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Properties of the thirty years old concrete in unfinished Żarnowiec Nuclear Power Plant

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Abstract

The construction of Żarnowiec Nuclear Power Plant (NPP) facilities was discontinued in 1989, despite the high level of work advancement. Already a large part of the concrete structures was built, now submerged in water from Żarnowieckie Lake. These structures were exposed over 30 years to the environmental conditions (rain, and varying high and low temperatures) without any special maintenance treatment. The technological documentation archives are not available. Experimental testing of specimens drilled out from different concrete structure elements was performed in September 2014.
The goal of the research was the identification of the composition of concrete and its present properties, especially the recognition of the effects of long-term environmental impact. The scope of the research covered macroscopic and microscopic analysis of concrete, compressive strength test, permeability test defined as the rate of chloride ions migration and water absorption. Unfortunately, the most important parts of the concrete structure are not available for testing because they are under water level. The obtained results allowed to classify the concrete structural elements in nuclear power plants buildings as of a quite good quality.

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1. Introduction

The implementation of Polish national nuclear power program started with the construction of the first Nuclear Power Plant (NPP) in Żarnowiec; it also assumed the future construction of a second power plant - "Warta" in Klempicz. NPP in Żarnowiec was under construction from 1982 to 1989, however the construction was cancelled despite a high level of work advancement. According to official statistics, the costs accounted for 40% of the total budget for the construction and commissioning of the power plant. Total 630 objects related to NPP Żarnowiec were built and many structural elements of the plant were manufactured and delivered into the plant, but they were never installed. There were 79 buildings belonging to the power plant and 189 temporary buildings for back-up facilities designed in the plans.

The plant was designed for pressurized water reactors of Soviet design - four reactors WWER-440 W-213 type with a total power of 1860 MW of gross electrical output (4 x 465 MW). The plant was located adjacent to Lake Żarnowieckie which was to be used for cooling. An adjacent pumped-storage hydroelectric plant was supposed to act as a load balancer and energy reservoir to ensure continued power delivery during reactor maintenance. The unfinished structures of reactor buildings, turbine buildings and many auxiliary buildings were left without any maintenance for almost 30 years until now. The remains of abandoned main building of Żarnowiec nuclear power plant are shown in Fig. 1, as seen in September 2014.

Fig. 1. The remains of abandoned concrete structures of Żarnowiec nuclear power plant.

The current energy policy in Poland includes a plan for diversification of electric power sources by introducing nuclear energy, MG.GOV.PL [1]. Therefore several studies are performed in this relation, one of them being a project funded by National Centre for Research and Development on the durability and efficiency of concrete shields against ionizing radiation in nuclear power structures. The project includes, among many other topics, a study of properties of concrete used for the unfinished nuclear power plant in Żarnowiec. The objective of this study is to gain enhanced knowledge of natural aging phenomena in concrete exposed to environmental factors characteristic for northern Poland, near sea area. The durability considerations of concrete for nuclear power structures include effects of both the operational and indicental low-probability loads as well as long term exposure to radiation and to the environment, Brandt [2], Glinicki [3]. To study the effects of long-term environmental impact the investigation employed several techniques for microstructure and transport properties evaluation. Unfortunately, the most important parts of concrete structures were not available for coring and testing because they were under water level.

2. Materials and laboratory test methods

2.1. Materials

The cores specimens were taken using the electric drill with a 100 mm diamond bit, 400 mm in length (Fig. 2). The work was performed according to the safety instructions NCBJ [4], Łuszcz et al. [5]. The core location is indicated on a sketch of buildings of unfinished nuclear power plant (Fig. 3).

Fig. 2. View of specimen coring from concrete containment wall.

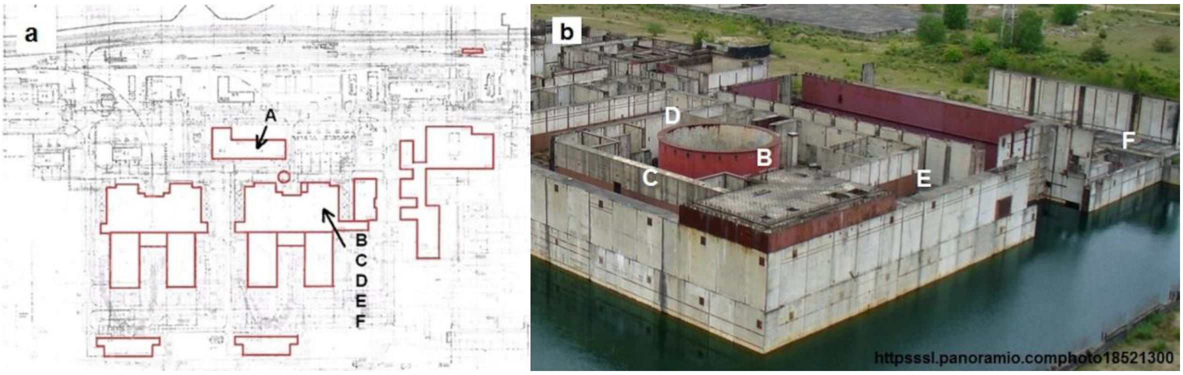

Fig. 3. Sketch of building location of unfinished nuclear power plant (a) and an aerial view of a part of the plant with indication of cored structural elements (b); (A...F – notation of core specimen series).

2.2. Testing methods

Macroscopic observations of concrete polished sections were performed with a naked eye and a measurement grid. The following macroscopic features of concrete sections were determined: the content of coarse aggregate, the uniformity of distribution of coarse aggregate, the content of entrapped air voids visible on the polished sections. Cored concrete specimens were prepared for the strength testing according to PN-EN 12504-1 using a rapid hardening mortar for surface adjustment. The compressive strength of concrete was determined according to the standard procedure PN-EN 12390-3 using Controls 50-C compressive tester.

The chloride penetration was determined with the rapid chloride migration test described in Nordtest Method NT Build 492 [6]. The principle of the test is to subject the concrete to external electrical potential applied across a specimen and to force chloride ions to migrate into it. Cylindrical specimens of diameter 100 mm and 50 mm in height were used. After finishing the ion migration process the specimens were split into two parts in order to determine the depth of chloride ions penetration. For this purpose the concrete section was sprayed with silver nitrate solution (0.1M $AgNO_3$). The conformity criteria for concretes according to Non-Steady State Migration Test are based on the voltage magnitude, temperature of anolite measured on the beginning and end of test and the depth of chloride ions penetration. The non-steady-state migration coefficient, D_{nssm}, is calculated from the Fick's second law. Estimated of the concrete resistance to chloride ions penetration: from very good ($D_{nssm} < 2 \times 10^{-12}$ m^2/s) to unacceptable ($D_{nssm} > 16 \times 10^{-12}\ m^2/s$).

The rate of water absorption was tested in accordance with ASTM C1585 [7]. Concrete discs 50 mm thick and 100 mm diameter were cut from cored specimens and placed in an environmental chamber at temperature of 50°C and RH of 80% for 3 days. Then, each specimen was stored in an individually sealed container for 15 days to attain an equilibrium of internal humidity. The specimens were placed in a pan containing water filled up to 3±1 mm above the top of the supporting device. The mass of the specimens was measured at regular intervals. The initial sorptivity (S_i) was calculated based on mass intake during the first 6 h, and secondary sorptivity (S_s) based on the mass intake in the 24 h to 7 day exposure period. Both S_i and S_s were obtained for all concrete mixtures that were initially cured for 56 or 112 days in saturated curing conditions.

The depth of carbonation front was measured on freshly split surface of concrete prisms. The indicator used in the testing was 1% phenolphthalein solution diluted in 70% ethyl alcohol. The phenolphthalein solution changes its color when pH > 9 and when this solution is sprayed on the concrete a purple-red coloration is obtained almost immediately in the unaffected interior of the sample and no coloration is observed in the outermost surface layer. The depth of the uncolored zone is measured in several locations obtain an average depth of carbonation according to the procedure described in PN-EN 13295 [8].

Evaluation of the concrete microstructure was performed using thin sections prepared from concrete prisms. The fluorescent epoxy impregnated thin sections used for this study were prepared according to Jóźwiak-Niedźwiedzka and Tucholski [9]. The concrete samples were cut in small blocks (40x50 mm) that were vacuum impregnated using a low viscous resin with yellow fluorescent. An object glass was then glued onto the fully impregnated concrete and the concrete slice was ground to thickness of 20-25 μm. The image analysis was performed using optical polarizing microscope Olympus BX51 connected with a digital camera. The thin sections were examined in plane polarized light (PPT), crossed polarized light (XPT), also with lambda plate and UV light.

3. Results and discussion

Macroscopic observations of concrete sections revealed the presence of natural rounded aggregates of inhomogeneous distribution. The presence of special heavy aggregate was not detected. The coarse aggregate content was between 31% (A-1) and 39% (E-1). The entrapped air content was between 0.2% (A-2) and 5.9% (B-2). The pieces of reinforcing bars of 10 mm (A-1, B-6, F-2) or 28 mm in diameter (F-3) were found, as well as organic impurities like wood pieces of 8 to 10 mm in diameter (F-2). A network of cracks was visible on the outer surfaces of concrete specimens, single, isolated cracks were also visible at the cross section.

The apparent density of concrete in the cores was between 2330 and 2430 kg/m^3. The compressive strength results are show in Fig. 4. The compressive strength was mostly higher than 60 MPa, while three cores exhibited even higher strength, above 70 MPa.

Test results of average chloride migration coefficient D_{nssm} are shown in Fig. 5. The criteria of evaluation are also indicated. Using the average value of D_{nssm} the resistance to chloride migration can be categorized as the admissible and inadmissible resistance of concrete. The lowest value of migration coefficient was recorded for concrete in the reactor containment C, E : $D_{nssm} \approx 8{,}6 \times 10^{-12}$ m^2/s, while the highest one $D_{nssm} = 22{,}9 \times 10^{-12}$ m^2/s was found for concrete in the walls of radioactive materials storage vault F.

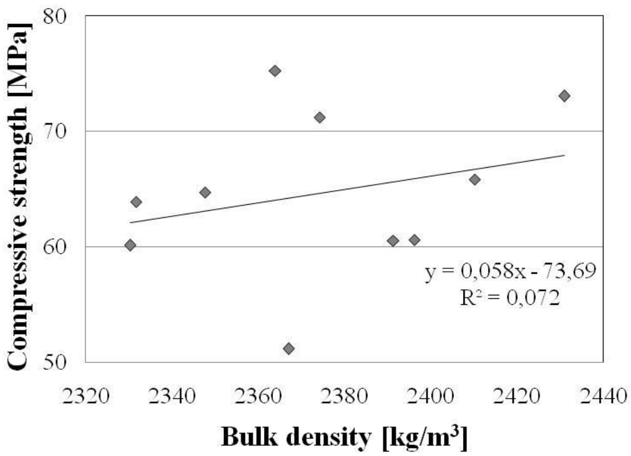

Fig. 4. The compressive strength of concrete cores shown as a function of the apparent density of concrete in cored specimens.

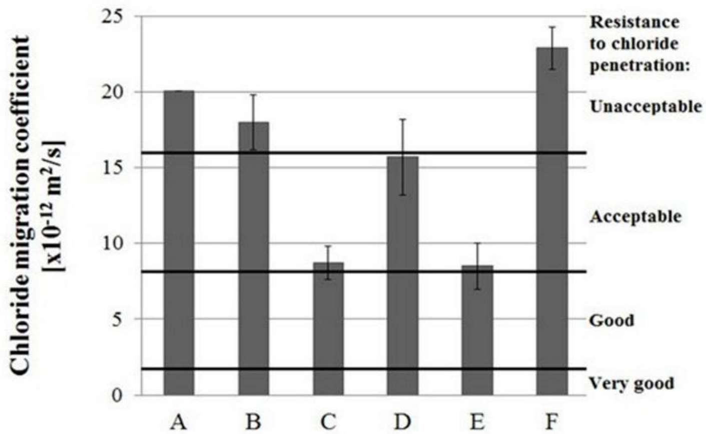

Fig. 5. Chloride migration coefficient D_{nssm} for tested specimens.

Tests of the rate of water absorption by concrete specimens revealed the range 8.9-26.7 x 10^{-4} mm/s$^{1/2}$ and 7.0-21.1 x 10^{-4} mm/s$^{1/2}$ for the initial and the secondary sorptivity, respectively. The scatter of results for the specimens taken from the same element was small. The differences in the rate of water absorption were rather large for the cores taken from different locations. The relative differences were roughly following the differences between the D_{nssm} values shown above.

The depth of carbonated zone measured with the phenolphthalein solution is illustrated in Fig. 6. The depth measurements were taken in five locations along the carbonation front. The average depth of carbonation of concrete in unfinished Żarnowiec NPP was: 10 mm (A-1); 5 mm (B-2); 9 mm (C-2). According to the standard PN-B-03264:2002 the minimum required depth of concrete cover is 20 mm when the exposure to carbonation is considered. Therefore the performance of concrete in the core specimens can be evaluated as very good in respect to carbonation.

Fig. 6. The carbonation depth measured with the phenolphthalein solution: (a) A-1; (b) B-2; (c) C-2 (the scale bar is shown).

Concrete microstructure analysis was performed in the cover layer of 50 mm in depth. Within the coarse natural aggregate grains several minerals could be identified (limestone, quartz and granite, Fig. 6), and the fine aggregate was quartz sand. The observations of the cement matrix did not reveal any mineral additives used; the matrix was homogeneous without visible cracks. Infrequently the relicts of unhydrated cement grains were found, that could indicate a high degree of cement hydration (Fig. 7). The air content in concrete specimens was insignificant, only few empty air voids were detected. Portlandite crystals were distributed over the whole matrix, particularly were observed in the contact zones with aggregate grains (Fig. 7). The zone of CO_2 ingress into the matrix was clearly visible on concrete thin sections observed with optical microscope. The depth of carbonation measured with this technique was about 5 mm (Fig. 8). This was in a good agreement with the results obtained with the phenolphthalein solution.

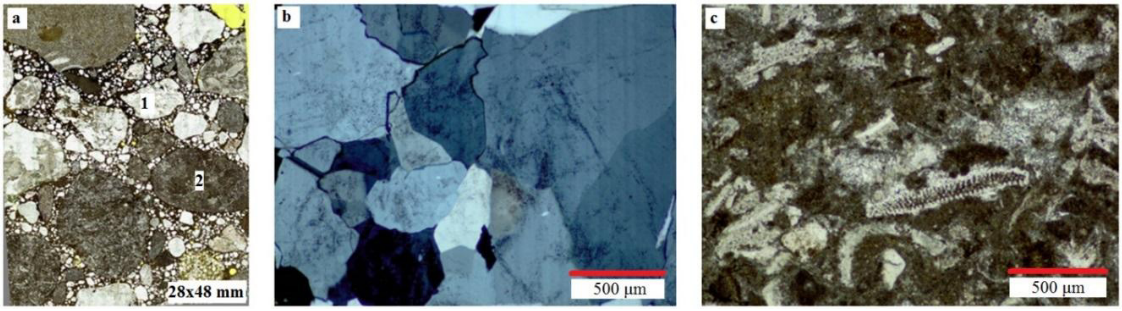

Fig. 7. The view of concrete microstructure visible on a thin section: (a) general view in transmitted light; (b) quartz aggregate „1" (XPL); (c) limestone aggregate „2" (PPL).

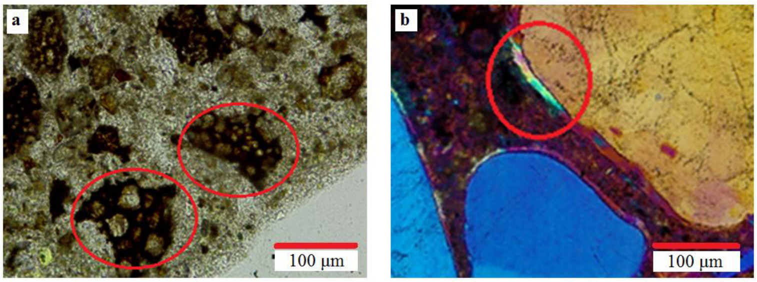

Fig. 8. (a) Relics of unhydrated cement grains, plane polarized light; (b) portlandite in the contact zone between the matrix and the aggregate, crossed polarized light with gypsum plate.

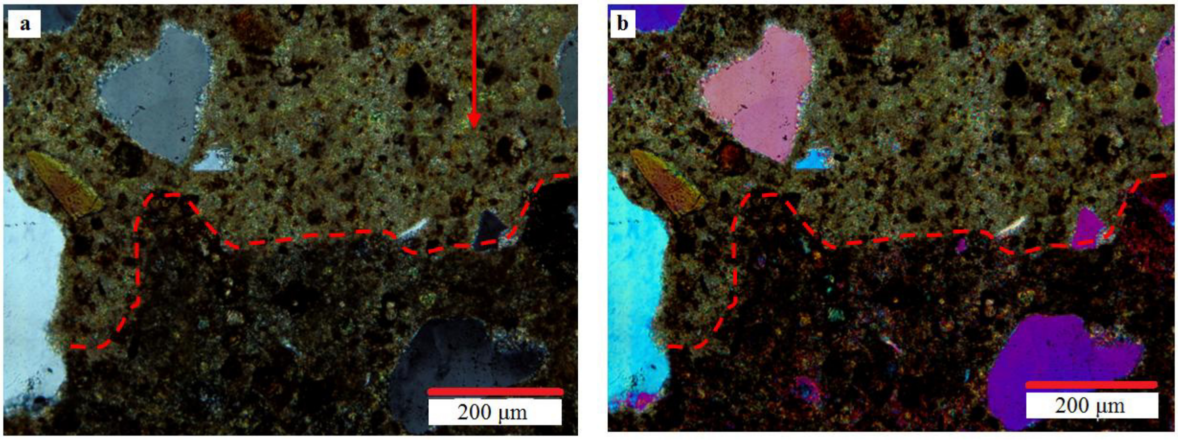

Fig. 9. The boundary of the carbonation front seen in transmitted light: (a) cross-polarized light; (b) cross-polarized light with gypsum plate; the arrow shots the direction of CO_2 ingress.

4. Conclusions

On the basis of performed investigation the following conclusions can be proposed.

The general evaluation of concrete quality in tested structures of unfinished Żarnowiec NPP is quite good. The cored concrete specimens did not contain any special heavyweight aggregates so the bulk density of concrete was from 2330 to 2430 kg/m^3. The compressive strength of concrete was most often above 60 MPa and its dispersion was low. The permeability evaluated using the rate of water absorption and the coefficient of chloride migration showed a large dispersion of concrete quality. The depth of carbonation was low, ranging from 5 to 10 mm after about 30 years of exposure to outdoor climatic factors.

Acknowledgements

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References

[1] MG.GOV.PL. Polish Energy Policy until 2030. http://www.mg.gov.pl/files/upload/8134/Polityka energetyczna ost.pdf, 2009.

[2] Brandt A.M. Application of concrete as a material for anti-radiation shielding – a review. *Cement Wapno Beton* 18, 2, 2013, p.815-822.

[3] Glinicki M.A. Concrete durability indicators for reactor safety structures in nuclear power plants (in Polish), 2015.

[4] NCBJ IBWR 2014.08.29 Sampling of concrete from unfinished Żarnowiec nuclear power plant (in Polish), 2014.

[5] Łuszcz M., Miśta E., Frelek M., Pawlak W., Gryziński M.A., Korab M. Scientific expedition to unfinished Żarnowiec nuclear power plant. NCBJ B-24/2014 (in Polish), 2014.

[6] NT Build 492. Nordtest Method NT Build 492 Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiments, 1999.

[7] ASTM C1585. Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, 2008.

[8] PN-EN 13295. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance to carbonation, 2005.

[9] Jóźwiak-Niedźwiedzka D., Tucholski Z. Reinforced concrete viaduct from beginning of the 20th century – microstructure analysis of 100 years old concrete. *Roads and Bridges - Drogi i Mosty*, 2010, Vol.9, No 3, p. 23-37.