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THE RESEARCH ON THE DETERIORATION OF REINFORCED CONCRETE STRUCTURES FUNCTIONING IN THE VARYING WATER LEVEL AREAS OF HYDRAULIC STRUCTURES

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There are a few hydraulic structures in Lithuania where reinforced concrete structures are used. The technical state of reinforced concrete structures is varying. Several structures have almost no damage in reinforced concrete structures, but there are those whose structures are quite severely damaged.
The research aims to determine the compressive strength of reinforced concrete structures of hydraulic structures functioning in varying water level areas and the relationship between the depth of damage and the service life of the structure.
Research objects were selected in Alytus, Anykšciai, Kaunas, Kėdainiai, Marijampolė, Pakruojis, Raseiniai, and Šiauliai districts. The age of the structures ranges from 65 years to 31 years.
The research found that reinforced concrete structures made from stronger concrete have shallower gullies. The highest compressive strength of concrete was determined in the Angiriai hydro scheme – 27.6 MPa, the lowest – in Antanavas and Savičiūnai – 5.8 MPa.
More affected are those reinforced concrete structures whose compressive strength is between 5.7 and 6.1 MPa, i.e., Antanavas, Savičiūnai, and Panevėžiukas hydro schemes. On average the gullies in the reinforced concrete structures deepened 5.4 mm per year in the Antanavas hydro scheme, 4.3 mm in Savičiūnai and 3.1 mm in Panevėžiukas. Gullies in the reinforced concrete structures developed the slowest in the Angiriai hydro scheme. The research found that the average compressive strength of concrete of this hydro scheme is 27.6 MPa, and the gully deepens an average of 0.2 mm per year.
According to the research data, the gully deepening rate and time dependencies on the average compressive strength of the concrete structure were determined. Knowing the thickness of the protective concrete layer of the reinforcement, it is possible to predict the time during which the reinforcement of the functioning reinforced concrete structure will become exposed. Based on the presented relationship, we can select concrete of such strength when designing reinforced concrete structures that will function in the varying water level areas, so that the reinforcement of these structures does not become exposed during the planned time.

Keywords: *compressive strength of concrete deterioration, service life of structures.*

INTRODUCTION

There are many hydraulic structures (HS) in Lithuania. In most of them reinforced concrete structures are used. The reinforced concrete is a durable material, but like any other, it deteriorates over time. The biggest damages on the surface of the mentioned structures are found in areas of varying water levels. These damages create not only favourable conditions for the rapid destruction of the structure but can cause a collapse of the whole structure as well.

It is established that damages of reinforced concrete structures of HSs in the time being were caused in many cases by poorly manufactured concrete, whose properties do not satisfy requirements for usage; unfit calculation of load-bearing capacity of structures, disregarding actual factors, influence of aggressive environments, unfit exploitation, and low-grade quality of building works.

All HSs must be regularly observed and in certain cases, necessary investigations be fulfilled. The data of investigations on-site may be used not only for improvement in designing and manufacturing new structures but also for repairing the damaged parts of already built ones promptly to avoid the collapse of the whole HS. The priority of retaining walls maintenance is analyzed in research (Abdulazeez, 2022).

At present time, the state of reinforced concrete structures of operational HSs varies. There are some structures in almost good condition, while the others are less or more damaged (Šadzevičius & Sankauskienė, 2013).

In order to describe the character of physical deterioration of structures initial data must be collected.

In 2020–2021 the reinforced concrete structures of 66 HSs were investigated on-site. The actual values of the main physical-mechanical properties of concrete, defects and deteriorations of structures were determined. The principal attention was given to determining actual values of compressive strength, volume mass, and absorptive power of concrete used in reinforced concrete structures of spillways (SW) and retaining walls (RW). Easily detectable deteriorations – gullies on the surface of structures were checked and measured as well.

The reinforced concrete structures of operational HSs are functioning in rather hard conditions. They are being affected by the atmosphere, water medium (surroundings), ice, high and low temperatures, precipitation, wind, solar radiation, etc. Mechanical deterioration of concrete structures by freeze–thaw cycles has been widely spotted, mainly in temperate zones (Yanjun et al., 2020). The mechanism of reinforcement corrosion, techniques utilized to monitor reinforcement corrosion and methodologies that are utilized for the prediction of remaining service life of structures are described in paper (Shamsad, 2003). Another physical deterioration mechanism (Mati et al., 2023) includes surface wear due to abrasion (Saidmurodov et al., 2022), erosion (Fiorio, 2005), cavitation (Momber, 2000), cracking under extreme temperatures (Fu et al., 2022), salt weathering (Thaulow & Sahu, 2004) or structural loads (Šadzevičius et al., 2009).

At present, several HSs and their structures have been exploited for 50 years and longer.

All reinforced concrete structures of HS following their importance to the whole structure may be divided into two groups (STR 1.03.07:2017): the main structures and auxiliary ones. Structure defects and deteriorations that can initiate the collapse of the whole construction are attributed to the main structures; defects and deteriorations which cannot cause the mentioned consequences are attributed to the auxiliary structures. All structures being pressured by water (bearing water pressure), retaining walls in upper and lower pools, spillways, bypasses, culverts, etc. may be assigned to the first group. The structures of inspection bridges, strengthening slabs and others may be assigned to the second one.

In this article, presented data and analysis are confined to the compressive strength of concrete and depth of gullies on the surface of the main structures – spillways (SW) and retaining walls (RW) – of HSs.

The aim of these investigations, based on research in the field, is to determine the actual values of compressive strength of concrete used in the main structures (SW and RW), the depth of gullies on the surfaces of structures, the actual service life of structures and relationships between them.

RESEARCH METHODS

The compressive strength of concrete structures was determined by non-destructive and destructive methods following standard requirements and instructional manuals of devices.

The compressive strength of the concrete of HSs was evaluated using the standard Schmidt hammer device.

These methods require that 10 readings should be taken from the tested area and that not less than two readings should be taken closer than 30 mm apart.

The dry surfaces of tested structures were selected. The test surfaces were prepared following the instructional manual and were struck in at least 10 places.

The diameter of marks (impact points) impressed with a Schmidt hammer on the surface of tested concrete and steel bars were measured by a special gauge with 0.1 mm accuracy.

The calibration curves of the mentioned device were used to calculate the strength of the tested concrete.

The sufficient quantity of impact points produced with a non-destructive device was controlled following the requirements of the manual.

When applying the destructive method, the compressive strength of concrete was determined using cubes and a test machine. 3–4 cubes from selected structures were prepared and tested following standard requirements.

The cubes were prepared from pieces of concrete split from the structures. They were split from such places and in such a manner that the structures would be less damaged.

Split concrete pieces were placed in hermetically sealed polythene sacks.

The volume mass and absorptive power of concrete were measured before carrying out the compression test.

From the split pieces of concrete, 10×10×10 cm cubes were sawed out. For that purpose, a special saw was used.

To avoid cracks, splits and other defects, prepared cubes were carefully inspected before testing.

Two opposite surfaces of cubes were smoothed out with a thin layer of gypsum mortar.

Prepared samples were measured with a calliper with an accuracy of 0.1 mm and tested with a hydraulic press (testing machine) MC-1000.

The structures on-site were visually examined, and their most deteriorated places were determined. The depth of the selected 3–6 biggest gullies was measured with the calliper with an accuracy of 0.1 mm.

RESEARCH RESULTS AND DISCUSSION

In this paper, the data and analysis of reinforced concrete structures of 16 operational HSs are presented.

For investigations, HSs were selected in various regions of Lithuania. Selected structures are in Alytus, Anykščiai, Kaunas, Kėdainiai, Marijampolė, Pakruojis, Raseiniai and Šiauliai districts.

The oldest HS was built in 1957, and the newest one in 1991. The investigations were performed in 2018–2020. 2022.

The actual service life of the oldest HS is 65 years and 31 years of the newest one.

The main reinforced concrete structures – spillways (SW) and retaining walls (RW) of HSs were investigated. The data of investigated HSs are given in Table 1.

Table 1. The data of investigated hydraulic structures (HSs).

No	HS, Location, date of construction	Service life in years	Structure	Concrete compresion strength, MPa	Depth of gully, mm	Deepening speed of gully, mm per year	T_{30}, in years
1.	Krokialaukis (Alytus distr., 1981)	41	SW	13.8	18	0.4	68.3
2.	Elmininkai (Anykščiai distr., 1975)	47	SW	8.6	46	1.0	30.7
			RW	9.9	37	0.8	38.1
3.	Leliūnai (Anykščiai distr., 1988)	34	SW	16.0	10	0.3	102.0
4.	Pagojė (Anykščiai distr., 1989)	33	SW	15.5	10	0.3	99.0
5.	Savičiūnai (Anykščiai distr., 1972)	50	SW	13.8	24	0.5	62.5
			RW	5.8	216	4.3	6.9
6.	Altoniškiai (Kaunas distr., 1978)	44	SW	22.4	12	0.3	110.0
7.	Gailiušiai (Kaunas distr., 1970)	52	SW	10.3	37	0.7	42.2
8.	Panevėžiukas (Kaunas distr., 1970)	51	SW	6.0	159	3.1	9.6
9.	Angiriai (Kėdainiai distr., 1980)	42	SW	27.6	9	0.2	140.0
10.	Akademija (Kėdainiai distr., 1968)	53	RW	10.4	29	0.5	54.8
11.	Antanavas HPP (Marijampole distr., 1957)	65	SW	5.8	349	5.4	5.6
12.	Jūrė (Marijampole distr., 1976)	46	SW	12.3	25	0.5	55.2
13.	Kazlai (Marijampole distr., 1991)	31	SW	10.4	16	0.5	58.1
14.	Laičiai (Pakruojis distr., 1975)	47	SW	7.8	46	1.0	30.7
15.	Anulynas (Raseiniai distr., 1978)	43	SW	17.8	16	0.4	80.6
16.	Kairiai (Šiauliai distr., 1970)	52	SW	10.4	32	0.6	48.8

Notes: HPP – hydropover plant; SW –spillway; RW – retaining wall; T_{30} – the service life (expressed in years) of covering layer 30 mm depth thickness.

The average compressive strength of the concrete of structures determined using non-destructive methods matches rather well with results received by testing cubes prepared from the concrete of the mentioned structures.

The strongest concrete with an average compressive strength of 27.6 MPa was determined in the structures of Angiriai HS (SW), the weakest one with an average of 5.8 MPa – in the structures of Antanavas HPP and Savičiūnai HS (SW).

The surfaces of all investigated structures located in the varying water level areas were deteriorated and had gullies.

In reinforced concrete structures of Antanavas HPS (SW) and Savičiūnai HS (RW) the deepest gullies were found. The average depth of the biggest gully in reinforced concrete structures SW of Antanavas HPS reached almost 5.4 mm, meanwhile the surfaces of SW structures of Angiriai HS were almost without gullies, on the surfaces of mentioned structures, the gullies found were only in the initial stage of development with the average depth of 9 mm.

The actual service life, the average compressive strength of concrete, and the average depth of the biggest gullies of investigated reinforced concrete structures are given in Table 1.

The surfaces of structures manufactured with a weaker concrete were more damaged.

As well as determining the actual service life of structures and an average depth of damages (gullies) it became possible to determine the average deepening rate of gully in structure – v expressed in mm per year.

The highest deepening rates of gullies were determined in structures manufactured with a weak concrete (f_c = 5.8 - 6.0 MPa) in Antanavas HPP, Savičiūnai, and Panevėžiukas HS.

The average deepening rate of gully in the structures of Antanavas HPP is 5.4 mm per year. In the structures of Savičiūnai HS, it is 4.3 mm per year and in the structures of Panevėžiukas HS – 3.1 mm per year.

The average deepening rate of gully in the structures of Angiriai HS was the lowest – only 0.2 mm per year.

The relationship between the deepening rate of the gully and the average compressive strength of concrete in HS is shown in Figure 1.

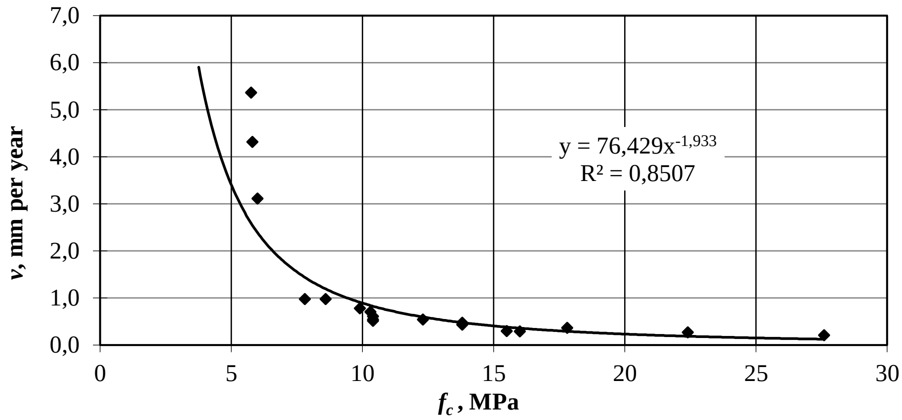

Figure 1. The deepening speed of gully – average compression strength of concrete relationship for WEC structures.

The mentioned values were processed using the computer. The theoretical curve was developed per analytical expression:

$$v = 76{,}429\, f_c^{\;-1{,}933}, \qquad (1)$$

where v – the average deepening rate of gully in the structures, mm per year;
f_c – the average compressive strength of concrete MPa. RSQ is 0.95.

Per equation (1) it is possible to find the time in which gullies grow to dangerous depths. The mentioned depth may be equal to the thickness of the concrete cover of the structure and for reinforced concrete structures of HS cannot be less than 30 mm, i.e., the depth of the gully cannot grow to 30 mm.

The service life of a concrete cover of 30 mm thickness is indicated as T_{30} and expressed in years.

Calculated values of T_{30} are given in Table 1.

According to the presented data, the 30 mm thick concrete cover manufactured with weak concrete (f_c = 5.8 MPa) will have deteriorated after 5.6…6.9 years of service life. The ones manufactured with strong concrete (f_c = 27.6 MPa) will have deteriorated after 140 years of service life.

The relationship between the service life of a 30 mm thick concrete cover and the average compressive strength of concrete is shown in Figure 2.

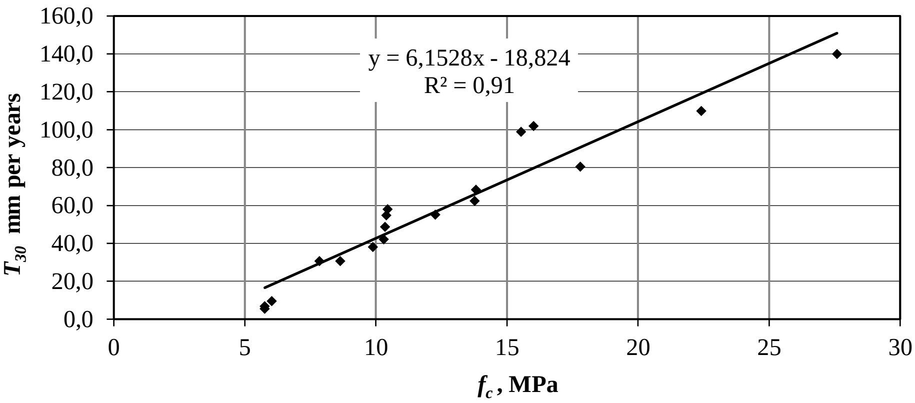

Figure 2. The relationship between the service life of a 30 mm thick concrete cover and the average compressive strength of concrete in HS.

The above-mentioned values were processed using a computer. The theoretical curve was developed per the best correlation coefficient nearest to 1 and has been taken as shown:

$$T_{30} = 6.1528\, f_c - 18{,}824, \qquad (2)$$

where T_{30} – the service life of the structure with a 30 mm thick concrete cover expressed in years;
f_c – average compressive strength of concrete MPa. RSQ is 0.9192.

Developed equations (1) and (2) can help to estimate and choose concrete strong enough to protect reinforcement of the structure located in the alternative level of water against it would be uncovered.

It has been determined that reinforcement of structures functioning in the varying water level areas, manufactured with concrete with compressive strength of no less than 18.9 MPa, and protected with a 30 mm thick concrete cover will become exposed after 100 years of service life.

CONCLUSIONS

1. It has been determined that reinforced concrete structures – spillways and retaining walls – of on-site investigated 16 HSs were manufactured using concrete whose compressive strength is between 5.8 and 27.6 MPa.
2. The deepening rate of the gully on the surfaces of reinforced concrete structures of HSs functioning in the varying water level area depends on the compressive strength of the concrete used for manufacturing. It is stated that surfaces of structures manufactured using concrete with compressive strength of 27.6 MPa (have deteriorated) were gullied at the rate of 0.2 mm per year. Reinforced concrete structures manufactured using concrete with a compressive strength of 5.76 MPa were gullied between 4.3 and 5.4 mm per year. The relationship between the average deepening rate of the gully and the average compressive strength of concrete has been determined according to the developed analytical expression.
3. Based on the developed equations, it may be provided that the reinforcement used in reinforced concrete structures of HS functioning in varying water level areas having 30 mm thick concrete cover manufactured from concrete with the average compressive strength of no less than 18.9 MPa (grade C12/15) will not be exposed in 100 years.

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