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PROGNOSIS OF DURABILITY OF CONCRETE BY EVALUATING FREEZING AND THAWING CYCLES

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Hydraulic structures are exploited in hard environmental conditions (impact of freeze-thaw cycling, ultraviolet, humidity and drying, acidity or salinity of water, abrasion etc.), so due to the impact of environmental factors some deteriorations will occur. The repeated cycles of freezing and thawing have significant effects on durability of concrete. They reducing durability, because of cracking and scaling of concrete. Using the research results of investigated hydraulic structures concrete average compression strength f_{ck} , water absorption by weight W_m , by formulae (1, 2) were calculated numbers of laboratory freeze-thaw cycles n_{50} , freeze-thaw resistance of concrete rate $F_5\%$ and from them – durability index – probable deterioration start time $T_5\%$ of investigated main hydraulic structures. (concrete strength f_{ck} loss in 5 % and 5 freeze-thaw cycles per year).

Relationships between shaft spillway or retaining wall freeze-thaw resistance of concrete rate $F_5\%$, durability index $T_5\%$, and average compression strength of concrete f_{ck} were evaluated. These equations may be used for the durability prognosis of existing shaft spillways or retaining walls exploited in hydraulic structures.

Keywords: freeze-thaw cycling, durability of concrete, hydraulic structures.

INTRODUCTION

The parts of main hydraulic structures - surplus water fall spillway (drop inlet, siphon, bucket, etc.) or spillway (rapids, piers, retaining walls, etc.) and downstream structures in stilling basin (retaining walls, downstream apron, slabs for protection of downstream channel) are made of reinforced concrete elements, which determines the reliability of the whole hydroscheme.

Reinforced concrete is a long-lasting and sustainable material, but it wears out when exposed to the environment. One of the most significant indicators of the durability of reinforced concrete structures is the freeze-thaw (hereinafter - F-T) resistance of concrete. There are many theories explaining how freezing and thawing causes damage to concrete (Hamoush et al., 2011; Gjörv, 2013). Such theories include: critical saturation, hydraulic pressure, ice accretion and osmotic pressure (Beaudoin et al., 2009; Mustafa et al., 2009).

Hydraulic pressure theory states that the buildup of hydraulic pressure from the resistance to flow of unfrozen water through capillaries causes damage to the concrete (Hamoush et al., 2011). The main cause of concrete cracking, crushing and shrinkage is the conversion of freezing water into ice in concrete pores. Ice occupies 9% more volume than water, so ice crystals creates hydraulic pressure inside the concrete pores and capillaries, expand the entire concrete structure and when it has no more room to expand - cracks can appear.

The magnitude of the hydraulic pressure force depends on the level of water filling in the pores and the cooling rate. If the water saturation is less than 75% of the pores, the freezing water pressure is not dangerous. In addition, it is believed that osmotic pressure forces act on freezing concrete due to the presence of dissolved salts in the water. As water turns to ice, the concentration of the solution increases and osmotic phenomena occur through the pore walls. Osmotic pressure forces can increase ice crystallization forces.

The degradation process of concrete element starts when the freezing water expansive forces exceed the tensile strength in the concrete. The mechanically stronger concrete has less water in its open pores and is more resistant to frost impact.

The concrete water absorption by weight (hereinafter - absorption) and freeze-thaw resistance depend on the porosity of the material structure, the size of the pores and capillaries and the type of pores. Pores can be open or closed. Open pores increase the water absorption of concrete and reduce frost resistance. Open pores and capillaries are formed during the hardening of concrete by evaporation of unused (free) water for hydration. Closed pores are formed during the hardening of concrete by the incorporation of air from the environment into the concrete mass and by the compression of the hardening cement stone. The inclusion of air promotes, as well as some special additives increase the concrete's resistance to frost to a certain level.

The European Standard, EN 206:2013, provides recommended specifications for designing concrete in certain exposure conditions. There are 4 specific exposure classes (XF1...XF4) for dealing with freeze-thaw attack with or without de-icing agents.

The freeze-thaw resistance of concrete is determined by alternately (cyclically) freezing water-saturated concrete samples in air and then thawing them in water or saline. There are several standardized methods for determining (F-T) cycles, but testing them requires a lot of time and labor. In the European standards (CEN/TR 15177:2006) three different methods (Slab-Test, CIF-method and Cube test) are mentioned for the estimation of the freeze-thaw resistance of concrete with regard to internal structural damage. European, Lithuanian and Russian standards (Setzer et. al., 1996; CEN/TS 12390-9; LST 1428.19:2016; GOST 10060–87, 1987) are used for the evaluation of frost related damage to concrete structures too. Therefore, methods are being sought that allow the determination of the freeze-thaw resistance of concrete indirectly - based on easier-to-determine indicators.

Aim of research. To evaluate the freeze-thaw resistance of concrete used in hydraulic structures and to predict the durability of investigated main structures in upper (shaft culverts) and lower (retaining walls in stilling basin) pool.

Object of research. The investigated main hydraulic structures in upper and lower pool in 36 hydroschemes are in the territory of Lithuania. The main attention is focused on Alytus (1 hydroscheme), Anykščiai (4 hydroschemes), Joniškis (3 hydroschemes), Kaunas (6 hydroschemes), Kėdainiai (3 hydroscheme), Marijampolė (6 hydroschemes), Pakruojis (2 hydroschemes), Radviliškis (3 hydroschemes), Raseiniai (2 hydroschemes), Šiauliai (4 hydroschemes) and Ukmergė (2 hydroschemes).

METHODS OF FIELD INVESTIGATIONS AND LABORATORY TESTS

The concrete can deteriorate under freezing and thawing cycles. Using the field investigations and laboratory tests (standard methods) the main physical – mechanic properties of main hydraulic structures – their concrete compression strength and water absorbability were determined and statistically evaluated. These properties are necessary for the evaluation of changes in concrete properties under freeze-thaw cycles, for the calculations of the constant of deterioration and the parameters of the durability of structures.

The compression strength of functioning concrete hydraulic structures was evaluated by the non-destructive method (EN 12504-2: 2021) and testing the samples of irregular shape (Vaišvila, Mikutskis, 2005). The non-destructive testing of compressive strength was performed in accordance with the European Standard EN 12504–2:2021 “Testing concrete in structures. Part 2. Non-destructive testing. Determination of rebound number” using the calibrated rebound device – the rebound hammer of concrete, Schmidt’s hammer, which was calibrated using the standard anvil before and after every examination.

The concrete compression strength of samples is evaluated by an ordinary compression test. For this purpose hydraulic or lever compression machines are used in accordance with the standard requirements. The concrete compression strength of the samples of irregular shape was calculated into concrete compressive strength of standard cubes of 100×100×100 mm. Such an evaluation was accomplished by means of the proposed formulae and corresponding coefficients.

From the statistically evaluated research results of hydraulic structures concrete compression strength, water absorbability and the rates of freeze-thaw resistance of concrete were calculated. We used a new, nonstandard freeze-thaw resistance mark determination method, developed by the researchers of Vytautas Magnus University (former Lithuanian University of Agriculture), where this property is approximately evaluated by concrete compression strength and water absorbability.

Knowing the compression strength f_{ck} of the concrete (EN 12390-3: 2009; EN 12504-1: 2009; EN 12504-2: 2021; EN 13791:2007) water absorbability by mass W_m (EN 12390- 8: 2009) and allowed or forecasted loss of the concrete strength Δf_c , it is possible to estimate laboratory (F-T) cycles number n_{50} (GOST 10060–87, 1987):

$$n_{50} = c \cdot \Delta f_c^{-d} \quad (1)$$

where n_{50} – numbers of laboratory (F-T) cycles freezing samples until $-55 \pm 2^\circ \text{C}$ by (GOST 10060–87, 1987),
 Δf_c – concrete strength loss in % due the influence of (F-T) cycles, calculated by (LST 1428.19:2016),
 c, d – coefficients found in the tables made by the researchers of Vytautas Magnus University.

The freeze-thaw resistance of concrete mark F shows the number of (F-T) cycles n_F when samples are frozen in $-18 \pm 2^\circ \text{C}$, so the number of standard (F-T) cycles is calculated according to the formula developed by the researchers of Vytautas Magnus University:

$$n_{F_5} = 34.848 \cdot n_{50}^{0.6157} \quad (2)$$

Function determination coefficient $R^2 = 0.9947$.

Evaluating the impact of (F-T) cycles to the change of investigated structures concrete physical– mechanic properties the freeze-thaw resistance of concrete parameters $F_5\%$ were used.

According to LST 1428.19:2016, deterioration beginning was fixed by the number of cycles, when from freezing the sample surface 5 % of sample mass (freeze-thaw resistance index $F_5\%$) deteriorate). From the first observed deterioration symptoms till absolute deterioration of the surface some time passes.

Natural (F-T) cycles, by means of corrective coefficients (chosen according to the graph elaborated by the researchers of Vytautas Magnus University), were recounted into the laboratory (F-T) cycles and further recalculated to the parameters of structures durability – probable deterioration time $T_5\%$ (the probable deterioration start time).

Dependences established between concrete physical – mechanical properties obtained by the field investigations and laboratory tests and calculated parameters of structures durability $T_5\%$, were examined by methods of correlation analysis. Formulae of dependences were established, correlation coefficients calculated and their reliability evaluated.

RESEARCH RESULTS

During field investigations, the main attention was focused on Alytus, Anykščiai, Joniškis, Kaunas, Kėdainiai, Marijampolė, Pakruojis, Radviliskis, Raseiniai, Šiauliai and Ukmergė districts. The main reinforced concrete hydraulic structures in upper and lower pool were selected for detailed analysis. Average compression strength f_{ck} MPa, concrete water absorption by weight $W_m\%$, numbers of laboratory (F-T) cycles n_{50} , freeze-thaw resistance of concrete rate $F_5\%$; probable deterioration start time $T_5\%$ of investigated main hydraulic structures are presented in Table 1.

According to the results presented in Table. 1 the lowest values of concrete average compression strength f_{ck} was founded in Panevėžiukas shaft spillway ($f_{ck}=6.0$ MPa) and in Antanavas HPS and Savičiūnai retaining walls ($f_{ck}=5.8$ MPa). The highest values of concrete average compression strength was founded in Angiriai shaft spillway ($f_{ck}=27.6$ MPa) and in Akademija retaining walls in stilling basin ($f_{ck}=27.9$ MPa).

The highest values of concrete water absorption by weight W_m was founded in Panevėžiukas shaft spillway ($W_m=13.8\%$) and in Antanavas HPS and Savičiūnai retaining walls ($W_m=14.1\%$).

Table 1. Evaluation of durability index $T_5\%$ of investigated main hydraulic structures

District Name of the pond	Average compression strength f_{ck} MPa, concrete water absorption by weight $W_m\%$	Average compression strength f_{ck} MPa, concrete water absorption by weight $W_m\%$	Coef- ficients	Coef- ficients	Numbers of laboratory (F-T) cycles n_{50}	Numbers of laboratory (F-T) cycles n_{50}	Freeze- thaw resistance of concrete rate $F_5\%$ in cycles n_F	Freeze- thaw resistance of concrete rate F_5 in cycles n_F	Durability index -the probable deterioration start time T_5 %	Durability index - the probable deterioration start time T_5 %
			c	c						
			d	d						
Investigated structures	SS	RW	SS	RW	SS	RW	SS	RW	SS	RW
1	2	3	4	5	6	7	8	9	10	11
Alytus										
Kriokialaukis	13.8 8.7	19.3 7.3	0.5 0.8	0.7 0.9	2.1	3.3	54.6	72.8	10.9	14.6
Anykščiai										
Elmininkai	8.6 11.3	9.9 10.8	0.2 0.7	0.4 0.7	0.7	1.2	27.7	38.5	5.5	7.7
Leliūnai	16.0 8.0	21.1 6.9	0.6 0.9	0.8 1.0	2.3	4.2	58.4	84.1	11.7	16.8
Pagoje	15.5 8.2	10.3 10.3	0.6 0.9	0.4 0.7	2.2	1.3	57.2	40.2	11.4	8.0
Savičiūnai	13.8 8.7	5.8 14.1	0.5 0.8	0.2 0.7	1.8	0.7	50.3	27.1	10.1	5.4
Joniškis										
Beržėnai	17.5 7.6	20.3 7.0	0.7 0.9	0.8 1.0	2.9	3.6	66.9	76.2	13.4	15.2
Linkaičiai I	18.6 7.4	- --	0.7 1.0	---	3.3		72.7	0.0	14.5	--
Linkaičiai II	25.7	16.0	1.0	0.6	5.8	2.3	102.8	58.4	20.6	11.7

	6.2	8.0	1.1	0.9						
Kaunas										
Altoniškiei	22.4	15.8	0.9	0.6	4.4	2.3	86.9	57.5	17.4	11.5
	6.7	8.1	1.0	0.9						
Babtai I	21.1	13.8	0.8	0.5	4.2	2.1	84.1	54.6	16.8	10.9
	6.9	8.7	1.0	0.8						
Babtai II	9.4	11.7	0.4	0.4	1.2	1.5	39.5	45.2	7.9	9.0
	10.7	9.6	0.7	0.8						
Gailiušiai	10.3	15.6	0.4	0.6	1.3	2.2	40.2	57.2	8.0	11.4
	10.2	8.2	0.7	0.9						
Gaižėnai	21.8	19.7	0.9	0.7	4.2	3.5	84.7	75.6	16.9	15.1
	6.8	7.2	1.0	1.0						
Panevėžiukas	6.0	8.4	0.2	0.3	0.6	1.0	25.4	34.6	5.1	6.9
	13.8	11.5	0.6	0.7						
Kėdainiai										
Akademija	16.2	27.9	0.6	1.1	2.3	6.1	58.6	105.9	11.7	21.2
	8.0	5.9	0.9	1.1						
Angiriai	27.6	18.7	1.0	0.6	6.0	2.3	105.5	58.4	21.1	11.7
	6.0	7.4	1.1	0.9						
Kruostas HPP	12.8	18.3	0.5	0.6	1.6	2.3	46.7	58.2	9.3	11.6
	9.1	7.5	0.8	0.9						
Marijampolė										
Antanavas	11.2	5.8	0.4	0.2	1.4	0.7	43.4	27.1	8.7	5.4
HPS	9.8	14.1	0.8	0.7						
Ažuolų Būda	--	9.6		0.4		1.2		39.8	--	8.0
	--	10.7		0.7						
Jūrė	12.3	9.8	0.5	0.4	1.6	1.2	47.0	39.0	9.4	7.8
	9.3	10.5	0.8	0.7						
Kazlai	10.4	11.7	0.4	0.4	1.3	1.5	40.5	45.2	8.1	9.0
	10.2	9.6	0.7	0.8						
Marijampolė	13.8	--	0.5		1.8		50.3	0.0	10.1	--
	8.7	--	0.8							
Netičkampis	21.6	16.3	0.9	0.6	4.9	2.4	92.9	59.2	18.6	11.8
	6.8	8.0	1.0	0.9						
Pakruojis										
Baltausiai	17.0	15.5	0.7	0.6	3.0	2.2	68.8	57.2	13.8	11.4
	7.8	8.2	0.9	0.9						
Laičiai I	7.8	16.0	0.3	0.6	0.9	2.3	32.0	58.4	6.4	11.7
	11.9	8.0	0.7	0.9						
Radviliškis										
Arimaičiai	16.1	16.2	0.6	0.6	2.3	2.3	58.8	58.9	11.8	11.8
	8.0	8.0	0.9	0.9						
Baisogala II	16.4	19.1	0.6	0.7	2.4	3.2	59.2	71.7	11.8	14.3
	7.9	7.3	0.9	0.9						
Gulbinai	18.0	7.6	0.7	0.3	3.0	0.9	68.2	31.6	13.6	6.3
	7.5	12.1	0.9	0.7						
Raseiniai										
Anulynas	17.8	16.5	0.7	0.6	2.9	2.4	67.4	59.5	13.5	11.9
	7.6	7.9	0.9	0.9						
Plikiai	19.6	17.4	0.7	0.7	3.3	2.9	73.3	66.9	14.7	13.4
	7.2	7.7	0.9	0.9						
Šiauliai										
Dargaičiai	23.6	12.5	0.9	0.5	4.6	1.6	88.9	46.6	17.8	9.3

	6.5	9.2	1.0	0.8						
Gudeliai	15.5	13.7	0.6	0.5	2.2	2.1	57.2	54.4	11.4	10.9
	8.2	8.8	0.9	0.8						
Kairiai	10.4	14.2	0.4	0.5	1.3	2.1	40.5	55.2	8.1	11.0
	10.2	8.6	0.7	0.8						
Šakyna	16.4	19.0	0.6	0.7	2.4	3.2	59.2	71.7	11.8	14.3
	7.9	7.3	0.9	0.9						
Ukmergė										
Kadrėnai	16.9	18.3	0.7	0.7	3.0	3.1	68.8	69.6	13.8	13.9
	7.8	7.5	0.9	0.9						
Virškėiai	13.0	18.8	0.5	0.7	1.8	3.1	49.3	70.2	9.9	14.0
	9.0	7.4	0.8	0.9						

Note:

SS – Shaft Spillway;

RW –Retaining walls in stilling basin;

HPS – hydropower station.

According to the results presented in Table. 1 the durability index - probable deterioration start time $T_5\%$ with concrete strength f_{ck} loss in 5 % and 5 (F-T) cycles per year for shaft spillway reinforced concrete structures varies from 5.1 (Panevėžius) to 21.1 (Angiriai) years, and for retaining walls in stilling basin varies from 5.4 (Antanavas HPS and Savičiūnai) to 21.2 (Akademija) years.

The dependencies of shaft spillway reinforced concrete structures durability index - probable deterioration start time $T_5\%$, freeze-thaw resistance of concrete rate $F_5\%$ and average compression strength f_{ck} are drawn in Figure 1.

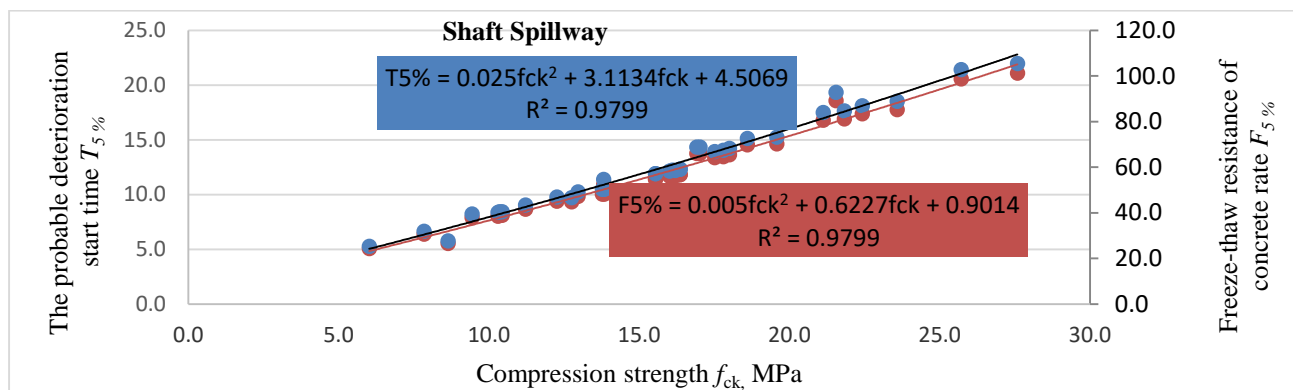


Figure 1. Relationship between shaft spillway durability index $T_5\%$, freeze-thaw resistance of concrete rate $F_5\%$ and average compression strength of concrete f_{ck}

The dependencies of retaining walls reinforced concrete structures freeze-thaw resistance of concrete rate $F_5\%$ durability index - probable deterioration start time $T_5\%$ and average compression strength f_{ck} are drawn in Figure 2.

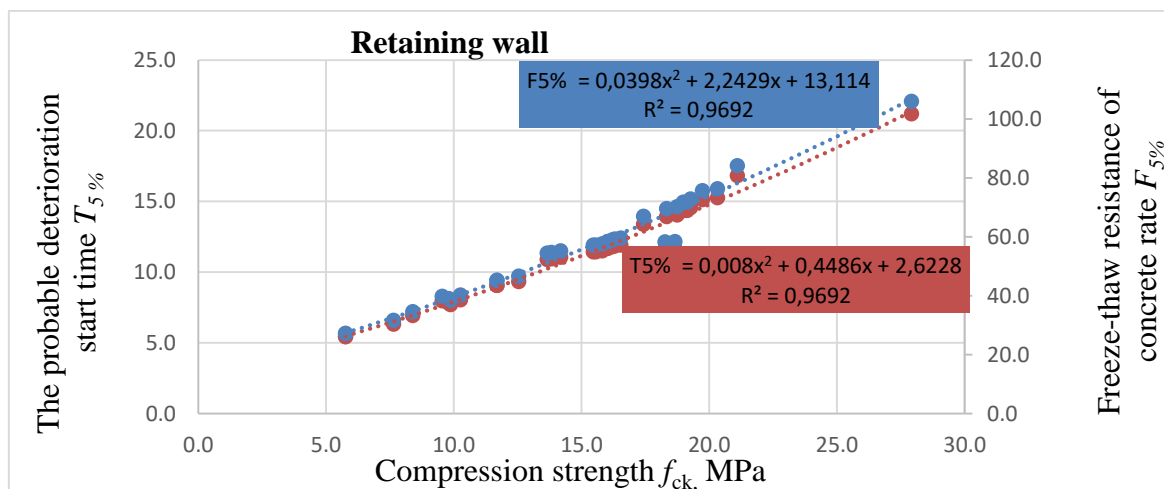


Figure 2. Relationship between retaining wall durability index $T_5\%$, freeze-thaw resistance of concrete rate $F_5\%$ and average compression strength of concrete f_{ck}

Concrete average compression strength's f_{ck} and durability index $T_5\%$ and freeze-thaw resistance of concrete rate $F_{5\%}$ reliability of functional dependences was checked by double correlation. It was found, that dependences are strong (r_{xy} 0,96...0,98). Calculated correlation coefficients are reliable, their importance level $p < 0,05$. The established determination coefficients $R^2 = 0.9799$ and $R^2 = 0.9692$, therefore can be stated that examined strength parameters influence investigated index of durability by 97.99% and 96.92%, other part belongs to the influence of less important parameters.

CONCLUSIONS

1. According to the results of investigated main hydraulic structures in upper and lower pool in 36 hydroschemes:
the lowest values of concrete average compression strength f_{ck} was founded in Panevėžiukas shaft spillway ($f_{ck}=6.0$ MPa) and in Antanavas HPS and Savičiūnai retaining walls ($f_{ck}=5.8$ MPa). The highest values of concrete average compression strength was founded in Angiriai shaft spillway ($f_{ck}=27.6$ MPa) and in Akademija retaining walls in stilling basin ($f_{ck}=27.9$ MPa);
the highest values of concrete water absorption by weight W_m was founded in Panevėžiukas shaft spillway ($W_m=13.8\%$) and in Antanavas HPS and Savičiūnai retaining walls ($W_m=14.1\%$).
2. Using results of calculated freeze-thaw resistance of concrete rate $F_5\%$ were calculated the durability indexes - probable deterioration start time $T_5\%$ (with concrete strength f_{ck} loss in 5 % and 5 (F-T) cycles per year) for investigated structures:
for shaft spillway reinforced concrete structures $T_5\%$ varies from 5.1 (Panevėžiukas) to 21.1 (Angiriai) years;
for retaining walls in stilling basin $T_5\%$ varies from 5.4 (Antanavas HPS and Savičiūnai) to 21.2 (Akademija) years.
3. Dependences established between concrete physical – mechanical properties obtained by the field investigations and laboratory tests and calculated parameters of structures durability $T_5\%$ may be used for the durability prognosis of existing shaft spillways or retaining walls exploited in hydraulic structures.

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