and interior of massive concrete member is low thermal conductivity of concrete which slows down the natural cooling process. In the meantime, during hydration of concrete shrinkage deformations are formed as a result of chemical reaction and the moisture transfer to the environment.

The volume changes due to the temperature and moisture variation have consequences in arising stresses in a concrete member. These stresses can be defined as self-induced stresses (related to internal restraints of the structure, resulting from non-uniform volume changes in a cross section) and restraint stresses (related to limitation of structure deformations freedom). In internally restraint elements during the phase of temperature increase tensile stresses originate in surface layers of the element and compressive stresses are observed inside the member. An inversion of the stress body occurs during the cooling phase: inside we observe tensile stresses and in the surface layers compressive stresses. The self- induced stresses can be expected, for example, within thick foundation slabs, thick walls, dams and each element with interior temperatures considerably greater than surface temperatures.

These stresses often reach significant values and can cause formation of cracks and micro-cracks in the structure. The magnitude of thermal–shrinkage tensile stresses and the possible cracking depend on many technological and material factors such as: concrete mix composition and type of materials used, concrete placing and curing conditions [7]. The other important factors are the dimensions, geometry and support conditions providing the freedom of deformation of the concrete element subjected to changes in volume [8]. Thermal cracking in early age massive foundation slabs as well as cracking resulting from drying and autogenous shrinkage, not only forms mechanical weaknesses and cracking but also causes a reduction in durability. Therefore, the recognition of the thermal-shrinkage stresses and the risk of cracking in massive concrete structures is the important engineering task.

The presented study is focused on the character of self-induced stresses related to internal constraints resulting from inhomogeneous distribution of thermal-humidity fields as well as restraint stresses related to limitation of structure deformations freedom. The results of numerical analysis of the abovementioned stresses during hardening of the massive foundation slab are presented. The numerical analysis was made with the use of the original numerical model and TEMWIL and MAFEM software [9,10].

2. Early Age Behaviour of Massive Foundation Slabs

2.1. Development of early age temperature and shrinkage

The variations of the concrete temperature during curing are the result of exothermic nature of the chemical reaction between cement and water. Thus, the concrete temperature increases as a result of heat released in this process. The cooling of surface layers of the structure and a relatively low thermal conductivity of concrete result in temperature difference between the surface layers and the interior of the structure. Particularly high curing temperature and its gradients between the interior and the surface of structural members may occur in structures with large thickness. Hence, the thicker the slab, the longer it will take the heat to be dissipated into the environment. The temperature development inside thick sections will resemble adiabatic conditions, since heat losses to the environment occur very slowly.

The temperature distribution through the concrete structure and its evolution in time depends on some thermal parameters as thermal properties of early age concrete, environmental conditions during concreting and curing of concrete, dimensions and geometry of concrete structure. Ones of particular importance are thermal properties of early age concrete such as the rate of heat evolution and the total amount of heat, specific heat and thermal conductivity. These properties are strongly dependent on the amount and properties of concrete components, especially the amount and type of cement. Furthermore, hydration process in hydrating concrete is also influenced by its current curing temperature and moisture content. The general development of heat released during the hydration process and generated temperature in exemplary massive foundation slab are presented in Fig. 1.

Concrete curing is also accompanied with a moisture transfer to the environment in conditions of variable temperatures. The loss of water trough evaporation at the surface of structural member results in shrinkage, which is defined as a drying shrinkage. There is also an internal drying resulting from the reduction in material volume as water is consumed by hydration, which is classified as autogenous shrinkage. It should be noted that autogenous shrinkage is separate from and additional to drying shrinkage, which will start when water curing ceases. The magnitude of shrinkage depends on many factors such as water-cement ratio, cement properties, relative humidity of the environment, geometry of the concrete member and the age of concrete. The loss of moisture is non-uniform in the concrete member. As the concrete member is exposed to environment, the top surface is more susceptible to drying than the interior. Similarly, the water consumption during the chemical reactions is diversified across the concrete section due to the various intensity of the hydration process. Thus, similarly as in the case of temperature, a moisture gradient creates a shrinkage differential through the slab thickness. The loss of moisture from concrete caused both by evaporation at the surface of the slab and internal drying due to the water being consumed during the hydration process and related shrinkage are schematically shown in Fig. 2.

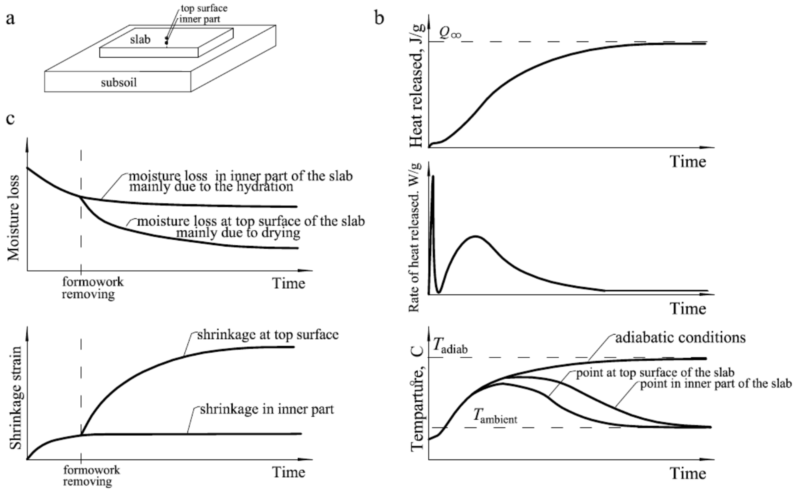

Fig. 1. (a) General view of massive foundation slab with essential points; (b) development of heat released in hydration process and temperature in essential points of massive foundation slab; (c) the moisture loss and development of shrinkage in essential points.

2.2. Development of early age stresses

Non-uniform volume changes due to temperature and moisture variation in the early age concrete have consequences in arising stresses in the concrete structural member. These stresses can be defined as:

- self-induced stresses which are related to internal restraints of the structure, resulting from non-uniform volume changes in a cross section; the significant self- induced stresses can be expected within thick foundation slabs, thick walls, dams and each structural member with thermal-shrinkage strains significantly differing for the inner and surface part of the member;
- restraint stresses which are related to external restraints of the structure and caused by the limited freedom of deformation of the structure. In case of massive foundation slabs such restraints exists along the contact layer of a slab and subsoil. Especially considerable restraint stresses can be expected in foundation slabs of large dimensions in a plan view or founded on piles restricting their longitudinal freedom of deformation.

The magnitude of thermal–shrinkage stresses arising in a concrete slab during hardening depends on many technological and material factors such as: concrete mix proportions and type of concrete components; 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; boundary conditions, such as ambient temperature, wind and humidity [1÷5]. The other important factors are the dimensions, geometry and support conditions limiting the freedom of deformation of the slab subjected to inhomogeneous changes in volume.

Fig. 2 presents the general distribution of self-induced stresses along a cross section of the massive foundation slab, which have a leading importance for the slabs with considerable thickness. In such case during the phase of temperature increase tensile stresses develop in surface layers of the slab and compressive stresses are observed in the inner part. Inversion of stresses occurs during the cooling phase: inside we observe tensile stresses and compressive stresses in the surface layers. Shrinkage stresses resulting from inhomogeneous drying and autogenous shrinkage strains have a uniform character throughout the period of concrete hardening. The tensile stresses are formed in the surface layers, and in the inner part of the slab the compression stresses are induced. It should be pointed that such mechanism of shrinkage stresses is valid if the drying shrinkage strains are significantly larger in comparison with the autogenous shrinkage strains. Otherwise the discussed distribution along of the cross section can be opposite to the above-described. Finally, the tensile shrinkage stresses increase the total self-induced tensile stresses in the heating phase, whereas in the cooling phase these stresses to reduce both surface compressive stresses and internal tensile stresses.

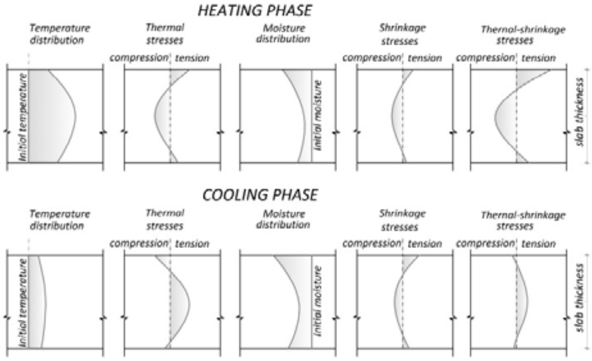

Fig. 2. General distribution of the self-induced stresses along the thickness of a massive foundation slab.

Restraint stresses have different character than self-induced stresses. In the phase of temperature increase the whole volume of the slab is subjected to compression while in the cooling phase tensile stresses occur. Restraint shrinkage stresses are tensile stresses in the whole period of concrete curing. The general distribution of restraint stresses along the thickness of a massive foundation slab is presented in Fig. 3.

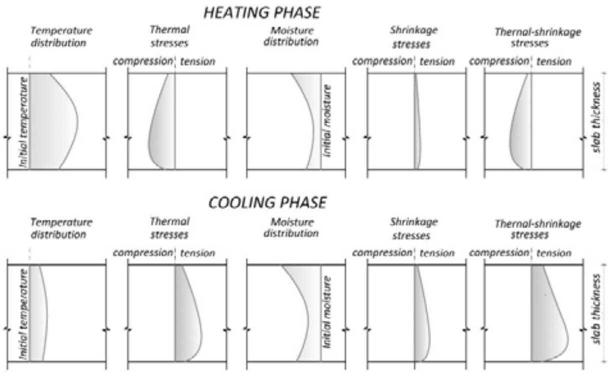

Fig. 3. General distribution of the restraint stresses along the thickness of a massive foundation slab.

It should be also highlighted that share of stresses generated by external restraint in total stresses depends on a degree of restraint existing between the bottom surface of the slab and the subgrade. In general, in thick foundation slabs the self-induced stresses reach comparatively higher values and, as a consequence, are predominant impacts. Greater importance of restraint stresses can be expected in foundation slabs of large dimensions in a plan view made without slip layer or founded on piles.

3. Numerical study

3.1. Numerical model applied in the study

Numerical model used for the analysis was presented and described in detail in the works [9,10]. This section presents only its main assumptions. The numerical model allows for analysis of the behaviour of reinforced concrete structures in early stages of concrete hardening, such as massive foundation slabs, foundation blocks, tank walls and bridge abutments. The 3D analysis of a concrete structure can be performed with consideration of the soil–structure interaction, different technological conditions as well as a different concrete mix. For the purpose of determination of the stress in the early-age concrete massive foundation slab the viscoelastic material model of ageing concrete is applied in the presented study. The model was implemented in a form of computer programs: TEMWIL [9] for thermal–moisture analysis and MAFEM for stress analysis [10].

3.2. Range and data for analysis

The numerical study on the above mentioned effects includes the investigations listed in Table 1. Basic data used in the analysis are collectively presented in Table 2.

Table 1. The list of analyzed cases.

Analyzed case	Slab thickness	Analyzed case
	0.7 m	Top and bottom surface with protection layer (formwork) over the entire curing period
Self-induced stresses	0.7 m	Top and bottom surface without protection layer over the entire curing period
	0.7 m	Top surface protection layer (formwork) removed at 168 hours after concrete casting
Self-induced stresses	1 m, 3 m	Concrete mix made of different type of cement in concrete mix
Restraint factor	2 m	Slab with different length/height ratio, different type of subsoil and contact layer
Total stresses	1, 2, 3, 4 m	Slab with different thickness, soil with medium stiffness, without contact layer

Table 2. Basic data for numerical analysis.

Properties/coefficient	Value
Concrete mix	w/c=0.5, sand (583 kg/m^3), coarse aggregate (1360 kg/m^3), cement (300 kg/m^3), on the basis of experimental tests [12]
Type of cement	CEMI 42.5R (PC cement); CEMII/B-S 32.5R (PC-68.3%, S-27.1%) CEM II/B-V 32.5R (PC 65.7%, V-29.9%) CEMIII/A 32.5N-LH/HSR/NA (PC 41.1%, S-58.9%) CEMV/A (S-V) 32.5R-LH/HSR/NA (PC-62.2%, S-18.2%, V-19.6%) VLH V/B (S-V) 22.5 (PC 32.3%, slag 34.4%, fly ash 33.3%)
Coefficient of thermal conductivity	2.96 W/(mK)
Specific heat	0.84 kJ/(kgK)
Coefficient representing the influence of the moisture concentration on the heat transfer	$9.375 \cdot 10^{-5}$ m^{2}K/s
Thermal transfer coefficient	6.0 W/(m^{2}K) – without protection; 3.5 W/(m^{2}K) – with protection
Heat of hydration	on the basis of experimental tests reported in [11]
Coefficient of the water-cement proportionality	$0.3\ 10^{-9}$ m^3/J
Coefficient of moisture diffusion	on the basis of Hancox's equation [9,10]
Thermal coefficient of moisture diffusion	$2\ 10^{-11}$ m^2/(sK)
Moisture transfer coefficient	$2.78 \cdot 10^{-8}$ – without protection, without wind; $0.18 \cdot 10^{-8}$ – with protection
Mechanical properties	on the basis of experimental tests reported in [12]

3.3. Results of the study

The results of computation cases listed in Table 1 are shown in Figs. 4–8. They can be summarized as follows:

- Fig. 4a presents the distribution of temperature and self-induced stresses along the thickness of the slab for two analyzed cases: with and without the protection layer (plywood) over the entire curing period. It is clearly visible from these graphs that boundary conditions affected the temperature of curing concrete. Application of a protection layer on surfaces led to slight increase of maximum temperature inside the slab (only 4°C) with a simultaneous significant reduction in the temperature difference between inner and surface part of the slab (about 50 %). The stresses visible in Fig. 4b reached the lower level in case of the protection layers applied on the surfaces, both in inner and of the slab. Nevertheless, it should be also remembered that the curing temperature exceeding 65-70^{o}C in the early age concrete can lead to the delayed ettringite formation (DEF) and consequently to possible later damage of concrete. Thus, this unfavorable effect should be also considered when the protection layer is intended to apply.
- Fig. 5 presents the distribution of temperature and self-induced stresses along the thickness of the slab for concrete mix made of different cements. These graphs confirm positive effect of low clinker cements used in a concrete mix. Significant reduction in a maximum temperature and temperature difference is clearly visible in the presented diagrams. Consequently, the magnitude of generated stresses and cracking risk decrease as well.
- Fig. 6 presents the results of analysis focused on the effect of removing of surface protection. In case of removing protection layer surfaces are rapidly cooled, which increases the temperature difference between the interior and the surfaces of the slab. As a result also in the cooling phase tensile stresses appear in the surfaces zones. This indicates the need of extreme caution in the removal of the protective layer.
- Fig. 7 presents distribution of the restraint factor along the thickness of the slab with the effect of the contact layer type between the slab and subsoil as well as the type of soil. The restraint factor, is defined as a ratio between the stress generated in the analyzed slab to the stress generated at full restraint of the slab. The dependence of the restraint factor and consistently restraint stresses on the type of the degree of restraint existing between the bottom surface of the slab and the subgrade as well on the length to thickness ratio can be noted. Presented graphs indicate that high restraint stresses can be expected in slabs founded on piles. In this case at the bottom surface of the slab tensile stresses can be expected in the cooling phase and not, as is typical in the heating phase. Of course, it is true if the self induced stresses will be much lower than the restraint stresses. The similar distribution of stresses can be expected in slabs of large dimensions in a plan view founded on hard soil without slip layer.
- Fig. 8 presents the total stresses and its dependence on the dimension of the slab. The influence of the restraint stresses on the distribution of the total stresses is well visible at the bottom surface of slab with 1m of thickness.

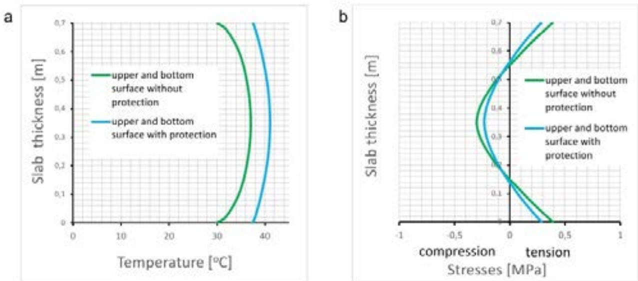

Fig. 4. Distribution of self-induced stresses along the thickness of a massive foundation slab for the different protection of bottom and top surfaces.

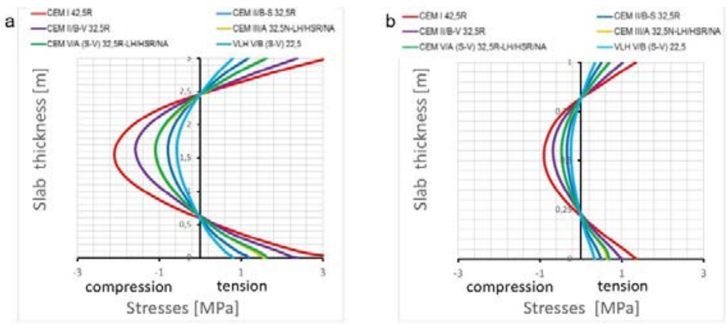

Fig. 5. Distribution of self-induced stresses along the thickness of a massive foundation slab for different types of cements in a concrete mix.

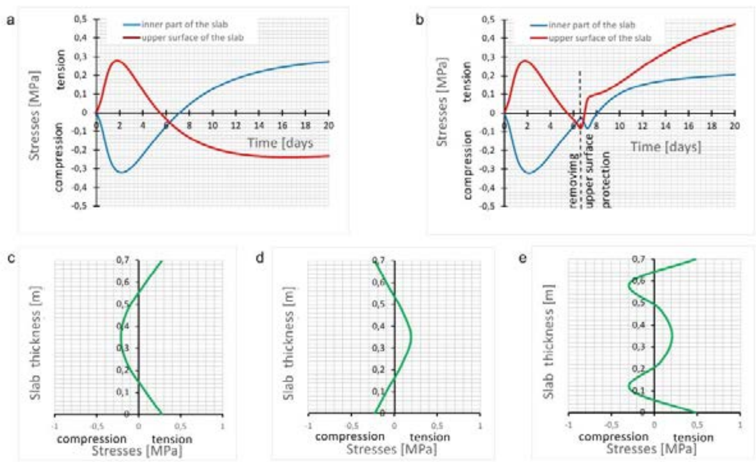

Fig. 6. Self-induced stresses in massive foundation slabs: (a) development in time - top and bottom surface with protection layer over the entire curing period; (b) development in time - protection layer removed during the curing period; (c) distribution along the thickness of the slab in a heating phase in case (a) and (b); (d) distribution along the thickness of the slab in a cooling phase in case (a); (e) distribution along the thickness of the slab in a cooling phase in case (b).

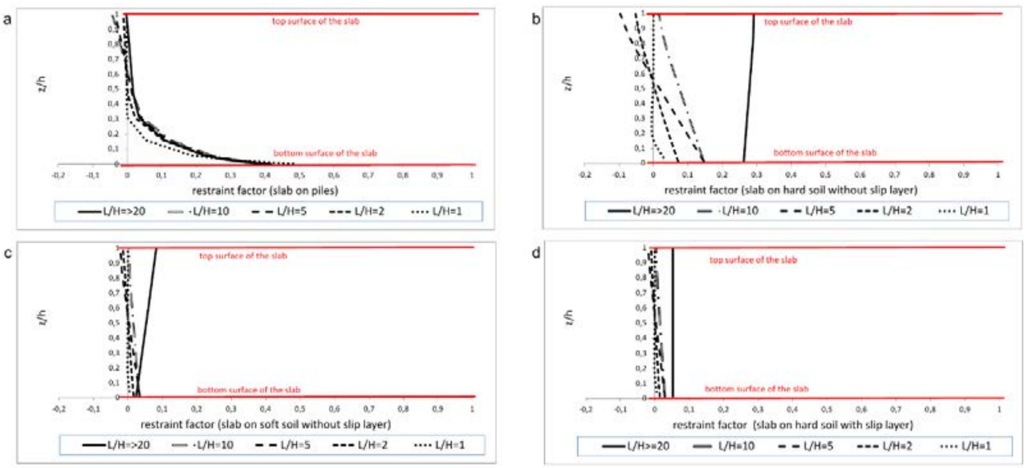

Fig. 7. Distribution of the restraint factor along the thickness of a massive foundation slab with different types of subsoil and contact layer.

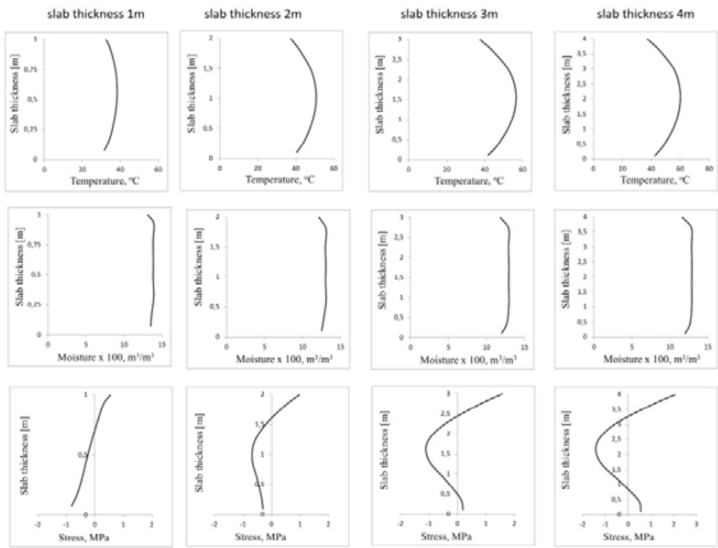

Fig. 8. Distribution of the total stresses along the thickness of massive foundation slabs with different thickness

4. Final remarks

Control of thermal and shrinkage cracking in early age concrete is of great importance to ensure a desired service life and function of concrete structures. Although early age cracking has been known for many years and it is continually the subject of extensive research, some issues for massive slabs are not exactly recognized in authors' opinion. This article briefly reviews causes and character of the early age stresses in massive foundation slabs. The application of 3D numerical analysis enables among the others the explanation of distribution of self-induced and restraint stresses and their dependence on the chosen factors.

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