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CURRENT PROBLEMS OF HARDENING MONOLITHIC ROAD AND AERODROME CEMENT CONCRETE CURING

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Studies of moisture loss from hardening monolithic cement concrete have been carried out. It was found that there is no consensus on the critical value of moisture loss from hardening concrete, at which shrinkage and cracking are possible, there is no common understanding of the possible critical width of the shrinkage crack opening. It is shown that when concrete hardens in air-dry conditions, their indicators, including durability, decrease by a factor of 2 or more. The critical value of moisture loss from hardening concrete was experimentally determined, which is 2 kg/m^2. In this case, the deterioration of concrete properties as a result of re-hydration of cement does not exceed 5 % and does not affect its durability. The possibility of restoring the properties of concretes, which were lost as a result of cracking during plastic shrinkage and contraction, has been experimentally proved if, after cracking, the concretes are placed for further hardening in a humid environment.

Keywords: monolithic road and aerodrome cement concrete, hardening, cement, hydration, shrinkage cracks, film-forming materials.

Introduction

The volume of cargo transportation by road in the world is continuosely increasing. It is carried out on roads with asphalt or cement concrete pavement. However, due to the dramatically increased traffic intensity and vehicle axle loads, asphalt concrete pavements are rapidly deteriorating. They are designed for 6...8 years of operation. On the other hand, cement concrete pavements are designed for 15...25 years of operation. In recent years, the volume of road construction with cement concrete in Ukraine has been increasing. This type of road surface requires strict implementation of technologies, especially the curing technology for the hardening concrete. Violation of this technology can lead to destruction of the pavement. Therefore, it is relevant to study the problems of this technology and the factors that affect its effectiveness.

A particular danger for hardening monolithic concrete is the evaporation of moisture from it. This leads to shrinkage and cracking, which, in turn, lead to a decrease of the durability of concrete and its collapse (Havlasek & Jirasek, 2016). Methods and materials for the hardening monolithic concrete curing have been developed (Pawar & Kate 2020). They were included to the recommendations of the SoyuzdorNII on the use of film-forming materials for the concrete curing and in (Instructions for the construction of cement concrete pavements for highways, 1980). It is especially important to carry out operations for the concrete curing in the initial period of its hardening (Gjorv & Sakai, 1999). With insufficient concrete curing, the value of internal stresses can reach 12 ... 16 MPa. This exceeds the tensile strength of the cement concrete.

Currently in Ukraine there is DBN V.2.3-4: 2015 "Highways. Part 1 Design. Part 2 Construction" (Highways. Part 1 Design. Part 2 Construction, 2015). This standard states that the maintenance of concrete curing is mandatory. A modern method of curing is the use of film-forming materials (FFM), which are aqueous emulsions, most often based on latex or paraffin. Emulsions are sprayed onto the surface of monolithic concrete after a certain time after compaction. The time for applying emulsions depends from the temperature and humidity conditions of laying, the presence and speed of wind, the composition of concrete, etc. In addition, the amount of FFM, which have different compositions, applied to 1 m^2 of pavement, is different. For each FFM under production conditions, it is necessary to determine how much is sufficient in order to protect the concrete from moisture evaporation, shrinkage and cracking. Currently, Ukraine does not have any criteria to quantify how effective the protection is. Until now, such an assessment is carried out visually: if shrinkage cracks have appeared, then the protection has been carried out poorly, if there are no cracks, the protection has been carried out well. However, even if there are cracks on the surface of the pavement, they may close over time. This can be due to the ongoing hydration of the cement within the fracture itself. Our studies, which have been confirmed in the practice of constructing concrete pavements, show that the concrete pavement may not always collapse when shrinkage cracks form. Therefore, it is relevant to develop a quantitative assessment of the protective ability of film-forming compositions and an assessment of the possibility of restoring concrete properties in the case of their partial loss.

Materials and Methods

Cement CEM I 52.5 produced by JSC “Podilskiy Cement” (Ukraine) and quartz sand with a fineness modulus of Mfm = 2.1 were used in the studies. A superplasticizer based on polycarboxylates, Fk59, manufactured by MC-Bauchemie, Germany, was also used. For comparison, a superplasticizer based on lignosulfonates purified from sugars, Sika 2607A, was used. which is manufactured by Sika, Switzerland. For research, mortar of the composition cement : sand = 1 : 3 was made. To protect it from moisture evaporation, FFM was applied to mortar surface: Emcoril (MC-Bauchemie, Germany), Tent (Promkhimgroup, Belarus), and Antisol E (Sika, Switzerland). The loss of moisture from the hardening mortar was determined by the loss of mass of samples of composition C : S = 1 : 3 during the first three days. The samples were inverted truncated pyramids with a bottom linear dimension of 95 mm and an upper dimension of 105 mm. The samples were weighed once a day.

Results and discussion

First of all, it is necessary to give a definition of what is the critical value of moisture loss from hardening concrete. This is the amount of moisture that can evaporate from a unit surface area of hardening monolithic concrete without significant deterioration of its properties. This definition is based on the quantitative characteristics of concrete, but can be clarified based on the results of subsequent studies. This is due to the fact that when analyzing the decrease in concrete performance, it is necessary to take into account the possibility of their partial or complete restoration. Such regain of properties can occur after their partial loss, for example, if concrete is placed in an aqueous medium for further hardening.

In numerous studies and experiments devoted to moisture loss from hardening monolithic cement concrete, attempts have been made to quantify the critical value of moisture loss at which the concretes did not lose their operational properties (Bushlaibi and Alshamsi, 2002; James, Malachi, Gadzama & Anametemok, 2011; Raheem, Soyingbe & Emenike, 2013). The reason for this is the statement about the possibility of rehydration of cement, from which water evaporated at the initial stage.

Back in the 80s of the last century, studies were carried out in which the maximum allowable value of moisture loss during hardening of concrete was established during the first three days. This value is equal to 0.055 g/cm^2 or 0.55 kg/m^2. This requirement was published in a regulatory document (Recommendations for testing film-forming materials for the curing of freshly laid concrete, 2014). If in the first 3 days the concrete did not lose more than stated amount of moisture, then later it was considered protected against shrinkage and cracking. Authors can agree with this, because in concretes based on modern cements and superplasticizers, the processes of structure formation are practically completed by 3 days (Taylor, 2013). By this time, the strength of pavement concrete reaches 90...95 % of the final strength.

In some European countries, for example, in Germany, moisture loss is controlled during the first day after placing concrete. This is not always justified, because moisture evaporation processes are influenced by temperature, humidity, quality and quantity of cement and aggregates.

Modern cements, obtained by a separation method, are characterized by significant fineness. The increasing loads from traffic and the external environment lead to the need to improve the characteristics of concrete. Therefore, chemical and mineral admixtures are introduced into concretes, and the cement content is also increased. Studies carried out in the USA and Europe, have shown that with a cement consumption of more than 430...450 kg/m^3, in addition to drying shrinkage, autogenous shrinkage (contraction) also occurs. It leads to cracking inside the concrete and these cracks do not appear on the concrete surface immediately, but after several months (Fig.).

Fig 1. Shrinkage cracks on concrete pavement

Therefore, in a number of countries, the consumption of cement in monolithic road concretes, including Ukraine, is limited.

The studies have shown that most of the FFM used in Ukraine meet the requirements for the limiting value of moisture loss (0.055 g/cm^2 or 0.55 kg/m^2) (Table 1). Obviously, with an increase in the FFM consumption from 200 to 400 g/m^2, the amount of evaporated moisture from mortars changes insignificantly. Considering that FFM is a liquid, with an increase in its consumption of more than 400 g/m^2, there is a risk of FFM dripping from the pavement due to the slope of the transverse profile. Therefore, such an increase of FFM consumption is often impossible.

Table 1

Moisture loss from cement mortars with CEM I 52.5

Type and amount of additives, % of m_c	Type and quantity FFM, g/m^2		Moisture loss, g/cm^2	
			After 1 day	After 3 days
Sika 2607A – 0.6	Emcoril	200	0.016	0.021
		400	0.012	0.017
	Tent	200	0.022	0.031
		400	0.018	0.025
	Antisol E	200	0.019	0.030
		400	0.017	0.025
Fk 59 – 0.6	Tent	200	0.032	0.043
		400	0.025	0.037
	Emcoril	200	0.016	0.023
		400	0.012	0.019

On the other hand, an increase of FFM consumption can lead to complete blocking of the concrete surface. In recent years, some countries have introduced a new requirement to ensure the vapor permeability of concrete (Mannan, Basri, Zain, & Islam, 2002). Therefore, the amount of water that has evaporated during concrete hardening is not limited only by the value of the maximum moisture loss. Evaluation of vapor permeability is quite complicated and requires special equipment. Therefore, in (Recommendations for testing film-forming materials for the curing of freshly laid concrete, 2014), another critical value of moisture loss is normalized - not less than 100 g/m^2 after 3 days of concrete hardening. If we consider the optimal range of moisture loss is 100...550 g/m^2, then FFM covered concrete with moisture loss close to 550 g/m^2 are more effective. This allows us to consider the problem of protecting concrete from moisture evaporation in a new way. Figure shows shrinkage cracks in a concrete pavement area. At the same time, despite the fact that FFM was applied to the concrete surface, shrinkage cracks still appeared several weeks after the concrete was placed. It is possible that the reason of the formation of these cracks is contraction, since the cement consumption was 430 kg/m^3, and the FFM consumption was minimal (about 200 g/m^2). The crack opening width did not exceed 1...2 mm. This area of concrete was periodically watered. Due to this, the number of these cracks decreased and then they disappeared. The cracks disappeared because of secondary hydration of the cement in the cracks themselves.

It should be noted that when a crack is formed at its edges and on its banks, opposite charges and electrosurface potential arise. Therefore, in general, the crack tends to "self-heal" as a result of attraction between electroheterogeneous contacts. However, when water or aqueous surface-active reagent get into the crack, electroheterogeneous contacts are screened. Equally charged surfaces appear, which will repel, and, thereby, promote the growth of the crack. This shows the effect of adsorption strength reduction (Rebinder effect).

The possibility of "self-healing" of cracks was noted by some researchers. For example, in (Domagala & Podolska, 2022) it was shown that water ingress into cracks and other defects in the concrete structure leads to the emergence of the wedging effect. In this case, the strength of concrete is reduced by up to 30 %. However, it is also shown that with prolonged exposure to moisture, the strength of concrete, which has decreased due to cracking, is not only restored, but can increase by 20...25 %. The author of the work explains this effect by a decrease in the value of the wedging pressure in the pores and cracks, as well as by the continuing hydration of the cement inside the cracks.

V. Vyrovoy and his colleagues developed a model of the formation and development of a shrinkage crack (Vyrovoy et al,1982), it was further developed in (Tolmachev et al, 2021). The characteristics of the growth and development of the crack are primarily affected by the continuous hydration of the cement, at the same time, its shape changes. If the rate of cement hydration is higher than the rate of crack development, then new formations will be deposited inside the crack and "self-heal" it. Then the main condition for "healing" the fracture is to provide an opportunity to continue the hydration of the cement. For this, it is necessary to ensure the delivery of water to the body of the crack.

Research conducted under the supervision of O. Batrakov, showed that the maximum crack opening width in a cement concrete pavement should not exceed 10-4 m, or 0.1 mm (Fordyce & Yrjanson, 1969). In this case "self-healing" effect may occur. However, experimental data showed that the maximum opening width of cracks in a sharply continental climate can reach 1.5...2 × 10^{-3} m, or 1.5...2 mm. In this case, if the conditions for ensuring rehydration of the cement are met, "self-healing" of shrinkage cracks will occur.

The studies have shown that when concrete hardens under normal curing conditions, moisture loss does not exceed 21 % of its total amount (Table 2). Changing the hardening conditions leads to an increase of moisture loss by 3 times. Such moisture loss leads to a decrease of the compressive strength of concrete by 53 % at the age of 3 days and by 46 % at the age of 28 days. In this case, not only strength will deteriorate, but also other concrete parameters. This will result in a significant loss of durability.

Table 2

Properties of concrete hardened in various conditions

Concrete composition, kg/m^3	Curing conditions	Moisture loss after 3 days		f_{ck} cube , MPa	
		% of the total volume of water	kg/m^2	3 days	28 days
Cement – 360 Sand – 580 Gravel – 1300 Water – 140 Fk59 – 2	normal *	21	0.61	31.4	51.3
	air dry **	63	2.30	14.7	28.5
	combined ***	63	2.30	15.1	49.6

* – temperature 20 ± 2 ° C, humidity 95...100 %;
** – temperature 20 ± 2 ° C, humidity 55 %;
*** – air-dry conditions during the first 3 days, then - hardening in water.

However, if concrete is placed in water after hardening for three days in dry conditions, then re-hydration of the cement begins and the properties of the concrete are restored. So, for example, in concretes that hardened according to this regime, the strength is practically restored in comparison with concretes that hardened in the normal conditions.

Our further research showed that there is a critical value of moisture loss, after reaching which the properties of concrete are not restored. They do not recover even if the concrete is placed for further hardening in wet conditions after hardening in dry conditions. To determine this critical value, the hardening concrete samples were subjected to different curing conditions. First, all samples were hardened in air-dry conditions. After the samples lost different amounts of moisture, they were placed into conditions of 100 % humidity for further hardening (Table 3).

Then, at the age of 28 days, the strength, water absorption, abrasion and frost resistance of the samples were determined (table 3). It was found that with a moisture loss of 500...1000 g/m^2, the properties of concrete do not change. An increase in moisture loss up to 2000 g/m^2 slightly worsens the properties of concrete (by 4…6 %) and this does not affect its durability. With a further increase in moisture loss, a significant deterioration of concrete performance occurs. For example, strength decreases by 10...17 %, water absorption increases by 22, and abrasion - by 35 %. Frost resistance, as the main indicator of the durability of concrete, is reduced by one grade. A further increase in moisture loss leads to a sharp decrease in strength (more than 20 %) and deterioration of other parameters of concrete by 50 percent or more.

Table 3

Determination of the critical moisture loss value

Moisture loss, kg/m^2	f_{ck} cube , MPa	f_{cti}, MPa	Water absorption, %	Abrasion, g/cm^2	Frost resistance grade, F
0.5	38.9	5.80	3.6	0.34	200
1.0	39.0	5.62	3.6	0.36	200
2.0	37.8	5.50	3.8	0.36	200
3.0	35.1	4.83	4.4	0.46	150
4.0	33.5	4.67	5.6	0.58	150
5.0	318	4.21	6.7	0.74	100
6.0	30.7	4.16	7.3	0.76	100

By analogy with frost resistance tests, where the value of strength should not decrease by more than 5 %, it can be taken as the critical value of moisture loss at which the main characteristics of concrete decrease by no more than 5 %. The obtained results indicate that the critical value of moisture loss is 2000 g/m^2. This is approximately 3.6 times more than the limiting value of moisture loss, which is recommended in (Recommendations for testing film-forming materials for the curing of freshly laid concrete, 2014). The results obtained do not call into question the limitations set in (Recommendations for testing film-forming materials for the curing of freshly laid concrete, 2014), since it is usually not possible to place monolithic concrete after significant moisture loss in an environment of 100 % humidity in real production conditions.

Conclusions

1. It was found that there is no consensus on the critical value of moisture loss from hardening concrete, at which shrinkage and cracking are possible. There is no common understanding of the possible critical width of the shrinkage crack opening.

2. It is shown that when concrete hardens in air-dry conditions, their indicators, including durability, decrease by a factor of 2 or more.

3. The possibility of restoring the concrete properties, which were lost as a result of cracking during plastic shrinkage and contraction, has been experimentally proved if, after cracking, the concretes are placed for further hardening in a humid environment.

4. The critical value of moisture loss from hardening concrete was experimentally determined to be 2 kg/m^2. In this case, the deterioration of concrete properties as a result of re-hydration of cement does not exceed 5 % and does not affect its durability.

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АКТУАЛЬНІ ПРОБЛЕМИ ТВЕРДІННЯ МОНОЛІТНОГО ДОРОЖНЬОГО ТА АЕРОДРОМНОГО ЦЕМЕНТОБЕТОНУ

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В останні роки в Україні збільшуються обсяги будівництва доріг з цементобетонними покриттями. Даний тип дорожнього покриття вимагає суворого дотримання технологій, особливо технології догляду за твердінням бетону. Порушення цієї технології може призвести до руйнування покриття. Тому актуальним є дослідження проблем даної технології та факторів, що впливають на її ефективність. Особливу небезпеку для твердіючого монолітного бетону становить випаровування з нього вологи. Це призводить до усадки і розтріскування, що, в свою чергу, призводить до зниження довговічності бетону і його руйнування. Особливо важливо проводити операції з твердіння бетону в початковий період його твердіння. При недостатньому твердінні бетону величина внутрішніх напруг може досягати 12 ... 16 МПа. Дослідження, які підтверджені практикою будівництва бетонних покриттів, показують, що бетонне покриття не завжди може руйнуватися при утворенні усадочних тріщин. Тому актуальною є розробка кількісної оцінки захисної здатності плівкоутворювальних композицій та оцінки можливості відновлення властивостей бетону у разі їх часткової втрати. Проведено дослідження втрати вологи при твердінні монолітного цементобетону. Показано, що при твердінні бетону в повітряно-сухих умовах їх показники, в тому числі довговічність, знижуються в 2 і більше разів. Експериментально визначено критичне значення втрати вологи при твердінні бетону, яке становить 2 кг/м^2. При цьому погіршення властивостей бетону в результаті повторної гідратації цементу не перевищує 5 % і не впливає на його довговічність. Експериментально доведено можливість відновлення властивостей бетонів, втрачених в результаті розтріскування при пластичній усадці і стягуванні, якщо після розтріскування бетони помістити для подальшого твердіння у вологе середовище.

Ключові слова: монолітний дорожній і аеродромний цементобетон, твердіння, цемент, гідратація, усадочні тріщини, плівкоутворювальні матеріали.