Service life of hydraulic structure reinforced concrete elements according to protective layer carbonization criteria

A A Yangiev, M R Bakiev, O A Muratov, J M Choriev and Sh Djabbarova

Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan

Abstract. In the given article the design of service life for hydraulic structure reinforced concrete elements has been performed analytically with the use of the basic techniques and by constructing reinforced structure protective layer carbonization models, mathematic modelling methods for physical processes. The main goal of the work is to determine the service life for reinforced concrete structures of spillways and its elements under impact of the environment during their operation.

1. Introduction
Choosing the minimal thickness for protective layer at the stage of design provides protection for rebar by concrete. In reinforced concrete structures the exterior concrete layer protects the rebar from corrosion and provides the monolithic behavior of rebar and concrete. Loosing the protective quality of concrete is especially crucial for prestressed reinforcement bars, where corrosion during hydraulic structure operation can result in sudden failure of reinforced concrete structure. Hydraulic structure operation conditions indicate about the necessity to determine concrete protective layer thickness during the design stage. This kind of design is relevant to forecasting the behavior of reinforced concrete structure at operation stage of hydraulic structure [1]. Carbonization process is considered to be well spread universal aggressive impact, affecting reinforced concrete structures under operation.
It occurs as follows: atmospheric carbon dioxide gas with mean concentration of 0.03% intrudes through the surface into pore structure of reinforced concrete element and reacts with calcium oxide hydrate and caustic alkali of concrete protective layer. As a result pH of the concrete drops from 13 to 11 and further down, protective capacity decreases and the effective reinforcement undergoes corrosion. Such process of concrete chemical composition change is called carbonization. The chemical reaction of carbonization is written as follows: Ca(OH)₂ + CO₂ = CaCO₃ + H₂O [1,2].

2. Method
Particularly dangerous failures of concrete and reinforced concrete hydraulic structures are observed under joint action of several deterioration types as the result of physical and chemical influences, salt crystallization in structure elements, alternation of freezing and melting effect, temperature damage, combined action, when damage resulting from one reason becomes the source of the other dangerous effect.
According to the existing research works, various aggressive environments affect on concrete and reinforced concrete elements of hydraulic structures [2]. Natural surface water and groundwater are...
divided into 4 groups according to their formation and pH value: acidic water, having pH<3 (acidity is due to the presence of free sulfuric or hydrochloric acid), pH ranging from 3 to 6.5 (the acidity in them depends on organic acids and carbonic acid), neutral and alkalalescent water with pH ranging between 6.5 and 8.5 (due to the presence of Ca(HCO3)2), highly alkaline water with pH>9 (due to sodium carbonate presence). The most aggressive gases are hydrogen sulfide, sulfur dioxide, nitrogen oxide, chloride and hydrogen chloride. Most gases are saline and acid-forming. Development of gases in them occurs only with the presence of water in the air or on the surface of structure. Therefore, high air humidity is an intensifying factor for corrosion processes in the presence of acidic gases.

In hydraulic structure operation practice it is noted that the process of carbonization plays positive role until it reaches to the depth of contact with steel rebar. Negative effect of deep carbonization is related with the decrease of its alkalinity and the loss of the structural element’s chemical characteristics, which prevent the corrosion of steel rebar.

In works [1,3] they use the following semi-empirical relationship for evaluation of carbonization depth based on Fick’s law:

\[ h_{\text{carbonization}} = K \sqrt{t} \]  

where:
- \( t \) – operation length of the structure until the time of inspection (years)
- \( K = \frac{\text{max} h_{\text{carbonization}}}{\sqrt{\tau_{\text{operation}}}} \) – empirical coefficient, taking into consideration the influence of climatic factors of the environment and operation conditions of the structure on the speed of carbonization (mm/year^{0.5}).

Structure operation practice shows that when humidity of the operation environment changes carbonization takes place slower than that calculated by the mentioned relationship. According to equation (1) the physical model of carbonization, curves are presented in a graphical form (Fig.1). According to many experimental research results the given formula (1) can be written as follows:

\[ x = K t^m \]  

where \( m \) – the degree indicator of the carbonization curve [1].

![Figure 1. Protective layer carbonization depth vs time relationship.](image)

Majority of factors, identifying the kinetics of concrete carbonization are stochastic. In the process of hardening pores appear inside of concrete, which are of a stochastic nature by size and permeability. On this basis diffusive resistance to aggressive gases is described by probabilistic laws [4]. As time goes and as the result of stochastic processes in the atmosphere the change of the environment influences the concrete carbonization.

\[ P(x < a) > P_H \]  

where \( a \) – concrete protective layer thickness.

The given formula is considered to be the provision to determining service life of the concrete protective layer of the structure with \( P_H \) probability. As time goes the carbonization depth increases. If the condition (3) is met, the probability of full carbonization of structure concrete protective layer will
equal to 1 - \( P_H \). Initial time \( t = t_1 \), mean depth of structure concrete carbonization layer is \( \bar{x}_1 \) (Fig.2), and the probability for loss of protective qualities concrete with respect to rebar is low. Carbonization depth increases with time.

**Figure 2.** Probability model for concrete protective layer carbonization. \( f(x; t_1) \) and \( f(x; t_2) \) – distribution densities of concrete neutralization depths at times \( t_1 \) and \( t_2 \), \( f(a) \) – distribution density of concrete protective layer with mathematical expectancy \( a \).

In structure operation practice the main task for reinforced concrete structure service life design there is a definition of time during which carbonization will not take place for the given concrete structure element with given thickness and probability \( P_H \).

On the basis of above listed research and works by scientists [1,2,3,5] we will analyze the probabilistic design of carbonization for structure concrete protective layer and safety characteristics with the use of the coefficient from our works [1,2].

According to the research it is stated that the distribution density of the concrete carbonization depth and protective layer thickness is considered by normal laws. On this basis the equation (3) for normal laws is given in the following form:

\[
\frac{\bar{a} - \bar{\bar{x}}}{\sqrt{(\bar{a}V_a)^2 + (\bar{V}_a)^2}} \geq \gamma_H
\]

where \( \bar{x}, V_a \) – mathematical expectancy and variation coefficient for concrete protective layer carbonization depth distribution.

\( \bar{a}, V_a \) – mathematical expectancy and variation coefficient for concrete protective layer thickness.

\( \gamma_H \) – safety coefficient.

For clarification we provided some factors of safety for \( P_H = 0.95 \) based on assumptions, for which safety coefficient is given within \( \gamma_H = 1.64 \) and for \( P_H = 0.90 \) the safety coefficient is given within \( \gamma_H = 1.28 \). Carbonization boosting process is such that it can fall within \( \bar{x} = \bar{\bar{a}} \), and for probability of \( t = T \) rebar corrosion can happen with \( P = 0.5 \). It is natural for this condition that factor \( T \) determines the service life for structure concrete protective layer with proposed reliability. The time \( T \) which determines the structure protective layer service life is the probability of the protective layer loosing its properties regarding to rebar to be given within 1 - \( P_H \).

Based on numerous experimental research results we input factor \( x \) into inequality (3) according to (2) for \( t = T_{\text{carb}} \), therefore the equation will take the following form:

\[
\frac{\bar{a} - \bar{R}_3 T_{\text{carb}}}{\sqrt{(\bar{a}V_a)^2 + \bar{V}_K^2 + \gamma_{\text{carb}}^2}} \geq \gamma_H
\]

where \( \bar{R}_3 \) and \( V_{K0} \) correspondingly mathematical expectation and variation coefficient of random value \( \bar{R}_3 \) distribution, which describes carbonization speed of the concrete protective layer.

Coefficient \( \bar{R}_3 \), describing the speed of carbonization process reflects values of random factors of technological and natural origin. The coefficient \( \bar{R}_3 \) is set experimentally and depends of structure
operation conditions, besides it is related with diffusion coefficient, concrete density, cracks, and environmental factors. In studies [6] carbonization speed factor $\tilde{K}_3$ is determined with the use of ultrasound.

In order to determine the service life of concrete protective layer for the structure under consideration provided $P_H$ from equation (5) $T_{\text{carb}}$ should be determined. Based on research [1] service life $T_{\text{carb}}$ for concrete structure protective layer transformed into the following form:

$$T_{\text{carb}} = \frac{a_{c}}{\tilde{K}_3} \left( \frac{1}{1 - a_{c} - \sqrt{1 - (1 - \gamma_H)^2 V_{K3}^2} \times (1 - \gamma_H V_{K3}^2)} \right)$$  \hspace{1cm} (6)

where $a_{c}$ - concrete air permeability parameter [7].

Based on economical views and operational conditions $T_{\text{carb}} \geq T_H$ and this condition must be met during the whole time of set service life of hydraulic structure element.

Keeping in mind that $T_{\text{carb}}=T_H$ from equation (6) we determine the mean design value of protective layer thickness of concrete structure:

$$\bar{a} \geq \tilde{R}_3 \sqrt{T_H} \times \frac{1 - \gamma_H^2 V_{K3}^2}{1 - a_{c} - \sqrt{1 - (1 - \gamma_H)^2 V_{K3}^2} \times (1 - \gamma_H V_{K3}^2)}$$  \hspace{1cm} (7)

Concrete protective layer thickness is adjusted with equation (7) and it is taken into consideration while designing and operation period which also consider variation coefficients $V_{a}, V_{K3}$ and mean carbonization speed $\tilde{K}_3$, which are included in the design [1].

### 3. Results

In order to design the service life for reinforced concrete spillway sidewall according to concrete protective layer carbonization criteria it is necessary to have data on probabilistic characteristics of concrete layer thickness $\bar{a}$, $V_{a}$, and carbonization speed factors $V_{K3}, \tilde{K}_3$. The design takes into account concrete water permeability grade W4 with the account of concrete air permeability $a_{c}$ from normative document [7]. Results, obtained from structure inspection [8] are used as initial data. The mean value of protective layer thickness $\bar{a}$ for hydraulic structures being designed can be taken equal to design value according to the requirements from normative documents [9]. The rest of the initial data for design must be accepted on the basis of statistical analysis and experimental data for protective layer carbonization of the structure under operation [1,10,11]. Henceforth in order to collect such data values $\tilde{R}_3$, $V_{K3}$ and $V_{a}$ from Table 1 can be used for design.

| Reinforced concrete structure operation conditions | Mathematical expectation $\tilde{R}_3$, m/year | Variation coefficient $V_{K3}$ | $V_{a}$  |
|--------------------------------------------------|---------------------------------------------|--------------------------------|---------|
| 1. In open air (walls, slabs, gangways and others) | 1,5 – 2,5 | 0,15 – 0,25 | 0,15 – 0,25 |
| 2. Internal structures (columns, structural units, crane beams ) | 1,5 – 3,0 | 0,1 – 0,25 | 0,1 – 0,25 |
| 3. In aggressive environment by concrete carbonization criteria (cover slabs): | | | |
| - weak | 2 – 3 | 0,1 – 0,25 | 0,17 |
| - medium | 3 – 5 | 0,1 – 0,3 | 0,17 |
| - high | 3 – 6 | 0,1 – 0,3 | 0,17 |

Note 1. $V_{a}$ parameter mean values for aggressive environments are given.
The task consists of determining the service life by the criteria of concrete protective layer carbonization for the right side of spillway structure steep flume sidewall in Tuyabuguz water reservoir. Based on the statistical analysis of numerous measurements of concrete carbonization depth and slab protective layer thickness the following values have been obtained: mean thickness of concrete protective layer $\overline{a}= (a+a_{w}+a_{w})= (35+25+20)/3 = 26.6$ mm; concrete protective layer variation coefficient $V_{a} = 0.15$; mathematical expectation for carbonization speed factor $\overline{K_{e}} = 1.5$ mm/год; coefficient of filtration for W4 grade concrete, we have $a_{c} = 0.154$ cm$^{3}$/s for concrete air permeability parameter; variation coefficient for carbonization speed factor $VK_{e} = 0.15$. Based on the results of our investigation in winter of 2018 we found failures and signs of corrosion in spillway sidewall of Tuyabuguz water reservoir (Figures 3 and 4).

**Figure 3.** Opening of rebar as the result of concrete protective layer loss in spillway right sidewall in Tuyabuguz water reservoir.

**Figure 4.** Concrete protective layer failure. Right sidewall of the flume. Failure size is 20x15cm.

Design is accomplished with the use of safety characteristics $P_{u}=0.9$, value $\gamma_{u} = 1.28$, using equation (6) we determined $T_{\text{carb}}$.

$$T_{\text{carb}} = \frac{26.6}{1.5} \times \left( \frac{1 - 0.154 - \sqrt{1 - (1 - 1.28^2 \times 0.15^2)} \times (1 - 1.28^2 \times 0.15^2)}{1 - 1.28^2 \times 0.15^2} \right) = 10 \text{ years}$$

Our design results show that concrete protective layer service life for spillway speed flume right sidewall is 10 years.
Considering $T_{\text{carb}} \approx T_{\text{fr}}$, from (7) we determine the mean design value for concrete protective layer:

$$\bar{a} \geq 1.5\sqrt{100 \times \frac{1-1.28^2 \times 0.15^2}{1-0.154-\sqrt{1-(1-1.28^2 \times 0.15^2) \times (1-1.28^2 \times 0.15^2)}}} = 15 \times 1.7 = 25.5 \text{ mm}.$$  

4. Discussion

In the process of carbonization pH drops and weakens the protective characteristics of hydraulic structure elements and provokes the corrosion of rebar. But it must be noted that carbonization process positively affects reinforced concrete element of the hydraulic structure, since it is pointed out in operation conditions, that $\text{CaCO}_3$ solubility is 100 times lower than that for $\text{Ca(OH)}_2$ and in this case leaching process passes much slower. It is noted in foreign research materials that carbonated layer of elements in hydraulic structures have much higher strength and density. Based on these assumptions in order to increase the density artificial carbonization of reinforced structures and their elements have been carried out. Calcium carbonate solutes slowly in water and when formed it tries to close all the pores on the surface of hydraulic structure concrete element. During the research [13] we have inspected the structure of pores in hydraulic structure concrete and reinforced concrete elements in South-Steppe canal. By determining the differential porosity, i.e. distribution of pores by their sizes, we have determined the structure of cement materials of various types. During the course of experimental data analyses, we have specified not only pore sizes and shapes in concrete composition, but also the nature of porosity (closed, capillary and open-end). Such process is observed in zones with variable water level, where water partially contacts with concrete surface. Based on field observations in our works [8,12,13,21,22,23] we have provided design results on all types of corrosion. As the result of observations we have determined zones, which have partially undergone concrete protective layer failure with even humidity, and those elements are for example sidewalls and dividing walls of open spillway flume structure. In work [14] the research is presented which show the decrease of pH factor, resulting in weakening of natural protective qualities of concrete and provoking rebar corrosion. Particularly dangerous failure of concrete and reinforced concrete elements of hydraulic structures are observed with joint action of several types of deterioration as the result of physical and chemical impact, temperature influence, combined action, that is when failure provoked by one reason become the source of formation of the other dangerous action. Based on above mentioned failure types, normative documents [15] list out requirements to the structures which are open to aggressive environment. In the works of foreign authors [14, 16, 17, 18, 19, 20] it is said that many gases are acidic and acid-forming. Formation of acids in them happen only with the presence of water in the air of on the surface of reinforced concrete structure. Based on that the scientists noted that boosting factor of corrosion processes in hydraulic structure reinforced concrete elements and other engineering structures is high humidity of air with the presence of acidic gases. Taking that into account several scientists considered concrete air permeability parameter in their design. In active standard GOST-12730.5-84 parameter values are presented for air permeability of concrete surface layers depending on the air permeability of concrete itself. Besides, it must be noted that on of the characteristics of hydrotechnical concrete is that concrete air permeability increases with the increase of its age. Based on the above mentioned assumptions it can be noted that in varying zones of hydraulic structure reinforced concrete elements when significant amount of water is evaporated from an element air permeability of structure element increases slower and it gives a start to the process of concrete dehydration. With significant drying of varying zones in hydraulic structure reinforced concrete elements the increase of air permeability of the element stops and cases of its decrease from the initial value are observed.

5. Conclusions

With the absence of the results from instrumental analysis table data (Table 1), mathematical expectations and variation coefficients have been used in the design in the given work. We have conducted visual observations of reinforced concrete spillway speed flume structure in Tuyabuguz
water reservoir. Concrete protective layer carbonization marks have been found in the left sidewall of spillway speed flume. Our calculations on determining the service life of the structure element showed that the service life is 10 years. Having determined the service life for spillway structure service life optimal time and scope of repair works can be determined.

References
[1] Ashrabov A A 2012 Reliability and durability of building systems (Tashkent: Politmehanika) p 358
[2] Chirkov V P 1997 Forecasting service life for reinforced concrete structures (Moscow: MIIT) p 56
[3] Chirkov V P 1980 Probabalistic methods for design of reinforced concrete structures (Moscow: Transport) p 128
[4] Shaliy E E, Kim L V, Leonovich S N and Stepanova A V 2018 Probabalistic design of the depth and spreading area of carbonization in hydraulic structures 2 J. Science and technics (Tashkent) pp 106-114
[5] Chirkov V P 1998 Theoretical basics of service life forecasting for reinforced concrete structures (Moscow: MIIT) pp 12-18
[6] Guzeev E A, Bondarenko V M and Savitski N V 1984 Integral method for evaluation of stressed and deformed condition of reinforced concrete structures when impacted by aggressive environment and power load “NIIJB” works (Moscow: Stroyizdat) pp 14-20
[7] GOST 12730.5-84 (Building codes) 2007 Methods for determining water impermeability (Moscow: Standartinform) pp 9-10
[8] Aliqulov P U, Muratov O A and Lapasov H 2009 Developing measures on improving frost resistance and corrosion resistance of hydraulic structures on the example of Tashkent water reservoir N21 Research work pp 4-55
[9] SNiP 2.03.11-85 (Building codes) 1985 Protecting building structures from corrosion (with Amendment N1) (Moscow) pp 23-30
[10] Moshanski N A and Puchina E A 1962 Determining comparative aggressiveness of main gases on steel, concrete and protective organic covers “NIIJB” works (Moscow) pp 5-27
[11] P3855 TRP 1981 Reconstruction of the headrace and tailrace of Tashkent water reservoir in Tashkent region N1-A Technical documentation (Tashkent) pp 2-36
[12] Ashrabov A A and Muratov O A 2018 Evaluation of service life for reinforced concrete elements of open spillway structures by concrete protective layer carbonization sign Vol.1 Int. sc. and practical conf. (Tashkent) pp 163-170
[13] Aliqulov P U, Muratov O A and Lapasov H 2008 Recommendations on improving the reliability of SSC hydraulic structures State registration N16/2008 (Tashkent: TIIM) pp 2-41
[14] Verbetski G P 1980 Mechanizm and kinetics of concrete and rebar corrosion in hydraulic structures, designed with crack formation allowance d.t.s. dissertation (Moscow) pp 210-220
[15] GOST 31384-2017 (Building codes) 2018 Corrosion protection of concrete and reinforced concrete structures. General technical requirements (Moscow: Standartinform) pp 23-30
[16] Benin A P, Trunkova M M and Ryabov V A 1970 Study of concrete in hydraulic structures under operation (Moscow: Energy) pp 24-30
[17] Verbetski G P 1976 Strength and durability of concrete in water environment (Moscow: Stroyizdat) pp 65-72
[18] Moskvin V M, Ivanov F M, Alekseev S N and others 1980 Corrosion of concrete and reinforced concrete, methods of their protection (Moscow: Stroyizdat) pp 231-240
[19] Central Research Institute 2001 Recommendations for evaluation of building structure reliability by external signs / industrial buildings (Moscow) pp 56-62
[20] Shaliy E E, Kim L V, Leonovich S N and Stepenova A V 2016 Design model for depth and spreading of chlorides in concrete of hydraulic structures Int. sc. conf. (Moscow) pp 291-292
[21] Yangiev A A, Ashrabo A A and Muratov O A 2019 Life prediction for spillway facility side wall Vol.97 XXI Int. Sc. Conf. on Advances in Civil Engineering E3S Web of Conferences

[22] Yangiev A A, Gapparov F and Adjimuratov D 2019 Filtration process in earth fill dam body and its chemical effect on piezometers Vol.97 XXI Int. Sc. Conf. on Advances in Civil Engineering E3S Web of Conferences

[23] Mirzaev B, Mamatov F and Tursunov O 2019 A Justification of Broach-Plow’s Parameters of the Ridge-Stepped Ploughing Vol.97 XXI Int. Sc. Conf. on Advances in Civil Engineering E3S Web of Conferences