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THE "VRLA" HE PLANT ENTRY STRUCTURE CONCRETE RESTORATION

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Professional paper

The paper presents an example of a structure exposed for a long period of time to the action of several aggressive factors: alternate freezing and thawing, efflorescence and carbonation. Representative samples were taken from the concrete structure of the facility, and the relevant properties of concrete were identified in the laboratory. The analysis of the collected data demonstrated significant deficiencies of the implemented concrete technology during construction of the facility. On this basis, a plan for restoration of the facility was made, and the restoration was accomplished, revitalizing the facility. This example too, demonstrates that implementation of new standards in the field of concrete technology is necessary.

Keywords: *concrete, chemical corrosion, physical corrosion, restoration*

Sanacija betona ulaznog objekta sustava HE "Vrla"

Stručni članak

U članku je prikazan primjer jednog objekta koji je u dugom vremenskom razdoblju bio izložen utjecaju više agresivnih djelovanja: naizmjenično smrzavanje i odmrzavanje, eflorescencija i karbonatizacija. Iz betonske konstrukcije objekta uzeti su reprezentativni uzorci na kojima su u laboratoriju utvrđene relevantne karakteristike betona. Analizom prikupljenih podataka utvrđeni su značajni nedostaci primijenjene tehnologije betona prilikom izvođenja objekta. Na osnovu toga urađen je projekt sanacije objekta, koja je potom izvedena, tako da je objekt revitaliziran. I ovaj primjer pokazuje da je primjena novih standarda iz područja tehnologije betona neophodna.

Ključne riječi: *beton, fizikalna korozija betona, kemijska korozija betona, sanacija betona*

1 Introduction

The concrete exposed in a long time period to the concurrent action of several aggressive agents must inevitably be damaged. The paper presents an example of the hydraulic structure which has been exposed to alternate freezing and thawing, efflorescence and carbonation in a period of around 50 years.

Certain of these reactions involve dissolution and physical migration of soluble salts with reprecipitation. When this occurs at depth, within pores in the solid matrix, the phenomenon is termed subflorescence. Subflorescence may on occasion be expansive with resulting physical disruption to the physical coherence of the matrix.

2 Some of the basic mechanisms of concrete deterioration

Portland cement and other building materials joined with Portland cement, e.g., brick, are liable to develop superficial deposits termed efflorescence. Several papers outline relevant considerations [1÷3]. These references suggest, and it is generally accepted that, other factors being equal, increased permeability of the construction results in increased intensity of efflorescence. However, simply reducing permeability is not necessarily a solution: some materials, e.g., clay brick and cement mortar, require a controlled permeability to achieve satisfactory frost resistance and control of moisture movement. Kubayashi and Uno [4, 5] correlate increased efflorescence with increased cement alkali, sodium and potassium, contents. They explain that soluble alkalis increases the solubility of $Ca(OH)_2$: this increased solubility, coupled with transport of soluble calcium towards the surface where atmospheric CO_2 was present, is postulated to result in $CaCO_3$ precipitation.

The best practical advice to mitigate calcium carbonate efflorescence is therefore as follows:

- Use low-alkali cements. If alkalis cannot be avoided, sodium is preferred to potassium. Alkali contents need to be compared on a mole basis; weight percentages are misleading.
- If possible, devise and agree a test to estimate alkali releases. Quick-release sources of clinker alkali, e.g., $(K, Na)_2SO_4$ should be avoided, so a test should determine both total release and rate of release.
- If an alkali sorber can be added to cement, this should improve performance. However, it must be able to act quickly and there is a doubt that some blending agents, which are claimed to sorb alkali, e.g., coal combustion fly ash, will work with sufficient rapidity totally to avoid efflorescence. Recent studies of alkali sorptivity may assist in materials selection [6, 7].
- Use impermeable mortars, so as to reduce the availability of alkali and decrease the effective thickness per unit time of the alkali-depleted layer.
- Do not use cement mortar to bind components that will themselves liberate soluble alkalis: check the potential of other components to liberate soluble sodium and potassium at pH=10÷13 and reject those that give high releases.
- Thoroughly wash exterior surfaces after final set of the cement to dilute and flush away alkalis. Do not, however, use acidic washes that will enhance the permeability of the cement surface and may subsequently worsen the problem.
- Where efflorescence is anticipated avoid if possible dark-coloured materials, e.g., dark brick or tile.
- Extend investigations to sulphate efflorescence [8].

The temperature at which water freezes in capillary pores is a function of the size of the pores and pore chemistry [9].

As pore sizes decrease, the temperature required to freeze the water also decreases. For example, in pores with a diameter of 10 nm, the water will not freeze until –5 °C (23 °F), and for pores with a diameter of 3,5 nm, the water will not freeze until –20 °C (4 °F) [10,11].

While the freezing of water damages the hardened cement paste, it is not the main contributor to the freezing and thawing deterioration of concrete. The primary damage is caused by the increase in hydraulic pressure within the pore spaces. As water freezes within a capillary pore, the ice that is formed compresses the unfrozen water within the pore. If the water can escape into an unoccupied void, the hydraulic pressure is relieved. However, if the distance to a void is too great and the hydraulic pressure cannot be relieved, the water pressure will expand the pores causing tensile stresses in the surrounding hardened cement paste. In saturated concrete, the tensile stresses may eventually exceed the tensile capacity of the paste and cracking will occur. Entrained air is added to the concrete to provide the voids necessary to relieve the hydraulic pressure [10, 11].

Carbonation of concrete itself does not do harm in view of the performance of structure, adversely a marginal enhancement of the compressive strength was observed [12]. However, when carbonation reaches at the depth of the steel, the high alkalinity of the concrete pore solution is neutralized and hydration products are dissolved then to lower the buffering capacity of hydrations against a pH fall [13]. At this moment, the passivation layer on the steel surface, which otherwise would protect the steel embedment from a corrosive environment, is destroyed, and steel is directly exposed to oxygen and water, eventually to corrode. It was previously reported that carbonation is strongly dependent on the degree of porosity [14] which is the path for carbon dioxide and water to transport in concrete, and the content of calcium hydroxide [15] which reacts with carbon dioxide and water to form carbonation of concrete. To refine the pore structure, pozzolanic materials, such as pulverized fuel ash and ground granulated blast furnace slag, have been used, but they adversely accelerated the rate of carbonation [16, 17].

Figure 1 Appearance of the entry structure of "Vrla" HE

The speed of carbonation essentially depends on the humidity of concrete and is maximal for values about 65 %. After carbonation it was observed that the porosity of concrete decreases due to a highest molar volume of carbonation products in comparison to the volume of hydrates. For concrete, the difference of porosity between non carbonated and carbonated concrete is higher for concrete with low porosities and can attain 10 % [18].

Then, in the presence of oxygen and water the corrosion process can be initiated. Such corrosion products are expansive, so very quickly the concrete is mechanically damaged and a spalling of cover can be observed with the reinforcement directly exposed to the environment. A very usual and reliable tool for assessing the phenomenon consists in measuring the carbonated depth by means of phenolphthalein [19].

3 Structure description

The entry facility of "Vrla" HE (hydro-electric power plant) is situated on Vlasinsko lake at the altitude of around 1200 m above sea level, Fig. 1. The external structure is placed over the concrete shaft of square cross section, which is in most part immersed in the lake water, Fig. 2.

Figure 2 Concrete shaft within the structure

On the bottom of the shaft, there is a steel pipe, with the diameter of 2750 mm with the GATE used to convey the water from the lake to the turbines of the power plant which are located at a considerably lower altitude ASL. The structure was constructed at the end of 60's as a massive structure of concrete which had a design grading of 220 kg/cm^2, which corresponds to the concrete class C16/20 (N/mm^2) in contemporary nomenclature. Even the visual inspection of the structure easily revealed that the concreting joints were purely constructed, so in spite of the very high thickness of the walls, the lake water penetrated, infiltrated the shaft. Water ran down the walls of the shaft and accumulated at the bottom from where it was evacuated by engaging the pumps at intervals. It is obvious that the implemented technology of concrete was inadequate to successfully provide a long-lasting endurance of concrete, so the restoration of the structure after around 50 years of service was necessary.

In this case, several types of concrete corrosion overlapped. One of the forms of corrosion which was observed on its interior surface is alkalization as there is practically a permanent pressurized filtration of water through concrete. Having in mind that the filtration process lasted very long, the porosity and permeability of concrete increased, which leads towards reduction of strength and increased sensitivity of concrete to other forms of aggressive actions. In the reaction of alite and belite with water, a certain amount of $Ca(OH)_2$ is obtained, and this is the most frequent alkalization product of concrete. The cement rock is insoluble in water, but a decomposition process may occur due to the existence of strong alkalization in a prolonged time interval. For that reason the cement rock with a high content of $Ca(OH)_2$ which is characteristic for pure Portland cements, is more liable to carbonation and efflorescence, and thus to decay when exposed to adverse conditions.

The exterior surface of concrete is exposed to direct action of lake water whose level varies throughout the year. Winter season on Vlasina is very long and cold, so the effects of alternate freezing and thawing are evident on concrete.

In Fig. 3, there is the appearance of the external surface of concrete at the moment when the level of water in the lake was lowered so that the restoration could be performed.

Figure 3 Appearance of concrete on the exterior of the shaft

Figure 4 Appearance of protective grille

In Fig. 4 there is a protective concrete grille preventing passage of large objects (tree trunks, limbs and branches, etc.) into the lake water intake pipe. The damage due to the frost action is also visible on these slender concrete elements.

4 Physical and mechanical characteristics of concrete

Prior to the production of a concrete restoration design, it was necessary to examine its physical and mechanical properties. For this purpose, samples of concrete were taken, by cutting out five cylindrical samples, 150 mm in diameter and around 400 mm in length, from the representative points of the internal walls of the shaft.

On the basis of the explicit request of the examination commissioner, a sample of one cylinder was taken precisely on one of the concreting joint locations, Fig. 5. Those locations are always critical for the concrete exposed to the action of water under pressure. It is known that due to the difference in shrinking of old and new concrete at their joint, even if the difference is only one day, there occurs a crack through which water may penetrate. After extraction of the drill from the concrete, a considerable amount of water started to penetrate inside, so after extraction of the sample cylinder, the measures to seal the cavity in concrete with adequate means were taken.

In Fig. 6 the appearance of the cylinder sample taken from this location is presented. As it can be seen, it is virtually separated along its height by the salt deposits, primarily carbonation products.

Figure 5 Water penetration at the concreting joint

Figure 6 Appearance of the cylinder sample taken at the location of concreting joint

Concrete samples were tested and examined in the Laboratory for building materials of the Institute of Civil Engineering and Architecture at the Faculty of Civil

Engineering and Architecture of Nis, and the following characteristics given in Tab. 1 were determined [20].

Table 1 Concrete testing results

Testing type and standard	Mean value
Density (SRPS ISO 6275)	2208 kg/m^3
Specific gravity (SRPS ISO 6275)	2451 kg/m^3
Total porosity (calculation method)	9,91 %
Water absorption (SRPS B.B8.010)	4,11 %
Compressive strength (SRPS ISO 4012)	23,88 N/mm^2
Penetration of water under pressure (SRPS U.M1.015)	Water permeable – water penetration along entire height

Testing results determined that the concrete had a relatively low density whose average value was around 2200 kg/m^3. Proportionately to the value of density an average value of compressive strength of around 24 N/mm^2, was determined, which is concrete class C 16/20 which corresponds to the designed concrete class. The concrete in question was obviously made with high water/cement factor, with no admixtures such as plasticizers and aerators, thus it features high porosity of around 10 %. With such properties, it is not suitable for construction of facilities or structural parts exposed to permanent action of pressurized water, variable level of water moisturizing them and to the action of low temperatures. Testing revealed water permeability of concrete, which was obvious at the site with the facility.

5 Concrete restoration

On the basis of the extent of determined damage, its cause, physical and mechanical characteristics of concrete, materials for restoration of the facility were selected [21]. For grouting of horizontal cracks at the locations of concreting joints on the internal surfaces of the walls, a two-component injection plastic material based on epoxy resin was used. The epoxy was injected under pressure through the tubes which were previously inserted in concrete from which all the loose parts were removed.

For the purpose of vertical hydro-insulation (water sealing) of internal surfaces, a coating was used – two-component polymer modified cement mortar intended for waterproofing works on concrete surfaces whose main purpose is prevention of water penetration and protection from freezing and thawing effects, filling of the pores, cracks and smoothing small irregularities.

Restoration of the external surface of concrete was performed by the multi-layered protection system, consisting of: primary layer – cement restoration mortar, with added latex and polypropylene fibres, then coating of three-component epoxy cement mortar and finally waterproofing coating intended for the potable water reservoirs.

The appearance of restored and protected structure is presented in Figs. 7 and 8.

Figure 7 Appearance of the exterior concrete surface after restoration

Figure 8 Appearance of protective grille after restoration

6 Conclusions

The concrete technology of half a century ago certainly was not at the present day level. The main difference is insufficient knowledge of possible forms of concrete corrosion, both chemical and physical in nature, because of which considerable damage of concrete occurred and operation of the facility was endangered. There are examples of that period, but unfortunately of the present times, where in choosing the concrete performance designers considered only the static issues, and ignored the service environment conditions.

In December 2000, in Europe the standard EN 206-1 [22] was adopted which envisages minimal concrete class C 25/30 to C 30/37 and the highest water cement factor 0,5 for concretes exposed to long-lasting contact with water – exposure class XC2 and cyclical wetting and drying – exposure class XC4.

As for freezing and thawing classes, XF3 exposure class, the minimum class of C 30/37 and the highest water/cement factor 0,5 are envisaged as well as aeration protection (min. 4 % of trapped air).

As it may be observed in the obtained testing results of the concrete in question, it does not meet the mentioned requirements which resulted in its inevitable degradation in time.

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