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Condition of reinforced concrete structures and their degradation mechanism at the former Auschwitz concentration and extermination camp

The paper presents the results of investigations on reinforced concrete structures present in the former Auschwitz I and Auschwitz II-Birkenau concentration and extermination camp. Field inspection employing non-destructive method of reinforcement potential measurement according to the ASTM-C 876-15 standard, followed by laboratory investigations performed on genuine historic reinforced concrete samples collected from the former Auschwitz camp allowed assessment of the actual condition of this 70-year old construction material. Electrochemical potential measurements allowed mapping of the regions characterized by enhanced reinforcement corrosion risk and the regions of its immunity. Composition of concrete, water absorbency, content of detrimental salts, degree and profile of carbonation as well as mechanical properties were evaluated. The obtained results revealed the most common and probable mechanism responsible for degradation of the reinforced concrete structures in the former Auschwitz camp.

Keywords: cultural heritage; historic buildings protection; degradation; reinforced concrete; electrochemical potential measurement; physico-chemical and mechanical parameters; mechanism of degradation

Introduction

Background

All over the world, Auschwitz has become a symbol of terror, genocide, and the Holocaust (Bigsby, 2006; Bergen, 2009; Winstone, 2010; Byers, 2014). It was established by the Germans in the 1940s, in the suburbs of Oswiecim, a Polish city that was annexed to the Third Reich by the Nazis (Knowles *et al.*, 2014). The concentration and extermination camp consisted of two parts – Auschwitz I and Auschwitz II-Birkenau. Auschwitz I was established on the grounds and in the buildings of pre-war Polish barracks (originally raised in 1917 but later rebuilt several times, also during World War 2 (Steinbacher, 2013). Auschwitz II-Birkenau was built from scratch from October 1941, but started to operate as extermination camp since 1942. Hence, the structures present in both parts differ in age. The buildings in Auschwitz I were raised by professional building companies from the materials stipulated in the projects, whereas Auschwitz II-Birkenau was built mostly by the camp prisoners during the war, often using random materials available at a given time. Difference in age of the structures, quality of construction materials and quality of workmanship are significant factors discriminating Auschwitz I and Auschwitz II-Birkenau parts of the camp. Therefore, this distinction is important and relevant. In many cases, despite the younger age, Auschwitz II - Birkenau requires more conservation efforts. That is why most of the samples and photos presented here come from this part. The grim landscape of Auschwitz II includes many reinforced concrete structures, including numerous poles of the electric fence (Fig. 1), fence plates, crematoria, gas chambers, barrack foundations, channels of sewage treatment plants or cesspits. Currently, two areas (former Auschwitz I and Auschwitz II-Birkenau) form the Auschwitz-Birkenau State Museum, which is visited annually by about 2.1 million people (in 2017) from all over the world (Memorial Report, 2018). In order to serve its function, the infrastructure should be preserved in as intact state as possible for future generations. Accordingly, there is a need to evaluate the current condition of buildings, ruins and other structural elements of the Auschwitz camp after over 70-year exposure to ambient atmosphere. Such assessment will be a step towards the necessary comprehensive maintenance.

Fig. 1. Landscape of the former Auschwitz II-Birkenau camp with numerous concrete structures including poles of the electric fence and sewage channels.

Current work

This paper reports the results of investigation into concrete and reinforced concrete structures at the former Auschwitz camp. These type of materials were extensively utilized for construction of the former camp's infrastructure including walls and floors of the buildings, fences, pillars, building foundations and many more. The authors performed visual assessment of concrete elements present on the area, carried out electrochemical potential measurements of the reinforcing bars of selected camp structures and collected representative samples for laboratory investigation. Visual evaluation is not sufficient for reliable assessment of the state of reinforced concrete elements. Lack of periodical condition inspection, complex maintenance and restoration procedures contributed to delamination of concrete cover and heavy corrosion of steel reinforcement. Corrosion of the hidden reinforcement is one of the most common causes of concrete structure degradation and failure (Fig. 2). Hence this is what has been concentrated on here.

Fig. 2. Former Auschwitz II-Birkenau camp – example of reinforced concrete pole degradation due to atmospheric exposure for about seven decades.

The reader should note that the work reported here is part of a larger effort to develop a comprehensive conservation and protection programme for the former camp. Previous studies concerned determination of corrosivity of environment and evaluation of the current state of the steel elements (Miszczyk *et al*., 2016a). Moreover, a concept of restoration and preservation of the reinforced concrete poles of fence has already been proposed (Miszczyk *et al*., 2016b).

Concrete testing methods

There are several methods available for testing concrete non-destructively (IAEA, 2002). Electromagnetic methods utilizing eddy current or magnetic induction effects localize and estimate reinforcement size and orientation as well as assess thickness of concrete cover

(Gaydecki *et al*., 2000). Reinforcement depth and concrete flaw depth can be measured with radiographic techniques taking advantage of absorption or scattering of the X or gamma rays (Buyukozturk, 1998). Large voids and delaminations in plate like structures such as pavements or bridge decks are identified with ultrasonic testing (Selleck *et al*., 1998). Infrared thermography utilizing a temperature gradient established in the structure can provide valuable information about internal structure voids, delaminations or concrete layer thickness (Clark *et al*., 2003). Ground penetrating radar is the non-destructive technique capable of detection of delaminations and all types of defects, which can occur in bare or overlaid reinforced concrete decks (Maierhofer, 2003). However useful as the above techniques are the historical and heritage related of the former camp structures calls for a non-destructive testing method with minimum impact upon the integrity of genuine elements and capable of providing information about passive-active corrosion behaviour of the reinforcing steel. Then the repair measures can be taken only where it is necessary due to actively corroding reinforcement. This suggests electrochemical techniques have got to be employed. One such is impedance spectroscopy, successfully employed for evaluation of condition and durability of organic coatings (Miszczyk *et al*., 2007; Szocinski *et al*., 2013). This has also found application in the field of concrete evaluation (Park *et al*., 2006; Poupard *et al*., 2004). This technique allowed description of the state of not only the concrete cover but of the reinforcing steel, too. However, field impedance examinations encounter problems associated with maintenance of electrolytic conditions and noise pickup during the measurement. Hence, it is more frequently employed as a laboratory method for investigation of the concrete specimens collected from field objects. However, this is troublesome in the case of historic and heritage objects where collection of samples should be kept to an absolute minimum. Therefore, the electrochemical potential measurement method has been the method of choice in the studies presented in this paper because it seems to be the most promising as far as evaluation of concrete and reinforcement state in field conditions is concerned.

Electrochemical potential measurements

Theoretical background

Steel in new concrete is normally in a passive state. This means that the steel corrosion rate is very low, in fact practically the steel does not corrode. This phenomenon is related to the formation of a protective iron oxide layer. This takes place in an aqueous medium having a pH between 11 and 14. Such an environment is present in the concrete due to the presence of hydroxides. Concrete pore solution mainly consists of saturated $Ca(OH)_2$ (pH 12.6), but the presence of NaOH and KOH increases the pH to about 13. When concrete is exposed to air, the calcium hydroxide reacts with carbon dioxide in the presence of water in the following reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$

This reaction is called carbonation. The effect of carbonation is to reduce the pH value of the concrete to less than 8.3. This pH is sufficient to make the passive layer on the reinforcement unstable and active corrosion initiates. But this tendency to corrosion is indicated by the potential of the metallic element measured in relation to a reference electrode. Due to the fact that electrochemical corrosion is associated with the moving of the metal to a solution as ions, electrons remaining determine the potential of the metal element. A larger corrosion rate means a larger number of electrons left in the metal and a more negative potential. The dependence of the   voltage on the pH is recognized in , so called, Pourbaix diagrams (Byers, 2014). Fig. 3 shows the simplified Pourbaix diagram for iron. Three areas are present: corrosion, passivity and immunity. Two oblique dotted lines indicate the area of stability of water, outside this area water is decomposed with the liberation of oxygen or hydrogen. The presence of promoters of corrosion in the environment, such as e.g. Cl- ions, change the position of the borders of the corrosion area. Thick arrows mark the carbonation process leading to a gradual reduction of the pH of the concrete environment and a transition from the passive to the corrosion area. This can occur more quickly if the environment contains e.g. Cl- ions. All these processes are reflected in bringing down the potential. Hence, by monitoring the potential changes in time, we can draw a conclusion about corrosion of the reinforcement or lack thereof. Monitoring and inspection of concrete structures with regard to reinforcement corrosion can be performed in combination with other non-destructive techniques, e.g. polarization resistance testing or concrete resistivity testing (Polder *et al*., 2000).

Fig. 3. Simplified Pourbaix diagram for iron with the indicated course of carbonation process (blue thick arrow). SHE – Standard Hydrogen Electrode.

Electrochemical potential measurements are addressed in corresponding standard (ASTM Standard, 1999). It provides detailed description of the measurement preparation and execution. This test method has been extensively used in corrosion risk assessment of various engineering structures (Huang & Yang, 1997; Poupard *et al*., 2006).

Materials and methods

Electrochemical potential measurements

Electrochemical potential measurements were carried out in accordance with the standard mentioned in *Theoretical background* section. The measurement procedure involves utilization of a reference electrode, typically copper-copper sulphate (CSE) electrode, which is placed on the surface of the concrete structure under investigation and connected to the negative (ground) terminal of a voltmeter. The positive terminal of the voltmeter should be connected directly to the reinforcing steel bar. To achieve that one can use a section of exposed reinforcement (which is quite common in case of historical, partially degraded structures) or remove some concrete to expose the reinforcing steel. In order to ensure electrolytic contact between the reference electrode placed on the concrete element surface and the reinforcing steel an electrical junction device was used. It is often a piece of sponge or fabric pre-wetted with low electrical resistance contact solution. In the case of measurements of extremely dry concrete, for instance indoor element examination, there may be a need for pre-wetting of concrete surface. Fig. 4 shows a scheme of reinforcement potential measurement set-up (a), an example of potential measurement execution on the remains of reinforced concrete fence pole (b) and reinforcement corrosion probability criteria (c). The potential measurement has a local character, which means it refers to and describes the condition of concrete-covered reinforcement that is localized underneath the reference electrode placed on the concrete surface (blue region indicated in Fig. 4a). In order to assess the state of the entire element the reference electrode should be transferred to the successive, neighbouring areas on the surface and the measurement procedure is repeated. As a result, one obtains a map of reinforcement potential illustrating the condition of all steel reinforcement embedded in concrete. It can be used for distinguishing between the regions, which call for renovation due to corrosion and the passive areas that do not require any intervention.

Fig. 4. Reinforcement potential measurement: (a) schematic set-up; (b) measurement of reinforcing steel potential on the remains of fence pole: 1 – voltmeter, 2 – copper-copper sulphate reference electrode, 3 – electrical junction fabric, 4 – electrical connection to reinforcement, and (c) reinforcement corrosion probability criteria.

The standard ASTM-C 876-15 distinguishes three potential measurement results:

- if the measured potential (E) is higher than -0.2V vs. CSE, there is a greater than 90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement;
- if -0.35V<E<-0.2V vs. CSE, corrosion activity of the reinforcing steel in that area is uncertain;
- if E<-0.35V vs. CSE, there is a greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement.

The measured value of the reinforcement potential does not depend exclusively on the state of reinforcement. Some contribution can also originate from electric resistance of the concrete cover influenced by numerous factors including porosity, presence of cracks, defects, carbonation progress, sometimes corrosion inhibiting or accelerating chemical compounds formed as a result of interaction with the ambient environment, etc. That is why the corrosion criteria are not fixed values of measured potential; they are represented by ranges of potential corresponding to a certain probability of reinforcing steel corrosion.

Composition of concrete

Investigation of concrete composition with respect to cement and aggregate content was conducted following the procedure presented in Drobiec *et al*., 2010. The samples of concrete were powdered and then immersed in hydrochloric acid diluted in water at a ratio 1:3. After liberation of carbon dioxide the mixture was heated and the acid was added until only aggregate grains remained. Then the solution was decanted and filtered. The filtrate was subjected to action of 50% aqueous sodium hydroxide solution in order to dissolve silica and other components of cement. After rinsing with distilled water and drying at 105°C the samples were weighted and percentage content of aggregate in concrete determined. The remaining part was associated with mass of cement, water and carbon dioxide.

Water absorbency

Water absorbency was evaluated with a gravimetric method. Having determined initial mass of dry samples using the analytical balance Radwag AS 220/C/2 they were immersed in demineralized water. The samples were withdrawn from water and weighted at regular time intervals. The total time of immersion was 24 hours.

Detrimental salts content

The procedure of chloride and sulphate ions concentration measurement involved powdering the samples and immersion in demineralized water at a concrete/water ratio 1:3. The samples of concrete remained in contact with water for 24 hours in order to ensure extraction of the salts from concrete into aqueous phase. After that time the extract was investigated for chloride and sulphate ions content using spectrophotometric method. Concentration of chloride and sulphate ions was determined using Palintest 5000 spectrophotometer.

A core sample was taken from a ceiling of ruins of gas chamber in the former Auschwitz II-Birkenau camp. The length of the sample was 10 cm and its diameter was 7 cm. Then the sample was divided into 5 cylinders of 2 cm height (Fig. 5).

Fig. 5. Cylinder-divided core sample from a ceiling of ruins of gas chamber in the former Auschwitz II-Birkenau camp.

Each cylinder was powdered and immersed in demineralized water at a concrete/water ratio 1:3. The powdered cylinders remained in contact with water for 24 hours. After that time the extract was investigated for chloride and sulphate ions content using spectrophotometric method.

Degree and profile of carbonation

Degree and profile of carbonation of concrete samples was determined using alcohol solution of phenolphthalein. Presence of pink colour indicated regions not subjected to carbonation. Moreover, the extracts from particular cylinders of the core sample from a ceiling of ruins of gas chamber in the Auschwitz II-Birkenau, described in *Detrimental salts content* section, were tested for pH in order to determine the pH depth profile along the core sample and thus depth profile of carbonation process.

Mechanical properties

Three core samples were collected from a ceiling of ruins of gas chamber in the former Auschwitz II-Birkenau camp using the crown drill HILTI DD 200. The samples were subjected to compressive test (using the EDT 1600 pressure testing machine) and bending test (using Fruhling-Michaelis apparatus (Fernea *et al*., 2017)).

Samples subjected to laboratory investigations

Table 1 presents the names (according to nomenclature used in the museum) of investigated samples together with the location of their collection. These elements were subjected to the following tests: composition of concrete, water absorbency, chloride and sulphate ions content.

Table 1. Names of the samples (according to nomenclature used in the museum) subjected to laboratory investigations together with the location of their collection.

Results and discussion

Electrochemical potential measurements

Fig. 6 presents investigation of electrochemical potential of reinforcing steel of a concrete pole of the fence located in a park outside the building of camp commandant in the former Auschwitz I. Potential measurements encompassed the entire height and width of the pole. Successive measurements formed a grid with 20cm spacing between measurements along vertical direction and 15cm spacing along horizontal direction. The grid was chosen in the way providing measurements at the position of reinforcements as well as in the locations where no reinforcement, just concrete was present underneath. Position of the reinforcement was identified prior to the measurements based on visual assessment of damaged bottom part of the pole, where the reinforcement had been revealed. The obtained potential map encompassing the entire pole height and width (Fig. 6a) shows that the reinforcement potential is between 0.206V and -0.312V, which according to the standard means that corrosion activity is uncertain. Generally, lower potential values are recorded along the right edge of the pole suggesting higher likelihood of corrosion. The measurement results are consistent with visual observations performed on site, which revealed no significant degradation of the pole. Only small concrete cracks running from the edge of the pole were detected. They probably resulted from mechanical stresses imposed by winds impacting the fence. However, neither large cracks penetrating the bulk of concrete cover nor any fragments of concrete spalling were noticed, which suggest at most moderate corrosion risk of embedded reinforcing steel.

Fig. 6. Electrochemical potential map (a) and potential measurement execution (b) on reinforced concrete pole of the fence in a park outside the building of Auschwitz camp commandant.

Investigation of electrochemical potential of the reinforcing steel of a concrete floor beam inside the ruins of crematorium no. 2 in the Auschwitz II-Birkenau is illustrated in Fig. 7.

Successive measurements formed a grid with 20cm spacing between measurements along the length of the beam and 15cm spacing along its width. The grid was chosen in the way providing measurements at the position of reinforcements as well as in the locations where no reinforcement, just concrete was present underneath. Position of the reinforcement was identified prior to the measurements based on visual assessment of damaged part of the beam, where the reinforcement had been revealed. The potential map encompassing a section of the beam 160cm x 45cm (Fig. 7a) reveals that the reinforcement potential is between -0.115V and -0.185V. The ASTM-C 876-15 standard classifies such situation as the one in which there is a greater than 90% probability that no reinforcing steel corrosion is occurring in that area at the time of measurement. Indeed, the examined fragment of the beam is characterized by high mechanical integrity, it is free of large cracks, protrusion and spalls. The reason could be that this floor beam is located inside the crematorium ruins (Fig. 7b) and hence it is not directly exposed to atmospheric precipitation. The latter could have contributed to impeding concrete degradation process. Moreover, further studies on depth of carbonation showed that such elements of the crematorium ruins as floors and beams possess a relatively thick layer of concrete cover over the reinforcing steel. Accordingly, the carbonation process has not reached the reinforcement yet, thus maintaining low corrosion risk.

Fig. 7. Electrochemical potential map (a) and potential measurement execution (b) on reinforced concrete floor beam inside the ruins of crematorium no. 2 in the Auschwitz II-Birkenau.

Fig. 8 shows investigation of electrochemical potential of the electric fence pole between the ruins of crematoria nos. 2 and 3 in the Auschwitz II-Birkenau. Potential measurements encompassed the entire height of the pole. Successive measurements formed a grid with 20cm spacing. The obtained potential map (Fig. 8a) shows that the reinforcement potential is between -0.163V and -0.43V. This exemplary pole is presented intentionally to illustrate the reliability of the potential measurement method in evaluation of reinforcing steel condition in concrete. The top and bottom parts of the pole are intact (as seen in Fig. 8b) and concrete cover provides sufficient protection of the reinforcement, which is confirmed by the relatively high potential values, higher than -0.2V vs. CSE. There is partially revealed steel reinforcement in the middle part of the pole, which is perfectly correlated with a gradual decrease in electrochemical potential as one approaches the central part of the pole. The lowest value of potential recorded is -0.43V that is almost 100mV lower than the threshold value regarded by the standard as greater than 90% probability that reinforcing steel corrosion is occurring in that area at the time of measurement.

Fig. 8. Electrochemical potential map (a) of the electric fence pole (b) between the ruins of crematoria nos. 2 and 3 in the Auschwitz II-Birkenau.

Composition of concrete

The investigation revealed that the percentage content of aggregate in concrete by weight is between 60.33% (retaining wall near the ruins of the crematorium no. 3 at the Auschwitz II-Birkenau) and 79.35% (ceiling of the cellar in the A-18 block at the Auschwitz I). A characteristic feature of concrete utilized for building of many elements, including Imhoff tanks, walls and floors of crematoria or firefighting reservoir, is the presence of relatively large amount of aggregate, mainly in the form of cobblestones.

Fig. 9. Percentage content of aggregate in analysed concrete samples.

Water absorbency

Fig. 10 illustrates water absorbency of the collected samples upon 24-hour exposure time in water. The highest absorbency of 12% is exhibited by concrete from the ceiling of the cellar in the A-18 block at Auschwitz I, concrete from Imhoff tank and firefighting reservoir at the Auschwitz II-Birkenau. Nevertheless, the obtained values of absorbency do not exceed the admissible thresholds for the engineering structures, so they do not constitute a risk of accelerated corrosion of the steel reinforcement.

Fig. 10. Percentage change of mass of collected concrete samples as a result of water absorbency upon 24-hour immersion in water.

Detrimental salts content

The presence of chloride ions (Cl^-) and sulphate ions (SO_4^{2-}) in concrete is a factor contributing to corrosion onset of reinforcement steel due to destabilization of the protective passive layer. Accordingly, it is important to determine the content of particular ions as well as their depth profile in order to verify if they impose a hazard to reinforcement passivity. The concentration of chloride ions in the investigated samples is from $7mg/dm^3$ to $68mg/dm^3$ (Fig. 11). These values are relatively low as for instance $800mg/dm^3$ is accepted level of chlorides in fresh concrete (Chloride resistance report, 2009). The origin of these ions could be soil (capillary suction via the pores of concrete cover, especially in the lower parts of structures neighbouring soil), air (chlorides carried by the aerosol, possibly from the Sola River located nearby, and deposited on concrete elements) and batched water (intrinsic content of chlorides in water used for preparation of mortar). A higher content of chlorides was detected in the samples collected in the former Auschwitz I camp, due to the fact that the Auschwitz II-Birkenau is located on open, flat area, where wind and precipitation cause partial removal of chlorides from the concrete material.

Fig. 11. Concentration of chloride ions in analysed concrete samples collected at former Auschwitz I and Auschwitz II-Birkenau camp.

The content of sulphate ions is between 3mg/dm^3 and 200mg/dm^3 (Fig. 12). In this case it is impossible to find any territorial relation either with the Auschwitz I or with the Auschwitz II-Birkenau. The main reason of SO_4^{2-} ions presence is most probably connected with atmospheric pollution due to industrial plants and transportation routes localized nearby. Emission of sulphur oxides to the atmosphere, where they combine with water forming acid is a direct source of sulphate ions. Presence of these acidic species contributes to a decrease in alkalinity of concrete and this enhances the process of carbonation.

Fig. 12. Concentration of sulphate ions in analysed concrete samples.

The results of analysis of depth profile of chloride and sulphate ions concentration are shown in Fig. 13 and Fig. 14, respectively. The chloride content in the cylinders no. 1 and no. 2 corresponding to bottom part of the element, neighbouring with ground (since the sample was taken from ruins of the ceiling of gas chamber, which has been resting on ground for over 70 years) is the highest. It can be associated with water and ions absorption from soil. The upper part of cross-section (the cylinders no. 3, 4, 5) reveal Cl^- ions concentration lower by one order of magnitude. The reason could be the fact that the top surface of the ceiling was covered with insulating layer of roofing paper, which was still present on the preserved ruins of the gas chamber.

Fig. 13. Concentration of chloride ions in particular cylinders of core sample from a ceiling of ruins of gas chamber in the former Auschwitz II-Birkenau camp. Cylinder no. 1 corresponds to the bottom part of sample remaining in contact with soil; cylinder no. 2 is the top one.

The concentration of sulphate ions is approximately constant along the entire depth profile and equal to 3 mg/dm^3. It is suggested that the concentration of both chloride and sulphate is relatively low and does not pose a serious risk to the reinforced concrete elements selected for analysis.

Fig. 14. Concentration of sulphate ions in particular cylinders of core sample from a ceiling of ruins of gas chamber in the former Auschwitz II-Birkenau camp. Cylinder no. 1 corresponds to the bottom part of sample remaining in contact with soil; cylinder no. 2 is the top one.

Degree and profile of carbonation

The degree and depth of carbonation of concrete cover depend on thickness of the element. The samples of bigger dimensions (thickness of concrete cover above 20-25 cm) reveal resistance to carbonation – pH of the aqueous extracts is above 12, which means that passive state of the reinforcement is maintained. Fig. 15 presents depth profile of the pH of the aqueous extracts from the core sample taken from ceiling of ruins of gas chamber. No significant carbonation of thick samples is also confirmed by phenolphthalein test illustrated in Figs 16 and 17. Presence of pink colour is the evidence of lack of carbonation process due to maintenance of sufficiently high pH of concrete.

Fig. 15. pH of aqueous extracts from particular cylinders of core sample from a ceiling of ruins of gas chamber. Cylinder no. 1 corresponds to the bottom part of the sample remaining in contact with soil; cylinder no. 2 is the top one.

Fig. 16. A fragment of a ceiling of ruins of gas chamber subjected to phenolphthalein test. Pink colour in deeper parts of concrete cover is the evidence of lack of carbonation process, also in vicinity of deeper located reinforcing bars.

Fig. 17. A fragment of a ceiling of gas chamber in the former Auschwitz II-Birkenau camp collected from bulk of the billet and subjected to phenolphthalein test. Pink colour is the evidence of lack of carbonation process, also in vicinity of the reinforcing bar.

Elements that are smaller and thinner in cross-section suffer from complete carbonation after 70 years of atmospheric exposure. The phenolphthalein test (Fig. 18) as well as pH of aqueous extracts maintained within the range 8-11 suggest significant carbonation. This does not guarantee a passive state of the reinforcement, contributing to reinforcement corrosion and causing concrete to crack and spall.

Fig. 18. Smaller fragments of a ceiling of ruins of gas chamber subjected to phenolphthalein test. Lack of pink colour is the evidence of complete carbonation of the samples.

Mechanical properties

Condition assessment of any concrete structure requires determination of its mechanical resistance. Tensile and compressive strength are the properties which are most frequently measured. Unfortunately, due to their destructive character, the number of such tests had to be limited due to the historical and cultural heritage nature of the former Auschwitz camp. Tables 2 and 3 present the results of mechanical investigations using compressive and tensile tests of the collected concrete samples.

Table 2. Results of compressive strength investigation.

Table 3. Results of tensile strength investigation.

Based on performed investigations it can be stated that the samples reveal relatively high compressive strength. The value of 30 MPa is accepted as typical for most present engineering structures.

Summary

Overall the most significant hazard to maintenance and preservation of concrete and reinforced concrete structures present on the area of the former Auschwitz camp is the carbonation process, which has now been lasting for over seven decades. Carbon dioxide present in the atmosphere contributes to gradual decrease in alkalinity of the concrete cover according to the reaction described by equation (1). This phenomenon is aggravated by reaction of alkaline hydroxides with sulphur dioxide and trioxide contained in atmosphere and entrained into the concrete cover in the form of sulphates:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O \qquad (2)$$

$$Ca(OH)_2 + SO_3 \rightarrow CaSO_4 + H_2O \qquad (3)$$

The salts formed in these reactions do not exhibit alkaline character, which results in a decrease in pH. As the carbonation front reaches the reinforcement, passive state of it is broken. Loss of passivity is facilitated by chloride and sulphate ions, which were identified in the concrete cover, however, it must be noted that although synergic the impact of the ions is not dominant and decisive in the investigated degradation process. Under these circumstances access of oxygen and moisture causes electrochemical corrosion of steel reinforcement. The resulting corrosion products occupy significantly larger volume than the volume of steel they originated from. The effect is cracking and spalling of concrete cover.

Conclusions

The investigations and analyses performed on concrete and reinforced structures present in the former Auschwitz I and Auschwitz II-Birkenau camp allow for the following conclusions:

- application of the reinforcement electrochemical potential measurement method, following the standard procedure described in ASTM-C 876-91 enables non-destructive evaluation of the condition and corrosion risk assessment of the reinforcing bars in selected reinforced concrete structures,

- the obtained results of electrochemical potential measurements are consistent with the laboratory analysis of the reinforced concrete artefacts, which proves the method reliable and well-suited for non-destructive assessment of historically valuable structures,

- the main hazard is the process of carbonation, a significant number of concrete elements exhibit complete carbonation; in case of reinforced concrete structures it results in corrosion of reinforcement yielding corrosion products, the volume of which is larger than volume of steel they originated from. It causes the concrete to crack and spall,

- the elements of bigger dimensions and thicker concrete cover as well as higher quality of workmanship reveal superior mechanical properties and offer better protection to reinforcement,

- the presence of chloride and sulphate ions has minor impact on concrete durability due to their relatively low concentration,

- the depth of carbonation can reach even 5-10 centimetres down the concrete cover. In less frequent cases, it penetrates the concrete down to a few millimetres.

Having assessed the state of selected reinforced concrete structures and having verified usefulness of electrochemical potential measurement technique in this field, we provided the authorities and services of the Auschwitz-Birkenau State Museum with a tool, which will be used for identification of the structures that need urgent repair. We also carried out parallel studies, in which the concept of restoration and preservation of the reinforced concrete elements was proposed. It included application of cathodic protection and dedicated semi-permeable, impregnating layers. As a result, a comprehensive approach, from identification of the most susceptible elements to elaboration of restoration methods, has been developed.

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References

ASTM Standard C 876-15 Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. 2015. American Society for Testing and Materials, USA.

Bergen, D. L. 2009. *War & Genocide: A Concise History of the Holocaust*. Rowman & Littlefield Publishers.

Bigsby, Ch. 2006. *Remembering and Imaging the Holocaust. The Chain of Memory*. Cambridge University Press.

Buyukozturk, O. 1998. Imaging of concrete structures. *NDT&E International*, 31: 233-243.

Byers, A. 2014. *Auschwitz, Bergen-Belsen, Treblinka. The Holocaust Camps*. Enslow Publishers.

Chloride resistance of concrete. Report. Cement Concrete and Aggregates Australia, 2009, Australia. https://www.ccaa.com.au/iMIS_Prod/CCAA/Publications/Reports/CCAA/Public_Content/LISTS/Reports.aspx?hkey=b463dfb5-ac36-4f10-83bd-85f82f35e9e4 (21.06.2009)

Clark, M. R., McCann, D. M. & Forde, M. C. 2003. Application of infrared thermography to the non-destructive testing of concrete and masonry bridges. *NDT&E International*, 36: 265–275.

Drobiec, Ł., Jasiński, R. & Piekarczyk, A. 2010. *Diagnostics of reinforced concrete structures*, Vol. 1. PWN, Warsaw.

Fernea, R., Tamas-Gavrea, D. R., Manea, D. L., Rosca, I. C., Aciu, C. & Munteanu, C. 2017. Multicriterial analysis of several acoustic absorption building materials based on hemp. *Procedia Engineering*, 181: 1005-1012.

Gaydecki, P., Silva, I., Fernandes, B. T. & Yu, Z. Z. 2000. A portable inductive scanning system for imaging steel-reinforcing bars embedded within concrete. *Sensors and Actuators*, 84: 25–32.

Huang, R. & Yang, C. C. 1997. Condition assessment of reinforced concrete beams relative to reinforcement corrosion. *Cement and Concrete Composites*, 19: 131-137.

IAEA Guidebook on non-destructive testing of concrete structures. 2002., Vienna.

Knowles, A. K., Cole, T. & Giordano, A. 2014. *Geographies of the Holocaust*. Indiana University Press.

Maierhofer, C. 2003. Nondestructive evaluation of concrete infrastructure with ground penetrating radar. *Journal of Materials in Civil Engineering*, 15: 287-297.

Memorial Auschwitz-Birkenau Report. Auschwitz-Birkenau State Museum, Oświęcim, http://www.auschwitz.org/muzeum/aktualnosci/ (03.01.2018)

Miszczyk, A., Szocinski, M. & Darowicki, K. 2007. Interlayer defect evolution in an organic coating system on steel under hydromechanical loading. *Journal of Applied Electrochemistry*, 37: 353-358.

Miszczyk, A., Szocinski, M. & Darowicki, K. 2016 (a) . Corrosivity of environment and the current state of the steel elements at the former Auschwitz concentration camp. *Studies in Conservation*, http://dx.doi.org/10.1080/00393630.2016.1224149.

Miszczyk, A., Szocinski, M. & Darowicki, K. 2016 (b). Restoration and preservation of the reinforced concrete poles of fence at the former Auschwitz concentration and extermination camp. *Case Studies in Construction Materials*, 4: 42–48.

Park, S., Ahmad, S., Yun, C. B. & Roh, Y. 2006. Multiple crack detection of concrete structures using impedance-based structural health monitoring techniques. *Experimental Mechanics*, 46: 609-618.

Polder, P., Andrade, C., Elsener, B., Vennesland, O., Gulikers, J., Weidert, R. & Raupach, M. 2000. RILEM TC 154-EMC: electrochemical techniques for measuring metallic corrosion. Test methods for on site measurement of resistivity of concrete. *Materials and Structures*, 33: 603-611.

Poupard, O., Aıt-Mokhtar, A. & Dumargue, P. 2004. Corrosion by chlorides in reinforced concrete: Determination of chloride concentration threshold by impedance spectroscopy. *Cement and Concrete Research*, 34: 991–1000.

Poupard, O., L'Hostis, V., Catinaud, S. & Petre-Lazar, I. 2006. Corrosion damage diagnosis of a reinforced concrete beam after 40 years natural exposure in marine environment. *Cement and Concrete Research*, 36: 504–520.

Selleck, S. F., Landis, E. N., Peterson, M. L., Shah, S. P. & Achenbach, J. D. 1998. Ultrasonic investigation of concrete with distributed damage. *ACI Materials Journal*, 95: 27-36.

Steinbacher S., *Auschwitz. A history*, HarperCollins e-books 2013 (first published in Germany under title: Auschwitz: Geschichte und Nachgeschichte by Verlag C.H. Beck in 2004).

Szocinski, M., Darowicki, K. & Schaefer, K. 2013. Application of impedance imaging to evaluation of organic coating degradation at a local scale. *Journal of Coatings Technology and Research*, 10: 65-72.

Winstone, M. 2010. *The Holocaust Sites of Europe: A Historical Guide*, I. B. Tauris.

Figure 1

Figure 2

Figure 3

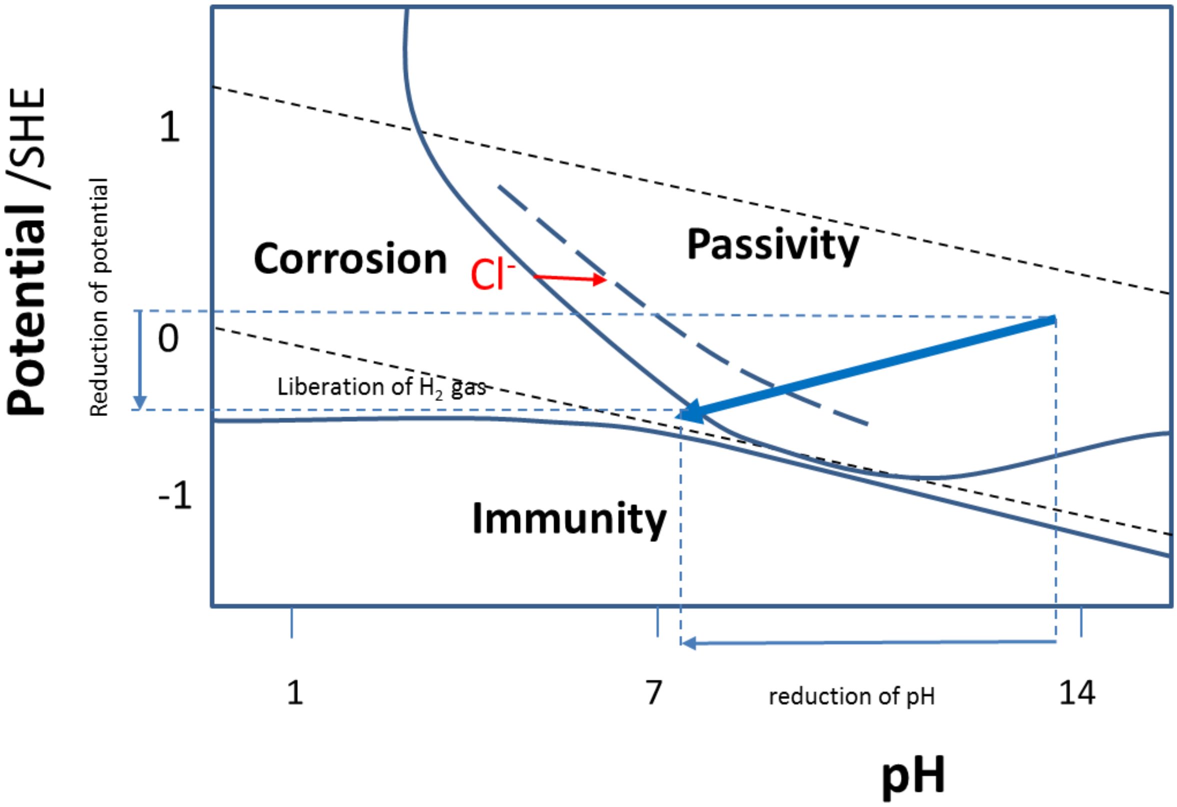
Potential /SHE
Reduction of potential
1
0
-1
Corrosion
Cl⁻
Passivity
Liberation of H_2 gas
Immunity
1
7
reduction of pH
14
pH

Figure 4a

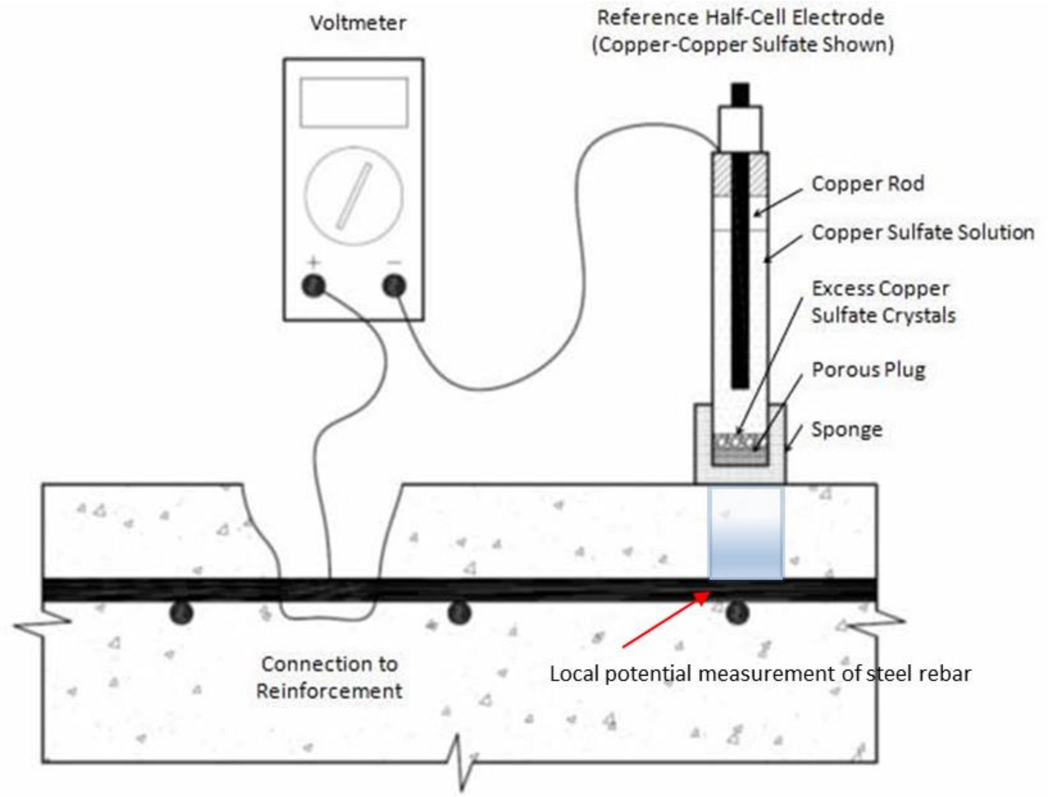
Voltmeter
Reference Half-Cell Electrode
(Copper-Copper Sulfate Shown)
+
−
Copper Rod
Copper Sulfate Solution
Excess Copper
Sulfate Crystals
Porous Plug
Sponge
Connection to
Reinforcement
Local potential measurement of steel rebar

Figure 4b

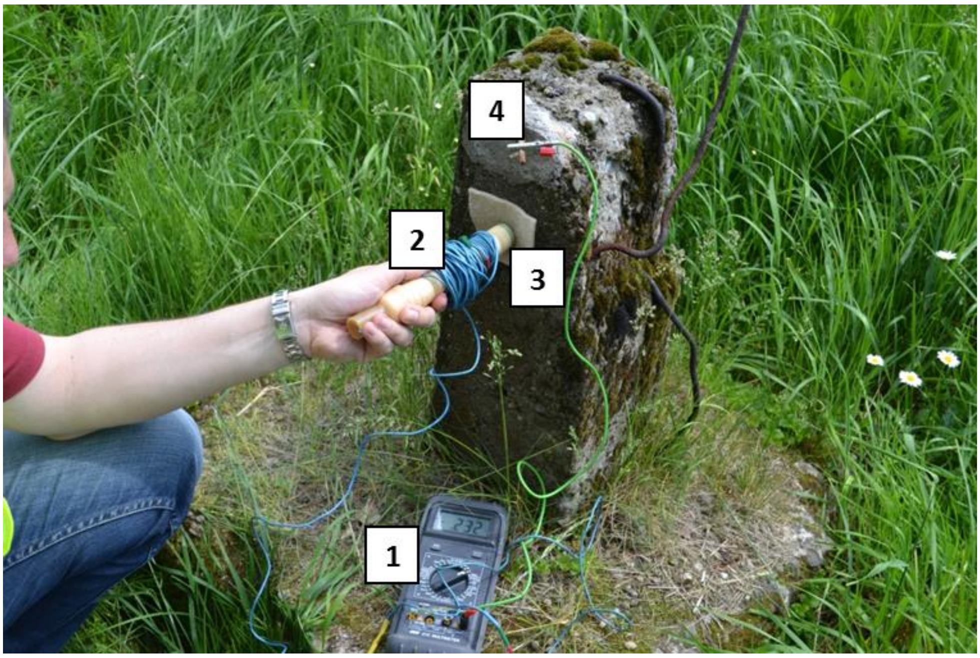

Figure 4c

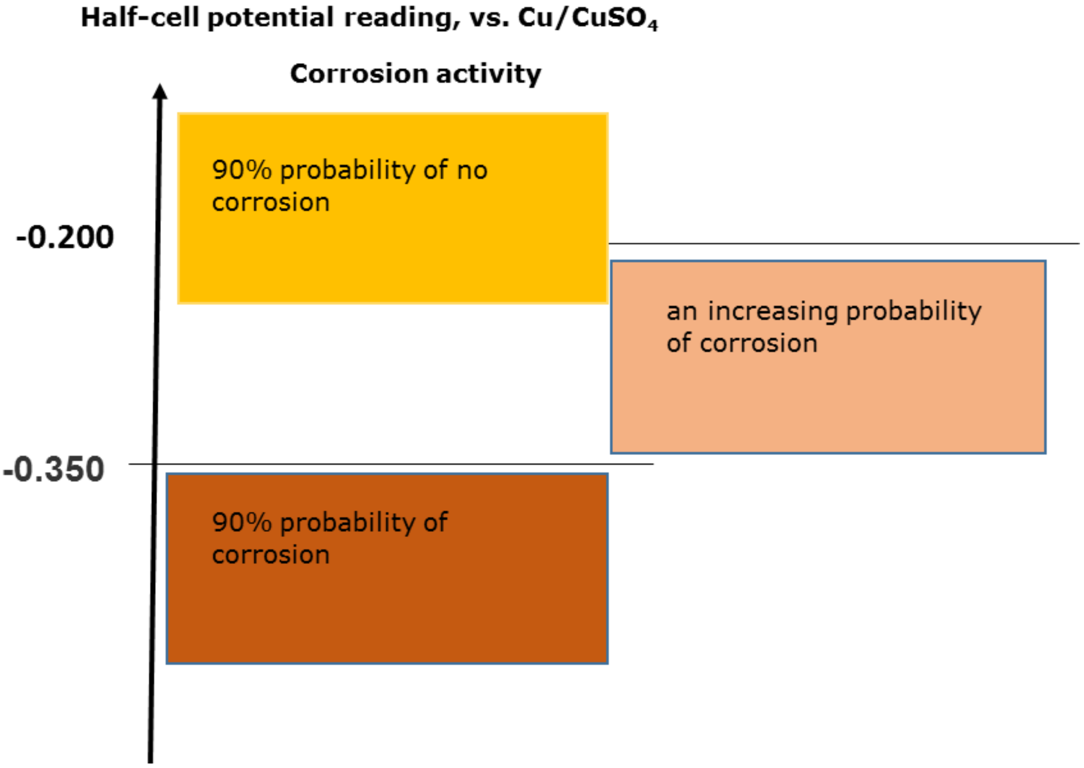
Half-cell potential reading, vs. Cu/CuSO$_4$
Corrosion activity
90% probability of no corrosion
-0.200
an increasing probability of corrosion
-0.350
90% probability of corrosion

Figure 5

Figure 6a

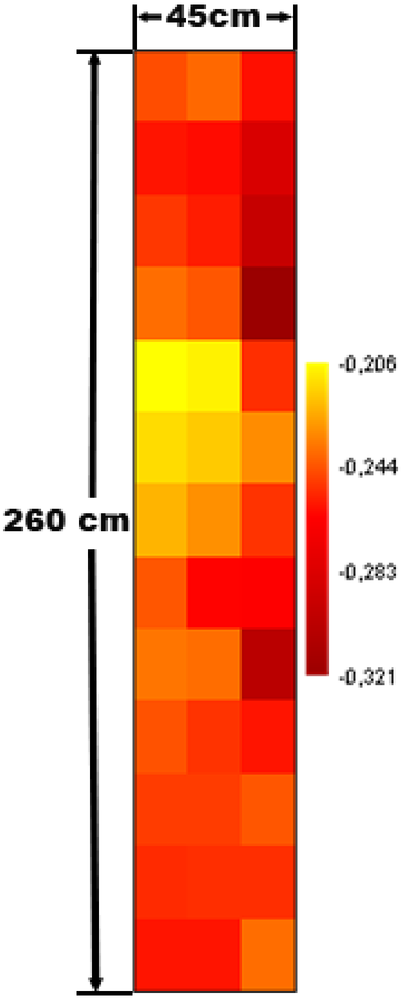

Figure 6b

Figure 7a

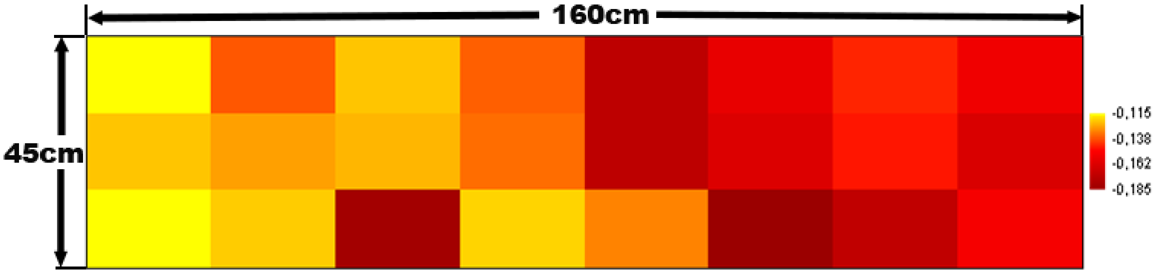

Figure 7b

Figure 8a

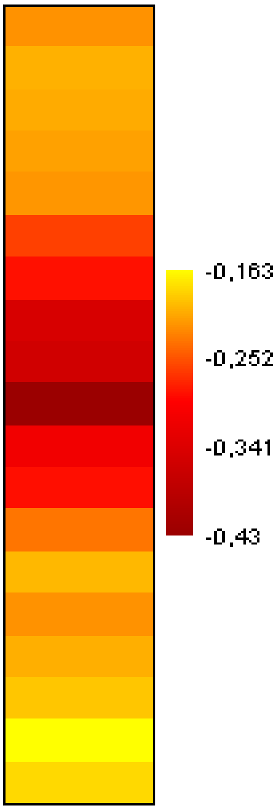

Figure 8b

Figure 9

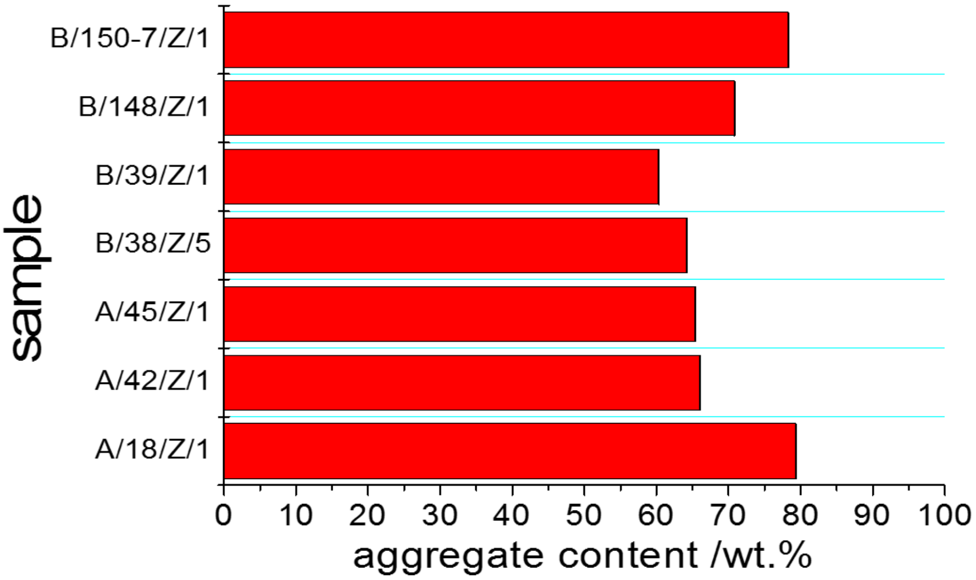
B/150-7/Z/1
B/148/Z/1
B/39/Z/1
B/38/Z/5
A/45/Z/1
A/42/Z/1
A/18/Z/1
sample
0
10
20
30
40
50
60
70
80
90
100
aggregate content /wt.%

Figure 10

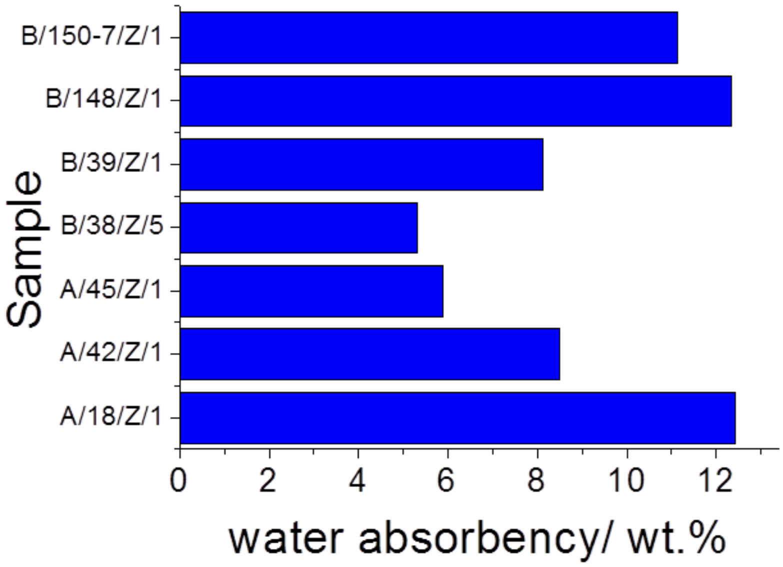
B/150-7/Z/1
B/148/Z/1
B/39/Z/1
B/38/Z/5
A/45/Z/1
A/42/Z/1
A/18/Z/1
Sample
0
2
4
6
8
10
12
water absorbency/ wt.%

Figure 11

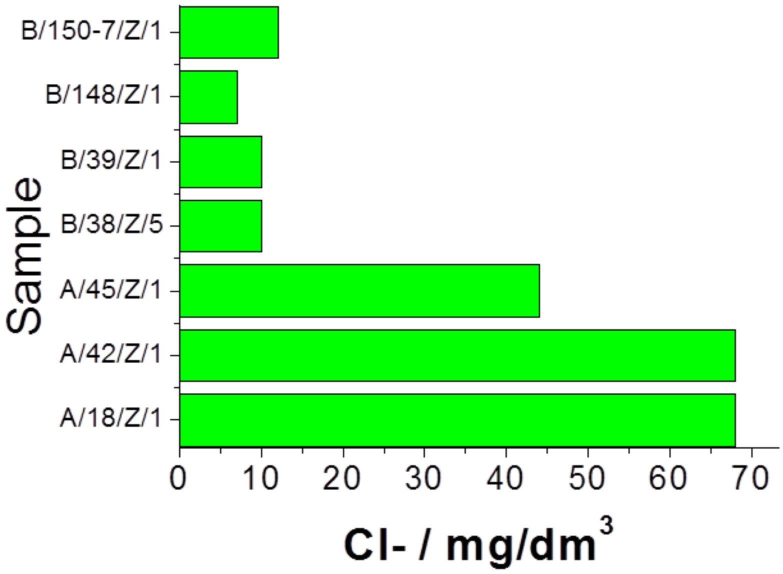
B/150-7/Z/1
B/148/Z/1
B/39/Z/1
B/38/Z/5
A/45/Z/1
A/42/Z/1
A/18/Z/1
Sample
0
10
20
30
40
50
60
70
Cl- / mg/dm3

Figure 12

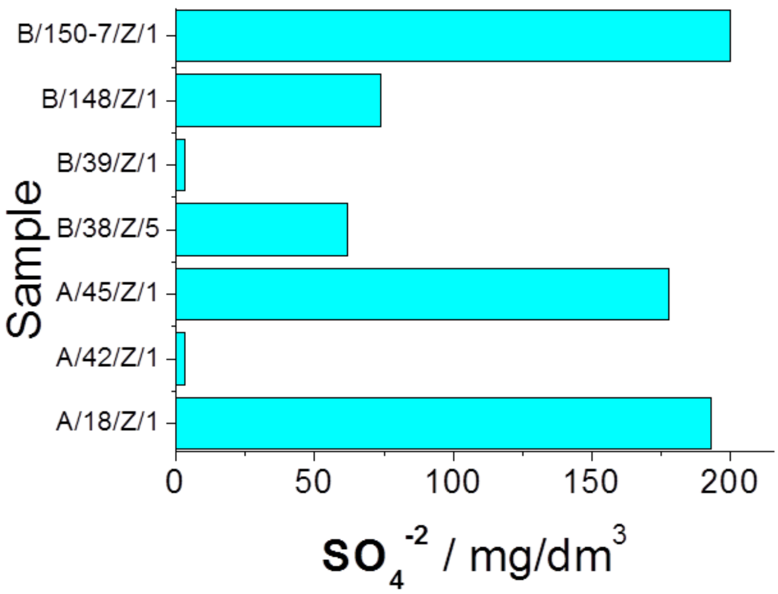
B/150-7/Z/1
B/148/Z/1
B/39/Z/1
B/38/Z/5
A/45/Z/1
A/42/Z/1
A/18/Z/1
Sample
0
50
100
150
200
SO_4^{-2} / mg/dm^3

Figure 13

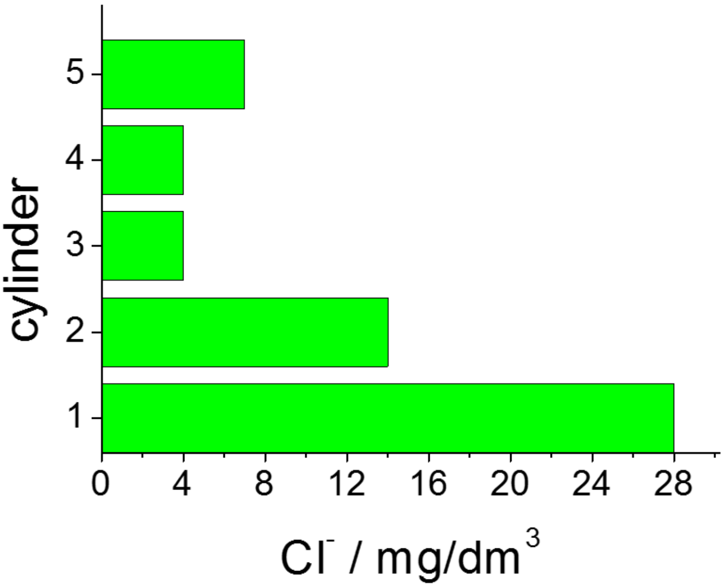

Figure 14

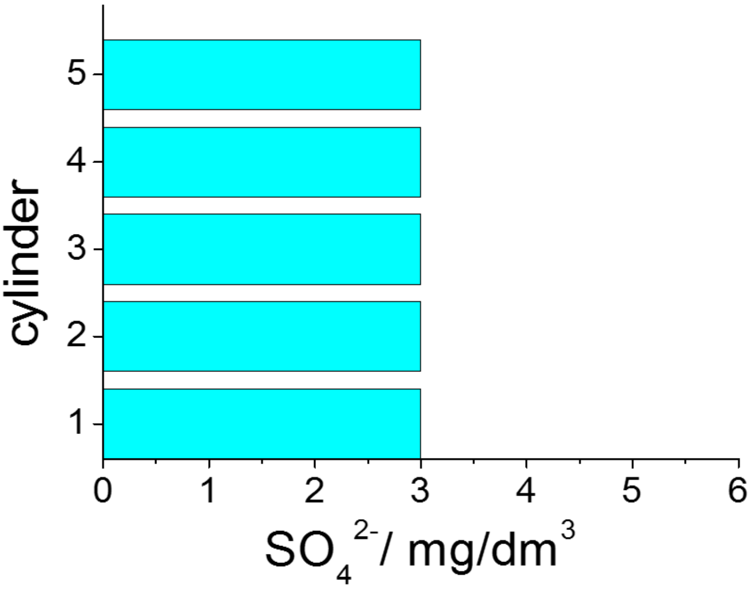

Figure 15

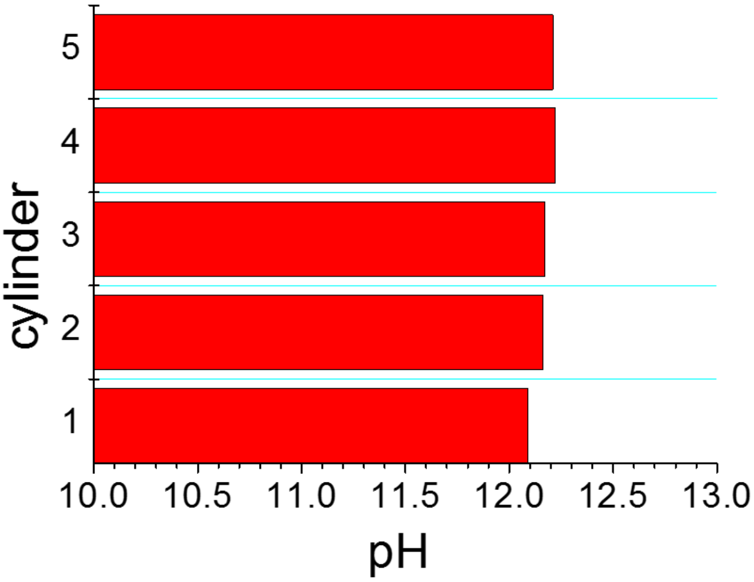

Figure 16

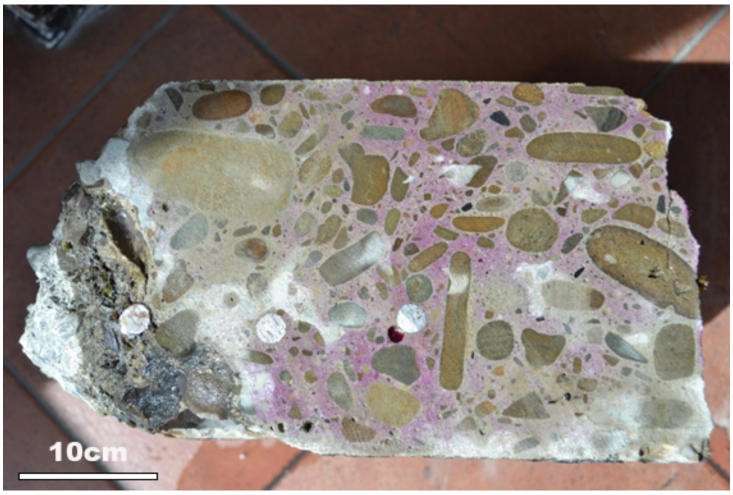

Figure 17

Figure 18

Table 1

No.	Sample name	Location
1	B/150-7/Z/1	External wall of Imhoff tank in the Auschwitz II-Birkenau
2	B/148/Z/1	Firefighting reservoir in the Auschwitz II-Birkenau
3	B/39/Z/1	Retaining wall around the crematorium no. 3 in the Auschwitz II-Birkenau
4	B/38/Z/5	Ceiling of gas chamber from ruins of the crematorium no. 2 in the Auschwitz II-Birkenau
5	A/45/Z/1	Roof above entrance to the A-45 block in the Auschwitz I
6	A/42/Z/1	Pole from fence located in park outside the building of camp commandant in the Auschwitz I.
7	A/18/Z/1	Ceiling of cellar in the A-18 block in the Auschwitz I

Table 2

No.	Sample	F/ kN	Compressive strength / MPa	
			R$_i$ / MPa	**R**$_{av}$ / MPa
1	Floor B/38/Z/5	142	36.9	44.5
2	Floor B/38/Z/5	126	32.8	
3	Floor B/38/Z/5	212	55.1	
4	Floor B/38/Z/5	205	53.3	
5	Fence A/42/Z/1	111	44.4	45.0
6	Fence A/42/Z/1	114	45.6	

Table 3

No.	Sample	Bending strength / MPa
1	Fence (concrete cover of pole) A/42/Z/1	5.2