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HEAT AND MASS TRANSFER IN ECOLOGICAL CONCRETE COMPOSITES

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Abstract

From the moment the concrete mix is mixed, the process of chemical interaction of cement with water begins. The duration of this process, depending on the type of cements used, can last for years. In this case, the concrete mixture is considered to be a viscous-flowing liquid, the properties of which change continuously. This is due to internal physical and chemical processes occurring at different rates at different stages of cement hydration in a hardening cement system.The work discusses the basics of heat and mass transfer processes during the hardening of concrete in helioforms (solar forms) with a translucent covering. The features of dehydration of concrete hardening under conditions of high temperatures and low relative humidity have been studied. It has been established that the quantitative indicators of moisture loss affect not only the physical, mechanical and operational indicators, but also the design features of helioforms that are used for aging concrete composites on complex binders obtained through the use of Portland cement and substandard natural and technogenic raw materials.

Keywords: Aging, concrete composites, complex binders, helioforms, natural and technogenic raw materials, Portland cement

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1. Introduction

As it is known, from the moment the concrete mix is mixed, the process of chemical interaction of cement with water begins. The duration of this process, depending on the type of cements used, can last for years. In this case, the concrete mixture is considered to be a viscous-flowing liquid, the properties of which change continuously. This is due to internal physical and chemical processes occurring at different rates at different stages of cement hydration in a hardening cement system.

2. Problem Statement

The process of structure formation of concrete is considered in detail in numerous works of domestic and foreign scientists (Barnes et al., 1979; Gorchakov, 1976; Krylov et al., 1981; Shahabov, 1981; Zasedatelev, 2020) and, despite certain differences among them in approaches, in general it can be considered rather deeply developed. However, for modern concrete composites, in which complex binders are used as a binder, the features of structure formation, heat and mass transfer processes have been studied insufficiently, especially for composites that are maintained in a dry hot climate. The authors of this article carried out a set of research works to study the effect of moisture loss of hardening concrete systems on the structure formation and properties of a concrete composite to solve this problem.

The peculiar climatic conditions in the southern regions of the country can cause negative consequences when obtaining the required physical, mechanical and operational parameters, since the production of concrete works is carried out in conditions of low relative humidity and high ambient temperatures. Therefore, at each stage of concrete hardening, it is necessary to provide for a set of measures to ensure the required curing conditions, ensuring the desired properties are obtained by minimizing the negative impact of environmental conditions. For example, the maximum decrease in the rate of plastic shrinkage in the initial period due to the organization of the care of hardening concrete.

According to numerous authors, (Barnes et al., 1979; Gorchakov, 1976; Zasedatelev, 1976), with traditional heat and moisture treatment and solar thermal treatment, the defining process for freshly laid concrete should be considered its dehydration. If the requirements of solar thermal treatment and the organization of care for freshly laid concrete in a dry hot climate in the first day are not met, moisture loss can be up to 50–70% of the total water consumption for preparing the concrete mixture, while its main amount is in the first 6–7 hours of incubation (Mele, 2022; Nikulin, 2023; Rawel, 2022).

3. Research Questions

As studies have shown (Dmitriev, 1979; Podgornov, 2011; Salamanova et al., 2015; Shchukina et al., 2015; Zasedatelev, 1976), for a hardening viscous-flow system (concrete mix), it is necessary to provide appropriate conditions to prevent evaporation of moisture from the open surface of concrete. According to (Zasedatelev, 1976), the intensity of moisture loss of freshly prepared concrete will depend on the time and method of caring for it, and, as a rule, considering the effect of the holding time, one distinguishes between the initial and final periods, which are essentially completely different.

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The indicator of the intensity of dehydration (j) is used to determine the moisture loss in the initial period of aging (Dmitriev, 1979), kg / m h:

$$j = 1/S\ \Delta m/\Delta\tau = \text{const}, \quad (1)$$

where Δm – the difference in the weight of concrete (kg) in the initial and final periods of time measurement, Δτ (hour);

S – evaporation area, (m^2).

4. Purpose of the Study

In the period under consideration, the rate of moisture loss is the highest and does not depend on the course of internal mass transfer processes. According to many scientists, the determining factor of this nature of the process are different indicators of the partial pressure of steam at the surface of moisture evaporation and in the environment, the speed of its movement and the indicator of the value of the evaporation area (Podgornov, 2011). The duration of this period, when intense evaporation at a constant rate is observed, depends on the value of the water-cement ratio, the holding conditions and the rate of the cement hydration reactions.

For the final period, a different process and rate of evaporation are inherent, which are determined by the value of concrete moisture at that time (Dmitriev, 1979). In this case, the evaporation process depends not only on the state of the surface of the hardening concrete, but is also determined by the processes of internal movement of moisture, changes in the rate of evaporation of moisture and deficiency of moisture growth from the open surface to the center.

Soft modes of concrete heating in helioforms contribute to the creation of ideal conditions for the formation of the concrete structure. This is guaranteed to provide high strength and performance indicators at the output. Confirmation of the presence of soft modes is the fact that during the first six hours of holding, temperature differences in the thickness of the concrete of the product are absent or minimal (Dmitriev, 1979; Shchukina, 2020; Semenov, 2023; Salamanova et al., 2015, 2019).

Thus, the hypothesis of a new approach to the use of solar radiation for heat and moisture treatment of concrete directly in thermoforms, proposed by leading domestic and foreign scientists-concrete experts, can be considered an effective way to accelerate hardening in conditions of high temperatures and dry hot climate for numerous regions of the country and the world (Salamanova et al., 2015; Zasedatelev, 2020). However, in this case, it is necessary to further study the features of the formation of the concrete structure, taking into account the flow of heat and mass transfer processes in hardening concrete in technogenic raw materials.

5. Research Methods

In this work, studies were carried out aimed at determining the dependence of the rate of moisture evaporation (j) on the indicator of the air gap between the concrete surface and the film (δ) with varying ratios of the areas Fc and Fe (Collet-Sabé, 2023; Manakbayeva, 2023; Sheveleva, 2024).

During the research, the following changed: δ, the ratio of the condensation area (Fc) and the evaporation area (Fe), the type of binder used and the number of film layers of the solar (helio) cap.

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6. Findings

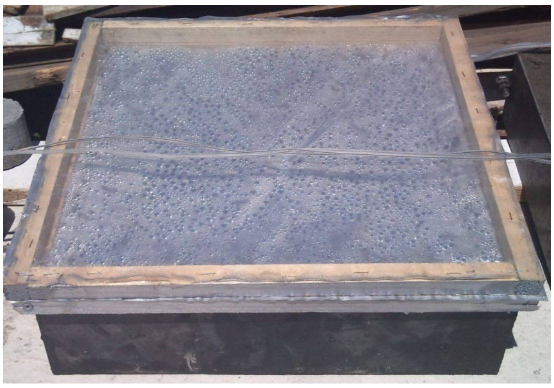
The studies were carried out using previously developed compositions of fine-grained concrete based on a complex binder (Table 01), including cement and screenings of crushing of concrete scrap.

Table 1. Compositions and properties of the investigated concrete mixtures

№	Binder type	Consumption binder, kg / m^3	Crushing Waste Consumption, kg / m^3	Water consumption, kg / m^3
	Composite binders (CB) 100	500	1500	140
	Ash-and-slag composite binders (ASCB) 70	505	1495	152
	ASCB 50	508	1524	152
	ASCB 30	512	1536	164
	Sand composite binders (SCB) 70	510	1490	153
	SCB 50	508	1492	162
	SCB 30	511	1489	164

A special form with dimensions 40x40x15 cm was developed for a research, which made it possible to take into account the scale factor of the heat flow and mass transfer processes. In order to prevent heat losses on the lateral edges of the mold, a five-centimeter special insulation was provided. The design of the solar cap was made of wooden frames, inside of which the number of layers of translucent coating was changed.

There were used the Terem-2 setup (Figure 01) and thermocouples based on an alloy of chromium and cobalt to record the current values of the temperature field in various sections along the thickness and on the product surface and the solar cap.



a

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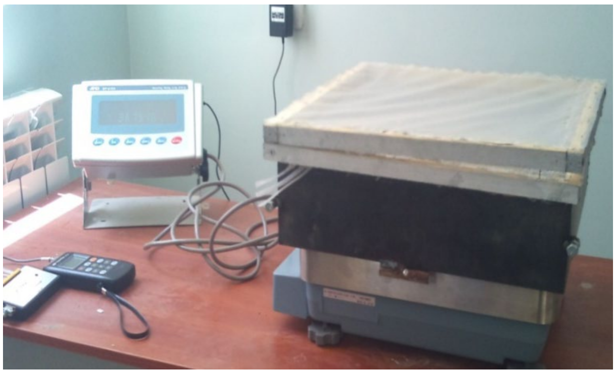

b

c

Figure 1. Studies of temperature and moisture loss in hardening concrete: a – temperatures in a modular block; b – simultaneously moisture loss and temperature; c – registration devices.

The strength of concrete was measured using an ultrasonic device "Pulsar 1.1", and then, after stripping, specimens 15x15x15 cm were cut out of the block and tested in a standard way using a hydraulic press for a comparative analysis of the measurements accuracy at daily and monthly ages.

The influence of the technological parameters of freshly prepared concrete and the design features of the solar cap on moisture loss was studied: the intensity of moisture loss from the type of applied binder of various values Fc/Fe from 2.0–2.5 to 20.0–21.0 cm, ratios from 1.0 to 4.4 (Giza, 2024; Mambetova et al., 2024; Mascareno & Chavez, 2024).

The choice of such options is due to the fact that in real production conditions only such changes are possible. The analysis of the studies (Figure 02) shows that the relative moisture loss in concretes with various binders is dominated by Portland cement, in contrast to similar ones on complex binders.

Studies of the influence of the air gap between the solar cap and the open surface of freshly laid concrete during variation Fc/Fe were established, that the values $\frac{\Delta W}{W}$ for the corresponding air gap thicknesses 2.0–2.5; 5.0–5.5 and 10.0–10.5 cm practically the same, with its increase to 21 cm, the relative moisture loss $\frac{\Delta W}{W}$ increased twice, while the design strength decreases by 15% or more for all the samples under study (Table 02).

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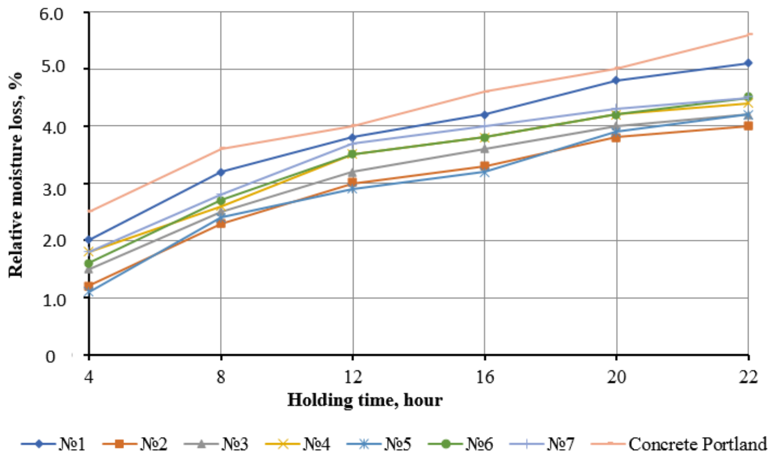

Figure 2. Dynamics of concrete moisture loss (compositions according to Table 01)

Researches to study the change in the value of moisture loss from the assumed thickness of the air layer between the solar cap and the open surface of concrete indicate that concretes on Portland cement have an intensity at a thickness of 2 cm that is two times greater than that of concrete composites at sand composite binders (SCB) (Figure 03). It is clear that with a further increase in this indicator, moisture loss increases linearly.

Table 2. Influence of moisture loss on the strength characteristics of concrete

δ, mm	$\frac{F_K}{F_n}$	Limit values of moisture loss of concrete,% of mixing water		Strength at daily age of concrete,% of R28n		The strength in the months of age concrete% of R28n	
		using SCB50	using CEM I 42.5N	using CB350	CEM I 42.5N	using CB350	using CEM I 42.5N
20–25 (2-layer covering)	1	2.9	3.4	55	47	115	105
20–25	1	4.5	5.6	52	42.0	102	99.0
50–55	1	7.2	7.5	41	39.0	98	96.0
100–105	1	8.3	8.6	40	38.0	98	96.0
200–210	1	14.9	15.3	38	36.0	32	30.0
50–55	1.5–1.6	12.6	12.9	42	40.0	94	90.3
100–105	2.0–2.2	21.0	21.3	41	39.5	87	85.4
200–210	4.0–4.4	32.0	32.5	40	39.0	80	77.4

In accordance with (Podgornov, 2011; Zasedatelev, 2020), moisture losses not exceeding 0.2 kg / m2·h are considered "critical" for guaranteed production of high-quality concrete for Portland cement. Analysis of the graph (Figure 03) shows that concretes with ash-and-slag composite binders (ASCB) in the initial period of the structure formation binds the mixing water more strongly, in comparison with concretes on Portland cement. The limiting distance between the surface of the concrete and the lower film of the solar cap for concrete using Portland cement should be no more than 14 cm. and for concrete with ASCB – no more than 18 cm.

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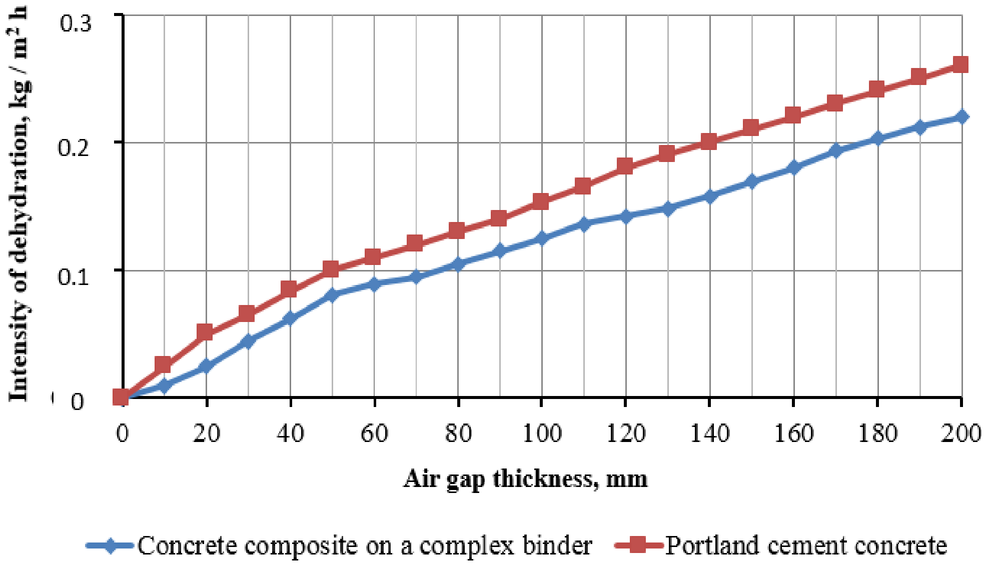

Figure 3. Dependence of the intensity of moisture loss on the air gap thickness

The results of the above studies suggests that regardless of the thickness of the vapor-air layer and the ratio of Fc and Fe and the process of moisture evaporation from the open surface of concrete can be divided into the following significant stages:

i. the initial stage (1–4 hours) is the time during which the air volume between the freshly laid concrete and the solar cap is saturated;
ii. the interval after 4 hours to 6 hours, when the free volume between the concrete and the solar cap is completely saturated with a vapor-air mixture, water drops appear on the lower surface of the film, the temperature in the upper section of concrete rises;
iii. the beginning of the active process of moisture evaporation starts within 7 and 8 hours;
iv. 8–12 hours is the most active period of moisture loss, during which concrete loses 70–80% of the total amount of moisture loss;
v. after 12 hours of placing the concrete mixture in a mold with a translucent coating, the process of moisture loss is completed, therefore, external mass transfer from the open surface of the concrete product is blocked.

The greatest moisture loss in the interval of 8–12 hours of holding can be explained by the fact that during this period the active influence of solar radiation ceases and the surface temperature of a film of solar cover decreases and balances with the ambient temperature. At the same time, the temperature of the concrete in the helioform, due to the ongoing hydration reactions and significant inertia, decreases with a smaller velocity gradient (Figure 04).

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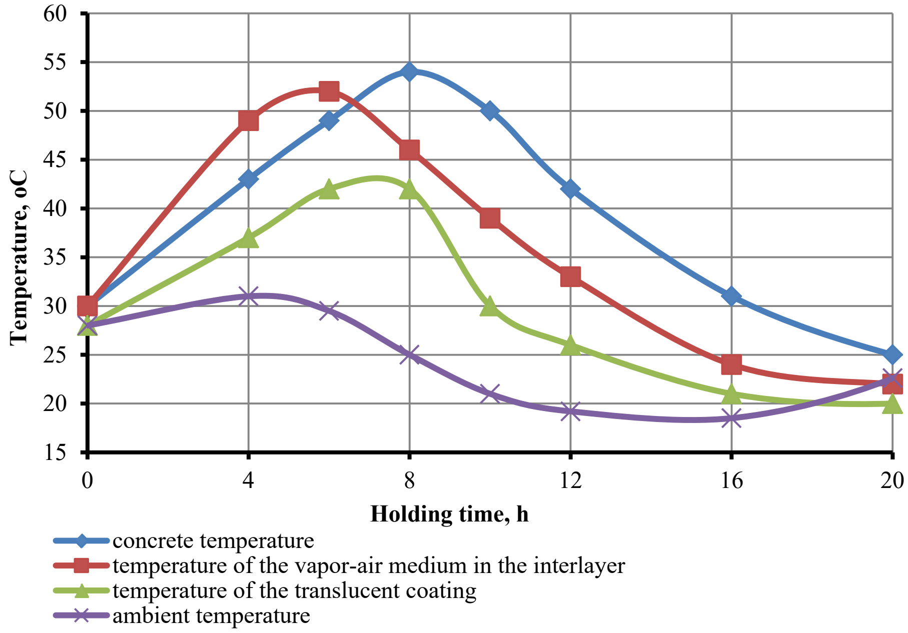

Figure 4. Formation of temperature fields of the translucent coating, concrete mixture and vapor-air layer depending on the ambient temperature during solar thermal treatment

This behavior of the hardening system "concrete-solar covering" leads to a noticeable temperature difference between the open surface of the concrete and the lower layer of the solar coating, which leads to an increase in moisture loss during the period under consideration.

The absence of moisture loss after 12 hours of holding is explained by the equilibrium of the partial pressures on the concrete surface and in the volume with the vapor-air mixture, as well as the completion of the forming process for the crystalline structure of the concrete composite.

7. Conclusion

In addition, studies have shown that a change in the indicator of relative moisture loss does not provide the proportion inherent in the ratio of areas of condensation and evaporation of moisture. This is due to heat and mass transfer in the vapor-air layer.

Thus, studies of heat and mass transfer processes in a helioform with hardening concrete have established that in order to increase the efficiency of using solar radiation for heat and moisture treatment of concrete composites, taking into account the sources of heat input, it is necessary to control the processes of internal and external heat and mass transfer, and the design of helioforms should be based on taking into account moisture loss and the need to create a water-saturated vapor-air layer between the concrete surface and the translucent coating.

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