Durability of Concrete Covering Layer of Reinforced Concrete Slabs for Earth Dam Slope Protection

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Abstract. In Lithuania there are over 1000 ponds constructed and 620 have been evaluated as potentially dangerous hydraulic structures. Our water-retaining infrastructure deteriorates under environmental impacts, therefore the ageing of building materials causes a greater probability of deterioration and even failure. Durability of hydraulic structures depends on maintenance circumstances, surveillance, timely repair of structures or rehabilitations. Prognosis of the deterioration speed and durability of slabs is the main problem in each pond. The durability of concrete slabs covering layer can be evaluated by time (T_{layer}), which equals the time to expose reinforcement of a reinforced concrete structure. Based on the results of the field investigation, the modelling of durability of reinforced concrete slabs for earth dam slope protection was performed. Regularities of concrete compression strength of reinforced concrete slabs for earth dam slope protection under the influence of freezing–thawing cycles and other environmental factors were established. Using the developed durability evaluation method of reinforced concrete slabs for earth dam slope protection, the remaining service life of the construction till the probable beginning ($T_5\%$) or end of its deterioration ($T_{50}\%$) may be calculated. It is also possible to determine the time (T_{layer}), during which the reinforcement of the reinforced concrete construction is uncovered/exposed. Using the estimated constant of degradation in designing of reinforced concrete slabs for earth dam slope protection for using them at changing water level, there is a possibility to choose concrete of such strength, that the reinforcement of the construction would not be exposed during the intended period of usage.

Keywords: Durability of concrete, earth dams, slope protection, concrete slabs, lifetime of covering layer

Introduction

Concrete durability has been defined by the American Concrete Institute (ACI) as its resistance to weathering action, chemical attack, abrasion and other degradation processes. The primary factor determining durability is a good-quality concrete with low porosity i.e. low permeability [23]. The other advantages of durable concrete include resistance to alkali-silica reaction and sulfates, increased corrosion protection, and reduced heat of hydration [1].

Every reinforced concrete construction degrades with time, but the degradation of reinforced concrete slabs for earth dam slope protection (hereinafter – slabs) occurs particularly often. Due to environmental impacts [15] (weathering action, chemical attack, alkalinity (alkali-silica reaction (ASR)), carbonation (alkali-carbonate reaction (ACR)), freezing and thawing (F-T) cycles and abrasive effects of waterborne silt, sand, gravel, rocks, ice, and etc.) some deterioration of the slabs occurs, which influences negatively not only some slabs, but after their failure danger arises for the whole slope not being protected, thus affecting the reliability, durability and safety of the water-retaining infrastructure in general.

The design service life of slabs is 30 years, but many slabs of hydraulic structures on Lithuania hydroschemes are older than 30 years, therefore the ageing of building materials creates a greater probability of deterioration and even failure. If

dangerous defects and deteriorations are not repaired in time, a huge technical and ecological loss may occur. From the economic point of view the execution of new slope protection is more expensive, therefore the preservation of the present reinforced concrete slabs and performing restoration and/or reconstruction at the right time is a more preferable measure.

The analysis of the methods for evaluation of the durability of usable reinforced concrete structures influenced by environmental factors [19] shows, that the technical state, the bearing capacity and the durability of reinforced concrete constructions of hydraulic structures are mostly influenced by aggressive humid environmental impacts (the most potentially destructive weathering factor is (F-T) cycles while the concrete is wet). Different types of suspected frost related damage to concrete structures in hydro power plants are identified and categorized in the thesis [18]. A number of mechanisms affecting the material performance during freeze-thaw are reviewed in the thesis [17]. In the European standards [4] 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 [5], [6], [12], [14] are used for the evaluation of frost related damage to concrete structures too.

Durability related deterioration is referred to as materials-related distress (MRD). The deterioration processes are caused by the freezing of water and

subsequent expansion in the paste, the aggregate particles, and forming erosion, development of pittings in the covering layer of slabs (Fig.1).

Fig. 1. Pittings and deteriorated concrete covering layer of slabs

A few investigations have attempted to establish a relation between porosity, strength, and durability-related properties. In [3] a non-linear relationship between compressive strength and density was observed. In general, as expected, compressive strength increased with density. Due to the relatively high porosity of the interfacial zone compared to other regions, it becomes a weak link in the concrete structure. As a result, concrete strength and durability-related properties to a considerable extent are dictated by the properties of the interface region. In order to improve concrete durability, it is essential to improve strength and durability of the interfacial region [20].

The prediction of nonair-entrained concrete service life in cases of deterioration due to freezing and thawing is described in [2].

The purpose of these investigations based on the field research is to establish the actual quantities of compression strength of concrete used in the slabs and to evaluate (F-T) cycles impact on the change of concrete properties and the durability of the concrete cover of slabs.

Methods of field investigations and laboratory tests

Using the field investigations and laboratory tests (standard methods) the main physical – mechanical properties of slabs – 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 frost impact, 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 [10] and testing the samples of

irregular shape [22]. 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 the slabs' concrete compression strength and water absorbability the rates of concrete resistance to frost were calculated. We used a new, nonstandard concrete frost resistance mark determination method, developed by the researchers of Aleksandras Stulginskis University (former Lithuanian University of Agriculture), where this property is approximately evaluated by concrete compression strength and water absorbability.

Knowing the compression strength f_c of the concrete [8], [9], [10], [11] water absorbability by mass W_m [7] and allowed or forecasted loss of the concrete strength Δf_c , it is possible to estimate laboratory (F-T) cycles number n_{50} [14]:

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

where

n_{50} – numbers of laboratory (F-T) cycles freezing samples until $-55 \pm 2^\circ \text{C}$ by [14],

Δf_c – concrete strength loss in % due the influence of (F-T) cycles, calculated by [12],

c, d – coefficients found in the tables made by the researchers of Aleksandras Stulginskis University.

Regarding concrete frost resistance, mark F shows the number of (F-T) cycles n_F when samples are frozen under a temperature of $-18 \pm 2^\circ \text{C}$, so the number of standard (F-T) cycles is calculated

according to the formula developed by the researchers of Aleksandras Stulginskis University:

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

Function determination coefficient $R^2 = 0.9947$.

Evaluating the impact of (F-T) cycles on the change of investigated slabs concrete physical–mechanical properties the frost resistant parameters $F_5\%$ and $F_{50}\%$ were used.

According to the [12], the beginning of deterioration was fixed by the number of cycles, when from freezing, the sample surface up to 5 % of sample mass (frost resistance index $F_{5\%}$) deteriorates. From the first observed deterioration symptoms till absolute deterioration of the surface some time passes.

According to the construction regulations [16] the deterioration end was fixed by a number of cycles $F_{50}\%$ where the concrete compression strength of the 25–30 mm thick outer (cover) concrete layer shrinks twice, i.e. to 50 % of the estimated strength during the research.

Natural frost cycles, by means of corrective coefficients (chosen according to the graph elaborated by the researchers of Aleksandras Stulginskis University), were recounted into the laboratory (F-T) cycles and further recalculated to the parameters of structures durability – probable

deterioration times $T_5\%$ (the probable deterioration start time) or $T_{50}\%$ (the probable deterioration end time).

Dependences established between the field investigations concrete physical – mechanical properties and calculated parameters of structures durability $T_5\%$, $T_{50}\%$, T_{layer} were examined by correlation analysis. Formulae of dependences were established, correlation coefficients calculated and their reliability evaluated.

Results

During the period of 2008–2014 we investigated concrete compression strength (mean value) and water absorbability of the slab samples made from coarse grained cement without additives. In total, 12 Lithuania’s earth dams were chosen for investigations. Using the research results of the 7 dams’ slabs concrete compression strengths f_c and water absorbability W_m and formulae (1, 2), concrete frost resistance parameters $F_5\%$ and $F_{50}\%$ were calculated, which were further used to determine the durability probable deterioration times $T_5\%$ and $T_{50}\%$, presented in Table 1.

For a practical use proposed dependences equations are presented in Fig. 2.

TABLE 1
Research Results of Concrete Compression Strength f_c , Water Absorbability W_m and Calculated Concrete Frost Resistance Parameters $F_5\%$, $F_{50}\%$ and Durability Parameters $T_5\%$, $T_{50}\%$ [Source: construction by authors]

No.	Name of dam	f_c , MPa W_m , %	$F_5\%$, cycles	$F_{50}\%$, cycles	$T_5\%$, years	$T_{50}\%$, years
1	2	3	4	5	6	7
1	Krokialaukis	27.6±1.2 4.54±0.28	171.8	1029.0	34.4	205.8
		28.9±1.4 4.24±0.21	192.1	1219.9	38.4	244.0
2	Anulynas	6.2±0.7 11.3±0.8	30.6	81.9	6.11	16.4
		3.4±0.1 15.5±0.2	22.7	54.1	4.53	10.8
		3.7±0.1 14.2±0.1	23.5	56.4	4.7	11.3
		3.9±0.1 13.7±0.2	24.9	60.7	4.98	12.1
		4.4±0.3 13.0±0.2	25.6	62.9	5.11	12.6
		4.7±0.3 12.5±0.1	26.4	65.8	5.27	13.2
		5.3±0.1 11.8±0.6	28.5	72.8	5.71	14.6
		6.2±0.1 10.5±0.1	31.5	86.1	6.29	17.2
		7.4±0.23 9.52±0.22	37.0	108.8	7.41	21.8
		8.8±0.1 8.64±0.14	45.1	134.3	9.02	26.9

TABLE 1 CONTINUED

No.	Name of dam	f_c , MPa W_m , %	$F_{5\%}$, cycles	$F_{50\%}$, cycles	T_5 %, years	$T_{50\%}$, years
3	Kazlai	6.3±0.6 12.6±0.3	27.9	71.6	5.57	14.3
4	Jūrė	7.1±0.4 14.6±0.2	26.8	68.2	5.35	13.6
		14.8±1.1 6.85±0.12	56.4	189.8	11.3	38.0
5	Marijampolė	6.0±0.9 12.8±0.4	27.2	69.0	5.44	13.8
6	Anulynas	20.6±1.5 9.54±0.32	76.4	301.7	15.3	60.3
		15.5±1.0 11.7±0.9	57.3	195.2	11.5	39.0
		15.6±2.1 10.0±1.4	57.3	195.2	11.5	39.0
7	Kaulakiai I	20.9±1.6 8.79±0.28	83.2	335.6	16.6	67.1
		15.0±2.2 9.23±0.70	56.4	189.8	11.3	38.0
		14.0±1.6 12.5±1.8	54.65	179.27	10.9	35.9

Fig. 2. Equations dependences of slabs concrete compression strength f_c , water absorbability by mass W_m , and probable deterioration times T_5 % and $T_{50\%}$

Functional reliability of concrete compression strength f_c , water absorbability by mass W_m , and probable deterioration times T_5 % and $T_{50\%}$ of slabs checked by double correlation. It was found that the dependence strength ranges from very strong (when $r_{xy} > 0.9$) to strong (when r_{xy} from 0.7 to 0.9). Calculated correlation coefficients are reliable, their importance level $p < 0.05$. Estimated determination coefficients R^2 range from 0.9 to 0.976, so it's true to say that researched strength and water absorbability parameters from 90.0 to 97.6% influence investigated durability parameters (the other part – influence of other parameters).

Using the proposed equations dependences, a calculation can be made for how many years are left for structure's use till probable deterioration starts (T_5 %) or ends ($T_{50\%}$).

These equations may be used for the evaluation of the state and durability of used reinforced concrete

slabs by the probable deterioration time. In calculations by the formulae one needs to know the values of the concrete compression strength f_c , water absorbability W_m and the size of concrete strength loss Δf_c because of frost impact.

By means of the proposed method reinforced concrete slabs durability parameters (T_5 % and $T_{50\%}$) of 7 Lithuania's earth dam were calculated. It was found, that the structure at $f_c = 28.9 \pm 1.4$ MPa (one of the biggest in the researched structures) and at $W_m = 4.24$ %, influenced of 5 laboratory frost cycles during the year, can be used till probable deterioration start T_5 % = 38.4 years and till probable deterioration end $T_{50\%}$ = 244.0 years. Under $f_c = 3.4 \pm 0.1$ MPa (one of the smallest researched structures) and $W_m = 15.5$ % such slab could be used accordingly: T_5 % = 4.53 years and $T_{50\%}$ = 10.8 years.

It was noticed during the expedition, that all the investigated surfaces of earth dam slopes slabs in the

zone of changing water level are more or less deteriorated in the form of pitting. There are several reasons of forming pitting, but the main is – erosion of concrete by influence of (F-T) cycles.

The surface of the structures on the changing water level zone is in contact with ice, swimming solids or sediments (especially gravel) abrasive impact. After establishing the most affecting impact in the separate ponds, there is a need to explore the reasons for pitting occurrence in a more detailed way.

Other reasons of concrete erosion presented in the sources of scientific literature, for instance, cavitation, are less frequently described with regard to the structures researched, because in the researched ponds, water flow pulsation speeds are small ($< 2\text{m/s}$).

The research results of 12 dams slabs’ concrete compression strength f_c and pitting depth are presented in the Table 2.

TABLE 2

Research Results of Dams Age, Concrete Compression Strength f_c and Pitting Depth
[Source: construction by authors]

No.	Name of dam	Age of structure, years	Concrete compression strength f_c , MPa	Pitting depth, mm
1	2	3	4	5
1	Angiriai	22	7.9±0.6	33.8
			9.0±0.7	23.9
2	Antanavas HP	47	8.2±0.9	36.3
			6.4±0.40	44.1
			6.0±0.4	43.6
3	Anulynas	24	15.5±1.0	9.4
4	Babtai I	31	8.3±0.7	36.9
			10.6±1.1	23.4
5	Gailiušiai	29	9.1±0.4	30.7
6	Graužė III	23	7.3±0.4	44.7
		22	8.2±0.8	29.9
			7.6±0.6	37.4
			6.2±0.3	45.3
7	Jūrė	23	9.8±0.5	20.4
		26	7.1±0.4	38.6
8	Kaulakiai I	25	14.0±1.6	11.5
9	Kazlai	13	7.6±0.4	22.6
		11	6.3±0.6	44.9
10	Kruostas HP	49	7.2±0.6	53.2
			9.5±0.4	46.7
			5.5±0.2	62.5
11	Marijampolė	20	6.0±0.9	55.3
12	Pilvė - Vabalkšnis	13	6.7±0.3	36.6
		13	7.1±0.6	28.0
		11	4.2±0.1	41.9
		11	4.4±0.0	50.6

According to the analysis of 12 earth dams’ slopes protection with reinforced concrete slabs testing results, the surfaces of structures made of weak concrete were damaged much more. The top speed of pitting deepening was established in slabs made of weak concrete ($f_c = 4.2\div 6.3$ MPa) at Pilvė–Vabalkšnis, Kazlai dams. The average deepening speed of a pitting was 4.6 mm and 4.1 mm per year in the structures of Pilvė – Vabalkšnis and Kazlai respectively.

The average deepening speed of pitting in the structures made of concrete with average compression strength $f_c = 15.5$ MPa (at Anulynas dam) was the smallest – only 0.4 mm per year.

The deepening speed of a pitting v (constant of degradation) – in relation to the average compression strength of slabs’ concrete f_c may be expressed by equation

$$v = 45.813 \cdot f_c^{-1.723} \quad (3)$$

Where:

v – average deepening speed of pitting in structures, mm per year,

f_c – average compression strength of concrete, MPa.

Determination coefficient of the function $R^2 = 0.6747$.

Using the formula (3), the time (T_{layer}) can be estimated through which pitting will reach a dangerous depth for the structure. This depth is to be equal to the thickness of the covering layer of the structure's concrete (according to the former design standards, it had to be no smaller than 30 mm, and due to the currently used design norms it must be 40 mm).

Time (T_{layer}), during which reinforcement of the reinforced concrete slab will be exposed, depending on concrete compression strength f_c may be expressed by

$$T_{40\text{mm layer}} = 7.7187 \cdot f_c - 26.852 \quad (4)$$

where

$T_{40\text{ mm layer}}$ – functioning period of a 40 mm thick covering layer of the structure expressed in years,

f_c – average compression strength of concrete, MPa.

Determination coefficient of the function $R^2 = 0.7956$.

Similar dependences equation, $T_{\text{ap.sl.}} = 7.5465 f_c - 42.859$, is created using the data of research on the retaining walls and shaft culverts and presented in work [16].

Durability time (T_{layer}), which was calculated using the constant of degradation and concrete compression strength, shows that in structures, manufactured in Lithuania from weak concrete ($f_c = 4.4$ MPa), when the concrete covering layer is 40 mm thick, reinforcement had to be exposed accordingly after 8.7 years of use. In structures, manufactured from stronger concrete ($f_c = 15.5$ MPa) it will be exposed accordingly after 102.4 years of use.

Using dependences (3) and (4) for designed earth dam slabs, which are used on changing water level, the concrete of appropriate strength can be chosen, so that reinforcement of these structures will not be exposed during a foreseen time.

For example, we calculated, that a 40 mm covering concrete layer of slab (under changing water level) would collapse just after 100 years, if it was made from concrete, the compression strength of which was 16.4 MPa.

Empirical dependences (3) and (4) may be used for the tentative evaluation of properties of coarse-grained cement, without additives concrete, during the evaluation of used earth dam slopes slabs condition.

Concrete compression strength f_c and parameters of structures durability $T_{40\text{mm layer}}$, during which reinforcement of reinforced concrete slab will be exposed, reliability of the functional dependences was checked by double correlation. It was found that the dependences are strong ($r_{xy} = 0.9$). Calculated correlation coefficients are reliable, their importance level $p < 0.05$. The established determination coefficient $R^2 = 0.7956$, therefore it can be stated that the examined strength parameters influence the investigated parameters of durability by 79.6%, other part belongs to the influence of less important parameters.

We did not calculate the effect of corrosion on the overall durability of slabs in our paper. Researcher [13] has investigated marine structures and found that “for a given concrete structure in a given environment, the overall durability requirement is based on the specification of a given service period before the probability for onset of corrosion exceeds a certain upper level, and for this level, a probability of 10% was adopted for marine structures. In order to calculate the probability of corrosion, durability analyses are carried out, and this provides the basis for selecting proper combinations of concrete quality and cover thickness. An increased concrete cover also would significantly affect the probability of corrosion. While a nominal cover of 70 mm for Portland cement concrete would give a service period of about 30 years, increased cover of up to 90 and 120 mm would increase the service period by up to more than 60 and more than 120 years, respectively”. These results conform to our research of thickness covering concrete layer of slabs.

Conclusions

1. The method for durability evaluation of reinforced concrete slabs for earth dam slope protection has been developed. By means of the method, knowing the values of a structure's concrete strength, water absorbability and allowed concrete strength loss due to frost action, the main parameters of slabs durability can be calculated – the probable deterioration start time $T_5\%$ (covering layer strength f_c loss under the frost influence by 5%) and the probable deterioration end time $T_{50}\%$ (covering layer strength f_c loss under the frost influence by 50%).
2. Durability of slabs covering layer can be evaluated by time (T_{layer}), which equals the reinforcement exposure of the reinforced concrete structure.
3. Using durability parameter (T_{layer}), it was calculated, that 40 mm covering concrete layer of slab would collapse just after 100 years, if it was made from concrete, the compression strength of which was 16.4 MPa.

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