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ESTIMATED FORECASTING CONCRETE WATER IMPERMEABILITY

РОЗРАХУНКОВЕ ПРОГНОЗУВАННЯ ВОДОНЕПРОНИКНОСТІ БЕТОНУ

РАСЧЕТНОЕ ПРОГНОЗИРОВАНИЕ ВОДОНЕПРОНИЦАЕМОСТИ БЕТОНА

Annotation. The article discusses the possibility of calculation of the filtration coefficient as a measure of water impermeability of concrete, which can taken into account in the design of concrete compositions. The known design dependences to connecting water imper-meability parameters with parameters of concrete compositions and structure are analyzed. It is given a nomogram for calculating the filtration coefficient of concrete linings for concrete channels, depending on the water pressure, wall thickness and the amount of filtrate. The calculating formulas filtration coefficient of concrete, depending from the porosity of the concrete and its strength, taking into account the conditions and duration of hardening are obtained.

Keywords. Water impermeability,filtration coefficient,porosity,water-cement ratio,design,concrete compositions,compressive strength.

Анотація. У статті розглядається можливість розрахункового визначення коефіцієнта фільтрації як показника водонепроникності бетону, який може враховуватися під час проектування складів бетону. Проаналізовано відомі розрахункові залежності, що зв'язують показники водонепроникності з параметрами структури і складу бетону. Наведено номограма для розрахунку коефіцієнта фільтрації бетону для бетонних облицювань каналів в залежності від тиску води, товщини облицювання й кількості фільтрату. Отримано розрахункові формули коефіцієнта фільтрації бетону в залежності від пористості бетону і його міцності з урахуванням умов і тривалості твердіння.

Ключові слова. ВодонепроникнІсть.коефициент фІльтрацІЇ,пористІсть,водоцементне вІдношення,розрахунок,склади бетонІв,мІцність на стиск.

Анотация. В статье рассматривается возможность расчетного определения коэффициента фильтрации как показателя водонепроницаемости бетона, который может учитываться при проектировании составов бетона. Проанализированы известные расчетные зависимости, связывающие показатели водонепроницаемости с параметрами структуры и состава бетона. Приведена номограмма для расчета коэффициента фильтрации бетона для облицовок каналов в зависимости от давления воды, толщины облицовки и количества фильтрата. Получены расчетные формулы коэффициента фильтрации бетона в зависимости от пористости бетона и его прочности с учетом условий и длительности твердения.

Ключевые слова. Водонепроницаемость,коэффициент фильтрации,пористость,водоцементное отношение,расчет,составы бетона,прочность при сжатии.

Formulation of the problem. Water impermeability of concrete is selected according to the admissible filtration characteristics of concrete and its stability to corrosion [1-4].

Proper selection of water impermeability requirements, as well as frost resistance of concrete, is accompanied by many difficulties. At the same time, producing concrete with proper water impermeability often leads at other equal conditions to cement consumption increase; therefore taking into account concrete water impermeability requirements at compositions proportioning stage may be dominant.

It is possible to use two normative characteristics of water impermeability for concrete compositions proportioning:

1) the maximum water pressure (MPa), that standard specimens (usually cylinders with diameter and height of 150 mm) can withstand without appearing on their surface signs of water infiltration (W_{imp}).

2) concrete filtration coefficient, characterizing the water quantity, penetrating through a unit section per time unit at gradient (the ratio between pressure in m of water column and the element's thickness in m) equal to 1 (C_f).

Regulation of the concrete water impermeability in some cases is recommended depending on the pressure gradient value, which is very imperfect. Often the concrete water impermeability which is an indirect parameter of their density is selected considering the experience of structures operation.

A more precise indicator of water impermeability, compared to maximum water pressure (W_{imp}) is filtration coefficient C_f, obtained from the following condition

$$C_f = \eta \frac{Q_f}{S\tau P} \qquad (1)$$

where Q_f is the filtrate quantity; S – concrete specimen surface area; τ – duration of filtration; P – water pressure; η – coefficient, considering water viscosity ($\eta = 1$ at $t = 20$ °C).

Concrete filtration coefficient has a correlative relation with maximum water pressure (W_{imp}). Following known recommendations, for water saturated specimens at W_{imp}=0.4 MPa the value of C_f varies from $1{\bullet}10^{-10}$ to $5{\bullet}10^{-10}$; W_{imp} =0.6 MPa – from $5\ 10^{-11}$ to $1{\bullet}10^{-10}$; W_{imp}=0.8 MPa – from $1{\bullet}10^{-11}$ to $5{\bullet}10^{-11}$, W_{imp} =1.2 MPa – less than $5.\ 10^{-12}$.

The easiest way for providing the required concrete water impermeability is limiting W/C according with recommendations of modern standards. These recomendations do not consider the influence of many factors, including such important ones like conditions and duration of concrete hardening.

Analysis of the basic studies. For calculating W/C and other parameters of concrete composition, depending on the required water impermeability polynomial regression equations were proposed [5,6]. These equations are valid just in a relatively narrow initial conditions region.

It was shown that it is possible to predict the concrete water impermeability (W_{imp}) at given cement-water ratio C/W or conversely to obtain C/W at given W_{imp} value using the following formula [7]:

$$W = \frac{AR_{cem}(C/W - 0.5)}{100}, \qquad (2)$$

where R_{cem} is the 28-day cement strength, MPa.

Coefficient A can be specified using a special nomogram, considering the influence of C/W, consumptions of water, admixtures and air pores volume. This approach is possible though it does not directly takes into account the essential influence of aggregates features and grading on water impermeability.

It was proposed [8] to select parameter X, i.e. the ratio between water-cement ratio (W/C) of cement stone in concrete and the value of cement paste normal consistence (N.C) depending on the required concrete water impermeability (W_{imp}). For vibrocompacted concrete at X = 1.2...1.3 – W_{imp} =0.2 MPa; X = 1.1 – W_{imp} =0.4 MPa; X = 1.05 – W_{imp} =0.6 MPa; X = 1 – W_{imp} =0.8 MPa.

At known value of parameter X, concrete strength (R_c) is found and after that aggregates and cement consumptions are obtained. However concrete proportioning methodology is based on insufficiently proved preconditions and yields questionable results (for example for concrete with water impermeability W_{imp} =0.4 MPa, 28-day concrete strength R_c= 50 MPa, Slump Sl =1 ... 5 cm are required: cement C = 345 kg/m^3; water W = 152 kg/m^3; sand S = 1088 kg/m^3; crushed stone Cr.S = 869 kg).

A wide research program was carried out on water filtration throug concrete [71]. It was shown that filtration coefficient depends on capillary suction pressure and its average values are: for W_{imp} =0.4 MPa – 1. 10^{-8}; W_{imp} =0.6 MPa – 5.10^{-9}; W_{imp} =0.8 MPa – 3.10^{-9}.

Filtration coefficient regulation is possible at known value of admissible filtration losses. A nomogram for design of concrete lining of channels, relating the water pressure, thickness of lining and filtration coefficient has been proposed by us (Figure.1) [1].

The operating life design of corrosion-resistant concrete is directly related with filtration coefficient:

$$C_f = wL/H\tau, \qquad (3)$$

where L is the structural element's thickness, m; H- water pressure, m; τ – design operating life, years; w – quantity of filtered water per unit time through a unit of area.

An equation of an ultimate filtration coefficient, depending on the quantity of substance (Q_{sbs}), which can be removed from or brought into concrete without any loss in its bearing capacity, per 1 cm^2 of concrete surface, was proposed:

$$C_f = Q_{sbs}L/C_{agr}H\tau\ , \qquad (4)$$

where C_{sbs} is the substance concentration, removed from or brought into concrete.

C_{sbs} is obtained according to the following formula:

$$C_{sbs} = CL_x, \qquad (5)$$

where L_x is the admissible depth of damaged concrete, cm; C – cement consumption, kg/m^3.

At leaching corrosion:

$$C_{sbs} = \alpha_1 q_{CaO} CL, \qquad (6)$$

where α_1 is the admissible degree of calcium oxide leaching; q_{CaO} – its content, g in 1 g of cement.

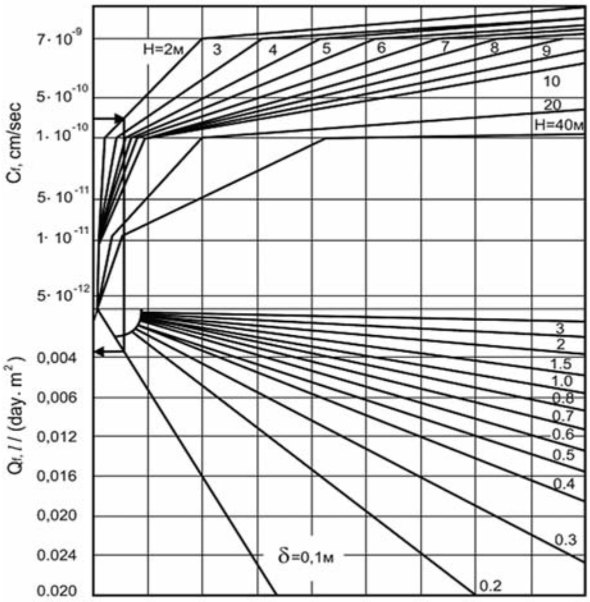

Figure 1. Nomogram for calculating water impermeability of concrete lining of channels. Above the abscissa axis – water pressure curves (H), below – concrete lining thickness (δ); C_f – filtration coefficient; Q_f – filtrate quantity.

In order to obtain the filtration coefficient in monolite concrete structures it is recommended to use its correlational relation with specific water absorption q_w [9]. The transfer coefficient c = C_f/q_w, is about 0.001.

Presently no quantitative theory, relating concrete permeability and its structure is developed due to a complex mechanism of water transfer in concrete and high number of affecting factors. At the same time, a wide research that has been carried out [4,9] enables to classify the fluids transfer mechanism in concretee into 3 kinds:

1) at pores radius more than 10^{-4} cm – viscous stream (regular concrete, porosity is at least 8%);

2) 10^{-5} ... 10^{-4} – capillary stream (dense concrete, porosity 3...8%);

3) < 10^{-5} cm – molecular diffusion (especially dense concrete, porosity 1...3 %).

Correspondingly, filtration coefficient, depending on the transfer mechanism, can be more than 10^{-4} cm/sec, 10^{-4} ... 10^{-7} cm/sec, or less than 10^{-7} cm/sec.

For cement stone, mortar or concrete a combined transfer mechanism, determined by prevailing pores size, is appropriate.

For most concrete compositions the water flows along capillaries with a radius of 10^{-3} cm and more. The liquid raising height in capillaries is inversely proportional to their radius.

For cement stone an equation relating the filtration coefficient with pores' hydraulic radius and porosity values was proposed [1,4]. This equation in essence reflects the main features of porous structure:

$$\lg C_f = 38.45 + 4.08\lg(Pr_p^2), \qquad (7)$$

where r_p –hydraulic radius; P – porosity.

Practical application of this dependence is however inconvenient, first of all because complicity of calculating the hydraulic radius, which is determined as an average size of capillaries, at the ends of which pressure difference is observed. An attempt of theoretical calculation of pores' hydraulic radius was made by Powers and Copeland using Kozeny–Carman equation. However, this method is not suitable for practical applications.

In order to obtain the capillaries radius in concrete experimentally the knowledge of maximum capillary pressure Pr and surface tension σ on the gas-liquid border are required. Stolnikov has proposed to obtain r_p as follows [10]:

$$r_p = \frac{4\sigma}{2.028\ \cdot 10^6\, Pr}\ \text{(cm)}. \qquad (8)$$

Eq. (7) can be presented in an exponential form:

$$C_f = A(Pr_p^2)^m, \qquad (9)$$

where A and m are empirical constants.

The exponential character of the relation between permeability and capillary porosity of cement stone was further proved in many researches.

It was experimentally proved that water impermeability, like gas permeability of concrete is not determined by total, but by through or effective porosity. The last is defined as a ratio of pores volume, being filtration ways, to the specimen volume. Unlike the total and capillary porosity it varies within wide limits, depending on duration of specimens and water interaction. The effective porosity is affected bu such processes like swelling of hydrated cement grains, pores colmatage by formed leaching products and the smallest mineral particles suspended in water, etc. Forming of effective porosity is, as known, affected also by sedimentation processes in concrete mixture [10].

A number of formulas, allowing considering the effective porosity P_e (water absorption coefficient) at obtaining concrete filtration coefficient, was proposed [1]. For calculating C_f at specimens testing the following empirical formula was offered:

$$C_f = \frac{78.2 \cdot 10^{-7} P_e}{(1 + n + 0.2h_{cap})n}, \qquad (10)$$

where n is the number of water pressure steps; h_{cap} – capillary suction pressure.

Presently, taking into account the complexity of processes forming $П_э$, no design method is offered to obtain its value. Therefore equations like (9) can be used for estimating C_f after P_e is obtained experimentally. Methodology, allowing obtaining the value of P_e experimentally, is described in details by various researchers [1,10].

Research aim. The aim of our study was to obtain an acceptable in practice the calculation dependences that can be used in the design of concrete compositions with the desired value of filtration coefficient.

Results of research. One of the first attempts to relate the water filtration coefficient of concrete to its total porosity without additional consideration of capillaries hydraulic radius yielded the following approximate formula [10]:

$$C_f = K_{vl} P_{28}, \qquad (11)$$

where P_{28} – porosity at 28 days; K_{vl} – water flow velocity coefficient (for W_{imp}=0.2 MPa – $K_{vl} = 2.6 \cdot 10^{-6}$; W_{imp}=0.4 MPa – $K_{vl} = 8 \cdot 10^{-7}$; W_{imp} = 0.6 MPa – K_{vl} = 4•10-7; W_{imp}=0.8 MPa – K_c = 2. 10^{-7}; W_{imp} = 1.4 MPa – $K_{vl} = 7 \cdot 10^{-8}$ cm/sec).

Velocity coefficient K_{vl} was calculated using Eq. (10) for standard testing of maximum water pressure (W_{imp}) of concrete specimens cylinders with diameter and height of 15 cm assuming that the water velocity in concretee corresponds to Darcy's equation, valid just for viscous Poiseuille flow. As known, this equation is valid for a liquid-concrete system, in which the pores are limited by a radius $r_p = 10^{-4} \ldots 10^{-3}$ cm. Following the data, obtained using mercury porosimetry, in cement stone with W/C = 0.3 the volume of pores with a size less than 10^{-4} cm is 15%, and at W/C = 0.5 – 25%. Results of another research show that the volume of pores with a size less than 10^{-4} cm in cement-sand mortar at moisture curing reaches more than 62%, and at hardening in water – almost 90% [1].

At the same time at concrete proportioning and given value of C_f formula like (10) can allow obtaining the required water-cement ratio (W/C) at known values of hydration degree α and water flow velocity coefficient (K_{vl}). To obtain the value of α in a case when required data is missing, it is possible to use known empirical dependencie, relating it with cement strength (R_{cem}) or proposed by the author dependence (12), taking into account the required concrete strength (R_c) and cement paste normal consistence.

$$\alpha = \sqrt[3]{\frac{xR_c}{238}}, \qquad (12)$$

where x – coefficient connecting strength of concrete and strength of cement stone.

In order to obtain K_{vl} depending on concrete strength, results of experimental measurements of C_f for concrete with W/C = 0.35...0.75 were processed (Table 1).

The following materials were used for concrete production: Portland cement with 28-day strength of 40 and 50 MPa (mineral admixtures content is 15%, tricalcium aluminate content C_3A = 6 … 8%) crushed granite stone fraction 5 – 40 mm; quartz sand of medium fineness.

Filtration coefficient was obtained for cylindrical specimens with diameter and height equal to 150 mm. The specimens were tested at 28 days. The tests results are given in Table 1,2.

As it follows from Figure 2, the value of K_{vl} decreases nonlinearly if the concrete strength increases (especially at R_c > 30 MPa).

Dependence can be transformed into exponential:

$$C_f = A \, {R_c^{28}}^{m}, \qquad (13)$$

where A and m are coefficients, which values depend on concrete compositions features, conditions and duration of hardening, etc. For the investigated materials A = 126, m = – 7.7.

Table 2 shows calculated ($C`_f$) values of C_f, obtained according to Eq. (12). Results of calculations show satisfactory convergence with experimental values of C_f.

Table 1

Values of coefficients K_{vl} and C_f depending on concrete strength at 28 days

№	R_{cem}, MPa	W/C	R_{c28}, MPa	$C_f \cdot 10^{-9}$ cm/sec	$K_{vl} \cdot 10^{-9}$ cm/sec
1	40	0.75	21.7	4.8959	32.0367
2	50	0.75	24.4	3.2236	21.5462
3	40	0.68	25.2	2.4215	16.1408
4	50	0.68	31.5	0.3077	2.1006
5	50	0.60	37.9	0.0702	0.4943
6	50	0.55	42.8	0.0257	0.1855
7	50	0.51	47.5	0.0179	0.1323
8	50	0.46	54.4	0.0046	0.0353
9	50	0.40	65.0	0.0017	0.0138
10	50	0.35	76.6	0.0003	0.0026

Table 2

Calculated and real values of C_f

№	$C_f \cdot 10^{-9}$ cm/sec real	$C`_f \cdot 10^{-9}$ cm/sec following Eq. (13)	$\Delta C_f = C_f - C`_f$	$\Delta C_f / C`_f \cdot 100\%$
1	4.8959	6.4511	1.5552	24
2	3.2236	2.6150	0.6086	23
3	2.4215	2.0398	0.3817	19
4	0.3077	0.3659	0.0582	16
5	0.0702	0.0881	0.0179	20
6	0.0257	0.0345	0.0088	26
7	0.0179	0.0155	0.0024	16
8	0.0046	0.0054	0.0008	16
9	0.0017	0.0014	0.0003	23
10	0.0003	0.0004	0.0001	23

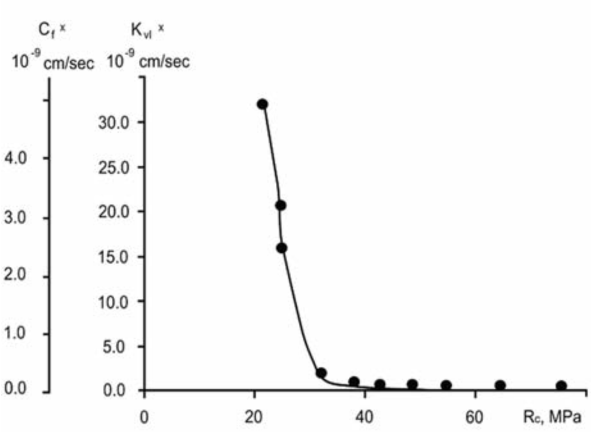

Figure 2. Dependence of concrete strength R_c, water velocity coefficient K_{vl} and filtration coefficient C_f.

Considering a big variety of factors, affecting concrete water impermeability, it is required to specify experimentally the coefficients in Eq. (12) at solving water impermeability prediction and concrete proportioning problems.

Conclusion. As a result of research was obtained formulas connecting the filtration coefficient with porosity and concrete compressive strength recommended for design of concrete compositions with a given water impermeability.

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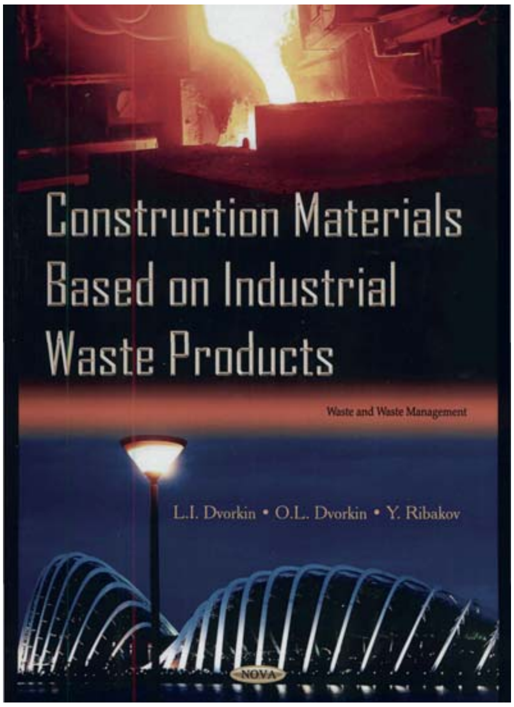
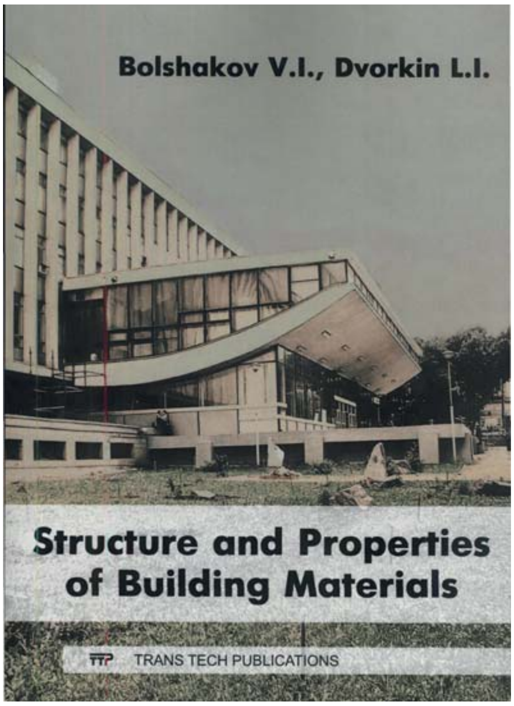
У 2016 р. вийшли монографії на англійській мові у американському видавництві «Nova Science Publishers» Construction materials Based on Industial Waste Products (автори д.т.н., проф. Дворкін Л.Й., д.т.н., проф. Дворкін О.Л. проф. Рибаков Ю. (Аріельський університет, Ізраїль) і швейцарському видавництві «Trans Tech Publication» Structure and Properties of Building Materials (автори д.т.н., проф. Большаков В.І. і д.т.н.,проф. Дворкін Л.Й.



Книга присвячена основним напрямкам використання промислових відходів для виробництва ефективних будівельних матеріалів; Розглянуті шляхи економії матеріальних і енергетичних ресурсів шляхом використання мінеральної та органічної сировини. Аналізується ефективність використання традиційних і нових будівельних матеріалів на основі вторинних продуктів (наприклад, металургійних шлаків, зол та шлаків теплових електростанцій і т.д.) Наведені різні технічні та економічні аспекти використання відходів виробництва різних галузей промисловості.



Книга призначена для широкого кола читачів і в основному для фахівців – будівельників, а також аспірантів і студентів будівельних напрямків. Розглянуті загальні положення теорії будівельних матеріалів. а також на її основі взаємозв'язок структури і властивостей основних груп будівельних матеріалів. Узагальнюючи дані численних досліджень, автори аналізують результати, отримані ними в Придніпровській академії будівництва та архітектури та Національному університеті водного господарства та природокористування (Україна).