Reduction of the thermal gradient in concrete mixture in dry and hot climates using Phase Change Materials.

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Abstract

Dynamic development of construction industry and related with it implementation of more and more modern design, forces the use of more advanced concreting technology. Tight, short construction deadlines force the contractors often to conduct works, regardless of weather conditions.

The development of materials technology, implementation of new products, measurement techniques and methods of registration "data" information makes regardless of still useful, traditional tools for rising concrete structure, there must be sought and developed new methods for reduction of adverse events inside the concrete elements, but also allowing faster construction rising.

Ageing of concrete is a result of cement hydration, which is an exothermic process. Approximately a full hydration of 1 kg of standard Portland cement causes emission of approximately 400 kJ of heat. The ambient temperature and emission of hydration heat of fresh concrete mix and encountered difficulties in transmitting heat to the outside of the element initiates the formation of thermal gradient in the concrete structure. As time goes by, as a result of hydration process progress, the hardening concrete acquires mechanical characteristics (it increases its strength). If the resulting stress, caused by the temperature gradient, exceed at any given time the strength of the forming "concrete structure", it is followed by its destruction, and result in emerging fractures and cracks in the constructed element [1].

From the above it can be concluded that the proper thermal care becomes one of the primary factors determining a solid monolithic concrete structure, hence the idea of application of PCM (Phase Change Materials) for the care of the inner concrete mix when ageing in hot and dry climates.

Keywords: phase change materials (PCM); heat of hydration; thermal curing
1. Specific problems during maturing of concrete mix and construction monolithicity.

The thermal stress problem caused by the heat of hydration is not limited only to massive constructions, but occurs whenever it is difficult to dissipate heat. In particular, it is often observed that the thermal damage occurs in a relatively thin items that were made from mixtures of ageing in the thermal insulation or in dry, hot climates. This is due to the fact that there are two different mechanisms of destruction as a result of hydration heat. The first of these occurs during heating of the structure (in the period of thermal impact) and is associated with stretching surface by extending of the Interior due to heating. It is known as the direct tension.

The second mechanism occurs during cooling of an element and is associated with preventing deformation of cooling down interiors by construction surface layer or external support conditions. It is known as the restraint mechanism. If the first of the mechanisms is possible only on large thicknesses of construction, the second of them may occur regardless of the construction thickness [2].

The next issue is inseparably linked to the implementation of the design is caring of the concrete laid in the construction. The temperature increase of an element within certain limits, of course, is not dangerous for the whole of the design, provided a uniform temperature throughout the volume. In real conditions such a case does not occur. There is always a difference of temperature in the volume of construction. The resulting thermal stress, as a general rule, the taking over of heat (Newton's cooling law) can be described by the formula:

$$ \rho_b = \alpha_p (T_s - T_z) $$

where:
- $\rho_b$ - heat dissipation from the surface of the element
- $\alpha_p$ - thermal conductivity on the surface of the item [W/m2K],
- $T_s$ - the surface temperature of the element,
- $T_z$ - ambient temperature.

From equation (1) are the following limitations of thermal stress in the construction:
- reduction of the coefficient of heat transfers through the use of surface thermal insulation,
- lowering the temperature difference by reducing the quantity and speed of heat during hardening which is possible thanks to the use of PCM. In the case of achieving critical heat dissipation values, the tensile stresses, related to positive volume change of the "element interior" and the thermal inertia of "outer layers", reach values exceeding tensile strength of hardening concrete. In such a case, it is followed by destruction of the continuity of the "concrete structure", what is imaged as scratches emerging on the outer surface, as shown in the fig. 1 [3].

The value of critical temperature difference at which tensile strength exceeds the strength of concrete were given by Neville [4], specifying it at the level of 15 ºC to 20 ºC.

Fig. 1. Adverse effects of poor thermal care-(www.cemex.pl).
Concrete construction technology, over the past decades, has developed a number of technological factors aimed at preventing the loss of monolithicity as a result of thermal stress due to the heat of hydration. These factors can be divided into 3 groups.

- Factors available at the time of making the concrete mix.
- Factors available during concreting.
- Factors available at the time of curing.

1.1. The factors available at the time of making the concrete mix.

This group consists of:

- Recipe of concrete mix,
- The initial temperature of the mixture.

Most of the recommendations relating to the limitation of hardening temperature of concrete in construction is focused primarily on the use of cements with low hardening heat and reducing the quantity of cement in 1 m³ of concrete. Regardless of the proper selection of the composition of the concrete, particular attention should be paid to the selection of concreting period. Because choosing the appropriate concreting period, a significant reduction in maximum hardening temperature can be achieved.

1.2. Factors available during concreting

This group includes these factors, which may be the subject of a decision in reference to preparatory steps performed on a construction site before concreting or direct concrete laying methods. These factors are usually referred to as industrial technology. The most important factor here is the dividing the construction into blocks often referred to as "industrial system". There are 6 basic systems [2]:

- Lace system,
- Pole system,
- Long blocks system,
- High blocks system,
- Band system,
- Carpet system.

1.3. Factors available at the time of curing of concrete

It has been mentioned before, that, in order to avoid scratches on the surface of the concrete due to heat emission, temperature difference in the inside and on the surface of the concrete should not exceed (15 ± 20 °c). A precondition for the continuation of hydration is to keep the relative humidity inside concrete of min. 80%. Because the essence of care is to keep the concrete in a saturated water or saturated enough, as far as possible, as long as the spaces filled with cement grout in fresh water originally have been filled to the desired degree by cement hydration products [4]. If we do not provide conditions for the continuity of the hydration, undesirable phenomena can be encountered, such as:

- Greater contraction of the plastic and the formation of cracks,
- Lesser strength gain
- Reduction in compressive strength
- Greater permeability and absorption,
- Reduced abrasion resistance.
1.4. It is proposed to use the following care options in hot and dry climate:

- Water Care - spraying the surface of the concrete by water mist, keeping the surface of the concrete noticeably wet,
- Laying on the surface of wet concrete mats and securing them from drying out,
- Coating wet concrete surface with building foil, which should be fixed on the edges and joints,
- The use of delay binding admixtures [cemex]
- Putting a sand layer (thickness approx. 0.1 m) on the surface of concrete, pouring it with water to prevent evaporation and scratches (as far as concreting surface is horizontal),
- Protective layer application of Alsimvel (rose Cimphil) type Pink material or Lanco-covers in order to prevent water evaporation and drying out the surface of the concrete,
- Application of Phase Change Materials (PCM) in order to limit the accumulation of concrete hydration heat temperature.
- Adding cold mixing water or ice cubes to the mixture.

Of course, a combination of these methods is possible, even indicated in the hot and dry climate [5].

In construction realities the most common used care method is water mist spraying on the surface of concrete. The longer concrete is kept wet, the better it is for all of its properties. Particularly susceptible to water loss are thin elements and large opened areas. Not without significance it is also competent to prepare the ground and/or formwork. It has to be noted that a fresh concrete mix, laid on dry ground can lose up to 50% of water in one day. A similar effect can occur if the formwork, in which the concrete is built into, are made of water absorbing materials.

Among the options mentioned above, the possibility of using Phase Change Materials deserves special attention (point 7). The use of this additive when concreting under elevated temperature (hot climate), is to provide the right temperature of the concrete mix in the initial phase of maturation, allowing the continuation of concrete works under high temperature and guarantees the monolithicity of the concreted element. The effects of their use in terms of reduced temperature (Bentz and Turpin, 2007), include both the initial phase of puberty (limiting the freezing of concrete) and the phase of the operation - the reduction of the number of freezing-thawing cycles by post-image phase transformation heat [6].

As it can be seen in Figure 2 (arrows) at the temperature of concrete and air 20°C, relative humidity 50% and the average wind speed of 20 km/h. During one 0.6 litres of water hour evaporates from the surface of 1 m² of concrete. Under conditions when the temperature of concrete is higher than the temperature of air, the quantity of evaporating water grows rapidly. Under the same conditions, but at a temperature of concrete at 25°C amount of evaporated water rises by 50%, which is 0.9 litres per m² per hour.
2. Example of application of Phase Change Materials during concreting (research).

The purpose of the research is to determine the impact of PCM (Phase Change Materials) to reduce thermal gradients within the concrete mix in the initial phase of maturing. Due to the different characteristics of the PCM phase change type materials are divided into two groups: organic and inorganic. The organic materials are saturated hydrocarbons (alkanes, paraffin), of the number of carbon atoms in the range of 16 to 20 (for applications in the construction industry), fatty acids, esters, alcohols (e.g., dodekanol) and other derivatives of hydrocarbons. Inorganic are mainly salts and their hydrates and eutectic mixture [7]. Phase change material used in the research is BASF granules (Micronal®). Polymer balls are filled with organic PCM material, which have diameters ranging from a few dozen to several hundred micrometers. This material has the ability to absorb heat when the temperature of the mixture exceeds 26°C, and release the heat when the temperature goes down below 25°C. There are microscopic spheres of polymers that contain waxy heat storage agent in the PCM material. When it heats up, the wax contained in capsules melts, and when the temperature drops it solidifies. This way, the microcapsules regulate temperature of the concrete mix.

For the research purposes, concrete mix with the addition of PCM materials in amount of 3.5% and sample size 0.50 x 0.50 x 0.15 m has been prepared. There are three sensors in this sample: on the bottom, in the middle and on the surface of the sample. The fourth sensor measures the temperature in the climatic chamber. For comparison, the same was executed in parallel sample of the same size, with the addition of PCM materials, and retarders. Third of
the sample has the same dimensions, but without any additives. The temperature of the output of all the slabs was about 30°C. The thickness of all slabs was the same of: 0.2 m, all of the samples were placed in a climatic chamber. The following graphs show temperatures progress in the three samples. The first chart (fig. 3) shows the temperature progress in the plate with the addition of Phase Change Materials.

![Fig. 3. Temperature progress in concrete with 3,5% PCM.](image3)

![Fig. 4. Temperature progress in concrete with 3,5% PCM and retarder.](image4)

The second graph (Figure 4) shows the temperature progress in the plate with the addition of PCM material with retarder.

The third graph (Figure 5) shows the temperature progress in the slab without any additives.

![Fig. 5: Temperature progress in concrete without additives.](image5)
Thanks to the use of PCM materials, high temperatures inside the compound, which leads to excessive differences in internal stresses, and consequently, to the formation of cracks, have been avoided. After 28 days, the samples have been collected from the material for endurance tests, these studies also show that the use of the PCM also has a negative side, they reduce (10 ÷ 15%) compressive strength of concrete. These adverse effects are more or less relevant depending on the specific applications (drainage ditches, roads, dams, logistic squares, airports, etc.).

The carried out so far studies, confirm that the above mentioned tasks are fulfilled because the materials used have a phase change type that when the temperature of the mixture comes to a temperature of phase transformation – the PCM material absorbs excess heat and turns into liquid, not allowing to cross the adverse temperatures inside the concreting component, and during the fall in temperature below the phase transformation, the PCM materials releases the excess heat stored, stabilizing the temperature inside the concreting component. The described mechanism of PCM usage in concrete is accompanied by typical climatic conditions of the Middle East characterised by a considerable daily amplitude of temperature.

3. Conclusions

Performed research allows to draw the following conclusions:

- The use of PCM materials reduces thermal gradients and unifies the temperature inside the concrete mix.
- Through the use of PCM material, it is possible to concrete during high temperatures (in dry, hot climates).
- The use of PCM material provides the right temperature of the concrete mix in the initial phase of maturation.
- Phase change type materials improve the heat exchange with the environment.

Further research will have to verify the usage of another Phase Change Material with varying temperature phase change.

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