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THE SUSTAINABLE CONSTRUCTION INDUSTRY VS. THE FINAL PHASE LIFE CYCLE ASSESSMENTS OF THE INTERNAL LAYER OF INDUSTRIAL CHIMNEYS

ZRÓWNOWAŻONE BUDOWNICTWO A KOŃCOWA FAZA CYKLU ŻYCIA WNĘTRZA KOMINÓW PRZEMYSŁOWYCH

A b s t r a c t

The properties of ceramic construction materials used in industrial facilities are constantly changing during the second Life Cycle Assessment (LCA) phase which relates to the accumulation of harmful substances. These materials are scrapped during subsequent maintenance, upgrade or demolition of the facility and their harmful properties may impact entire ecosystems. This means that the final phase of the LCA in such facilities involves waste products that are difficult to reuse or neutralise due to the polluting effect of the harmful substances they contain. This problem with the final phase of an LCA is highlighted by the example of an industrial chimney in Poland with a height of 160 m. During modernisation, after 30 years of service, the chimney was updated by processes that include the exchange of the thermal insulation of mineral wool and the ceramic liner (made of ordinary bricks bound with cement mortar), which were replaced with foam glass and a liner with acid-resistant bricks layed with silicate putty, respectively.

Keywords: *industrial chimney*, *demolition*, *construction waste*, *LCA*

S t r e s z c z e n i e

Na etapie remontu, modernizacji czy też rozbiórki obiektu budowlanego wiele materiałów, z których są wykonane, staje się odpadami niosącymi realne zagrożenia dla środowiska. Jest to związane z procesem akumulacji w drugiej fazie LCA substancji zagrażających środowisku. W artykule wykazano, że w ostatniej fazie cyklu życia obiektu budowlanego powstają odpady trudne zarówno do ponownego wykorzystania, jak i utylizacji, ze względu na stopień zanieczyszczenia substancjami szkodliwymi dla człowieka i ekosystemu.

Słowa kluczowe: *kominy przemysłowe*, *wyburzenie*, *odpady budowlane*, *LCA*

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1. Introduction

Currently, when designing a building or structure, attention needs to be paid to the environmental impact that the construction would have on the site in question; although the primary focus is durability, it is equally as important for an account of the influence construction has on the environment to be included [5, p. 18-21; 17, p. 105-110; 14]. This effect starts early at the stage of selecting and obtaining raw materials, it continues through to the preparation of land, which introduces significant changes to the local ecosystem, and is finally concluded at the time of demolition and the effective utilisation and disposal of waste [1, p. 23-38; 16]. Generally, the disposal of scrap material after demolition has not been taken into consideration in recent years. Primarily, projects have focused on aspects of the bearing capacity and usefulness of the structure, but with time, more attention is also being paid to durability with regards to the environment in which it will be used [7, p. 38-39].

Taking into account the life cycle of the raw materials used in the building process, construction waste can be divided into two categories [21]:

– waste which is created during the production process of the construction work, the production of products or the construction works,
– waste which arises from the demolition of the object.

The discussion below deals with the problems of environmental pollution associated with the second category – that of waste generated during demolition – and will be presented with the selected example of industrial chimneys. This example has been chosen as it represents a type of industrial chimney currently utilised throughout Poland.

Industrial chimneys commonly use a ceramic liner to protect the concrete of the chimney shaft against the effects of aggressive flue gases aiding them in securing a relatively long life [11, 22]. However, as practice shows, a ceramic liner – especially that which is made from ordinary bricks – gradually degrades as a result of the impact of discharged flue gases [8, p. 91-98; 3, p. 55-58; 2, p. 219-220].

These flue gases include: carbon dioxide, sulfur oxides, nitrogen oxides and fluorine oxides. When these components come into contact with water vapor, oxidisation occurs and they transform into sulphates, nitrates and chlorides, respectively. During the transportation of flue gases through the interior of the chimney, a proportion of these compounds penetrates into the porous structure of the ceramic bricks and accumulates within them. Structures implenting binded are also subject to this destructive effect as they often allow for the easy migration of harmful substances into the chimney shaft. After decades of use, it is typical for a significant accumulation of these harmful substances to have occurred. Furthermore, in addition to the fly ash collected by electrostatic precipitators, there is a thick layer of ash that is not captured and builds up on the liner of the chimney. This fly ash is eventually embedded into the liner and this creates the need to replace the lining.

Thus, beyond the economic aspect associated with the cost of replacing the lining and the organisational issues resulting from the need to maintain the continued use of the chimney, there is the additional problem connected with the utilisation or disposal of the demolished ceramic liner.

It should be noted that both brick and ceramic binding materials are at risk of containing compounds that are a direct threat to the environment. During many years of use, and as a result of the impact of discharging flue gases, many substances embed into the porous structure of ceramic bricks, mortar and isolation [9, 12, 15]. In fact, none of these compounds have a neutral effect on the environment – this hinders attempts at finding safe alternatives for waste management. These problems also arise during the demolition of industrial concrete chimney shafts [6]. Figure 1 shows the interior of a chimney, construction waste resulting from the demolition of the structure or its element (removal of the inner layers) and a photo of the demolished chimney.

a) b)

Fig. 1. Construction waste: a) the interior of the chimney, b) the ceramic liner removed from the chimney

After the demolition of the liner, the space unveils (opens) itself, which hitherto was practically closed between the hearth and a chimney liner, which was originally occupied by the thermal insulation. In many cases, when the space of a chimney that has had a long life is examined, the insulation is found to be heavily damaged and filled with precipitates which are the products of the corrosion of the insulation, concrete and ceramic brick [19, p. 378-386]. The occurrence of this type of waste material after the modernisation of the lining or demolition of a chimney liner carries the risk of having a negative impact on the environment. In particular, these compounds contribute to acidification and the salinisation of soil and groundwater, inserting hazardous substances into the ecosystem of plants, animals and humans [13; 18, p. 2032-2040; 23, p. 737-749].

Research findings of examined industrial chimneys indicate that both the ceramic bricks and the binding mortar become contaminated [10]. Evidence for this is understood by changing pH levels and increased levels of sulphate and chloride ions in both of the tested materials. Furthermore, the level of contamination of ceramic bricks, binding material and thermal insulation is significantly different. An analysis of the results carried out by examining 15 chimneys helped to systematise the available information [9]. Due to the different degrees of contamination, the received results are shown in the form of histograms. The frequency distributions of the quantitative contamination of the material were prepared and are presented in Figs. 2–4. Intervals of occurrence were chosen in this way to illustrate the gradual build-up of the content of chlorides and sulphates in the lining materials of the chimney.

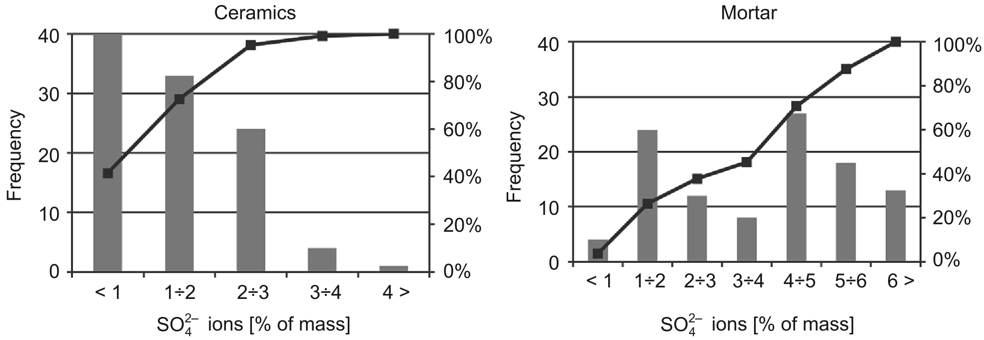

Fig. 2. The frequency distribution of occurrence, defined by intervals, the content of sulphate ions in the ceramics and mortar. Number of samples n = 106

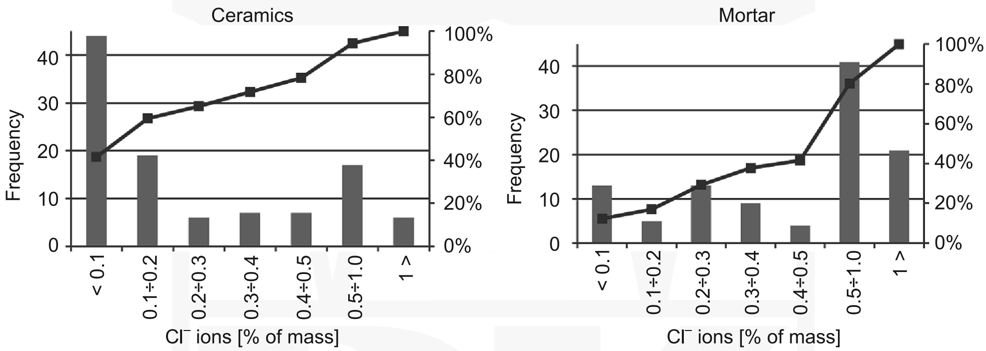

Fig. 3. The frequency distribution of occurrence, defined by intervals, the content of chloride ions in the ceramics and mortar Number of samples n = 106

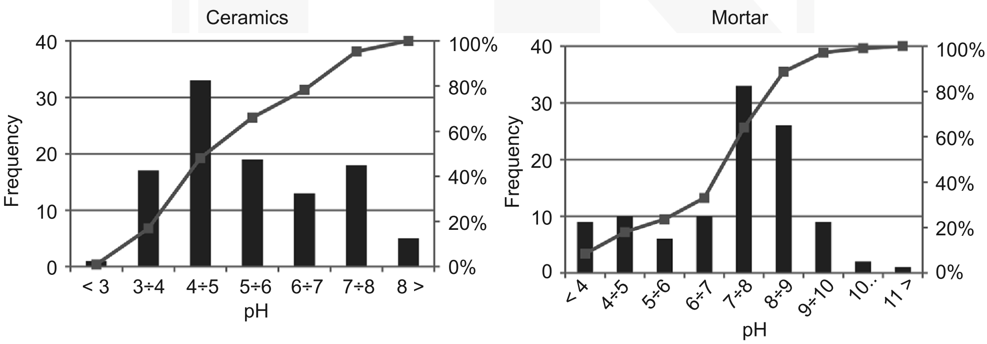

Fig. 4. The frequency distribution of occurrence, defined by intervals of the pH in aqueous extracts of ceramics and mortar. Number of samples n = 106

The data explains that the problem which the accumulation of harmful substances in materials has at the time of partial or complete demolition of an industrial building is the danger that the contaminated waste poses for the environment.

Based on the histograms of frequency of occurrence in the defined ranges of the content of sulphate ions, it was found that in 95% of tested ceramic samples, the content of SO_4^{2-} does not exceed 3%. However, in the mortar, in 62% of tested samples the content of sulphate ions exceeds 3% by weight of the binder. The analysis of histograms concerning the frequency of occurrence of the content of chloride ions shows that among the tested samples of bricks, 63% of them contain occurrence of Cl^- at a level of 0.2% by weight, whereas in the case of mortar, 62% of samples include Cl^- more than 0.3% by weight of binder.

Distribution of values of the pH of ceramics in the analysed chimneys indicates that it has been contaminated by acidic corrosion products (78% had a $pH < 7$). It can be concluded that the porous structure of these materials accumulates a significant amount of aggressive ingredients discharged from flue gases. Similarly, the distribution of the pH of the cement mortar, where cement was mainly used as a binder, indicates that the mortar was significantly contaminated. The dominant pH value is within the range of 7 to 9, which indicates that the accumulation occurs in the binder and, in a sense, neutralisation (inactivation) of the aggressive components of the flue gases discharged through the chimney.

2. Materials

The results of research presented in this article concern a chimney of 160m, in which the scope of modernisation, after 30 years of utilisation, includes the exchange of the exploited thermal insulation of mineral wool and ceramic lining ceramic brick binding with ordinary cement mortar.

This paper deals with free-standing industrial chimneys. Such chimneys are constructed with concrete cores converging towards the top which are protected inside by thermal insulation and a ceramic liner. Figure 5 shows a schematic cross-section of an industrial

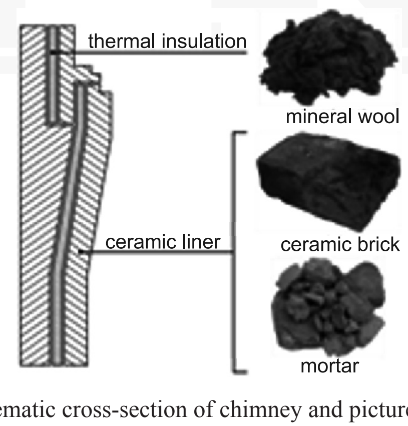

Fig. 5. Schematic cross-section of chimney and pictures of materials

chimney and its materials. Table 1 presents the weight of the ceramic lining removed from the chimney including the mass fraction of ceramic bricks and the binding material and the mass of the thermal insulation which was originally applied.

Table 1

Presentation of the mass of materials inside the chimney

Level [m]	Surface of the linear ceramic [m^2]	Weight mortar [t]	Weight ceramic [t]	Weight thermal insulation [t]
147–157	176	10.0	30.1	3.7
137–147	185	10.6	31.6	3.9
127–137	194	11.0	33.1	4.0
117–127	202	11.5	34.5	4.2
107–117	210	12.0	35.9	4.4
97–107	217	12.4	37.2	4.5
87–97	226	12.9	38.6	4.7
77–87	234	13.3	40.0	4.8
67–77	247	14.1	42.1	5.1
57–67	266	15.1	45.4	5.5
47–57	283	16.1	48.4	5.8
37–47	300	17.1	51.3	6.2
27–37	317	18.1	54.3	6.5
17–27	332	18.9	56.8	6.8
7–17	355	20.2	60.7	7.3
sum	3744	213.3	639.9	77.1

As a result of the demolition of the degraded inner layers of the chimney, 930 tons of construction waste were created, including 640 tons of contaminated ceramic bricks, 213 tons of mortar and 77 tons of damaged mineral wool. Long-term use caused an accumulation of harmful substances to occur in the brick and the binding material. The materials were taken from different heights of the chimney at random so that the results obtained characterised the quantitative state of contamination of the removed inner layers.

3. Methods and apparatus for testing

The aim of this study was to determine the nature of the formed corrosion products and accumulated substances in the removed ceramic lining. Another important element of the research was to carry out a quantitative assessment of substances which are harmful to the environment. A major issue, from the point of view of the environmental impact of the scrap, was to determine the amount of substances that can be easily leached from the structure of tested materials. For this purpose, a ceramic brick and cement mortar were percolated to leach out all the substances from tested materials. The next test was to study the structure of porosity of ceramic bricks and mortar. In order to determine the size of the pores, which is where principal pollutants accumulate, the study was conducted in two stages. The first stage involves the determination of the pore structure of the samples of a contaminated material, while the second stage involves determining the porosity of the samples after leaching (through the percolation process).

3.1. The test apparatus

X-ray studies were conducted in Diffraktometer Philips PW 1050/70 apparatus with X'Pert High Score. For this purpose, the samples were dried and crushed to a grain size less than 0.063 mm. The results were obtained in the form of diffraction patterns together with a description of crystalline phases.

Observations of the microstructure and EDS analysis were conducted with a Zeiss scanning Nova 100 microscope. Tests were carried out on fractures of samples. Photos were taken in the choosen places and an EDS point analysis was performed.

The percolation process was carried out using Soxhlet apparatus. The aim was the leaching out of substances that have accumulated over many years of exploitation of the porous structure of ceramic bricks, cement mortar and thermal insulation. In this way, three aqueous extracts were obtained which have been used in chemical analysis, the sample materials being tested in a mercury porosimeter.

The chemical analysis of the received water extracts (in the percolation process) was carried out with a spectrophotometer V-630. The aim was to determine the content of sulphate and chloride ions and the pH.

The study of the pore structure was carried out in a Quantachrome Poremaster Nova 1000e mercury porosimeter. The study involved samples containing accumulated materials and samples of the same materials after the percolation process (leaching out).

4. Results and analysis

4.1. Results of *X*-ray crystallography

The aim of the *X*-ray crystallography tests was to verify the presence of crystalline phases present in the tested materials, including substances which are corrosive. Table 2 shows the test results of the substances in question and reveals that the contaminants in the brick, binding material and thermal insulation are, for the most part, harmful to the environment [19, p. 378-386; 20, p. 282-284].

Based on the results of *X*-ray crystallography on the waste materials, traces of sulphate compounds, such as gypsum, kaledonit, ferrous sulphate, magnesium sulphate, potassium sulphate, and ettringite and alunogen were identified. Compounds of chlorine and calcium carbonate were also identified. Some compounds are sparingly slightly soluble (gypsum, anhydrite), which will slowly leach out of the material. However, there are also readily soluble compounds which, in contact with moisture or water, will dissolve quickly and easily penetrate into the ecosystem. These include magnesium sulphate or potassium sulphate, for example. These salts are a major threat to the environment and reduce the possibility of utilising the waste.

Table 2

Environmentally hazardous substances identified in the inner layers of industrial chimneys

Materials	Chemical compound	Chemical formula
Ceramic brick	anhydrite gypsum kaledonit ferrous sulphate magnesium sulphate	$CaSO_4$ $CaSO_4 \cdot 2H_2O$ $KAl(SO_4)_2 \cdot 3H_2O$ $FeSO_4$ $MgSO_4$
Cement mortar	anhydrite gypsum calcium chloride potassium sulphate ettringite alunogen ferrous sulphate magnesium sulphate	$CaSO_4$ $CaSO_4(H_2O)_2$ $CaCl_2$ $K_2\ SO_4$ $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32\ H_2O$ $Al_2(SO_4)_3$ $FeSO_4$ $MgSO_4$
Thermal insulation	anhydrite alunogen ferrous sulphate magnesium sulphate hydrate gypsum carbonates, bicarbonates	$CaSO_4$ $[Al(H_2O)_6]_2(SO_4)_3(H_2O)_5$ $FeSO_4,$ $FeSO_4(H_2O)_4$ $MgSO_4(H_2O)$ $CaSO_4(H_2O)_2$ $CaCO_3$, $Ca(HCO_3)_2$

4.2. Results of Microstructural Research

The purpose of microstructural observations and EDS analysis was to identify non--crystalline (amorphous) corrosion products present in the studied materials. By using the EDS probe, a qualitative assessment of the contamination of exploited materials was possible. In representative (characteristic) places scanning photos were taken and EDS

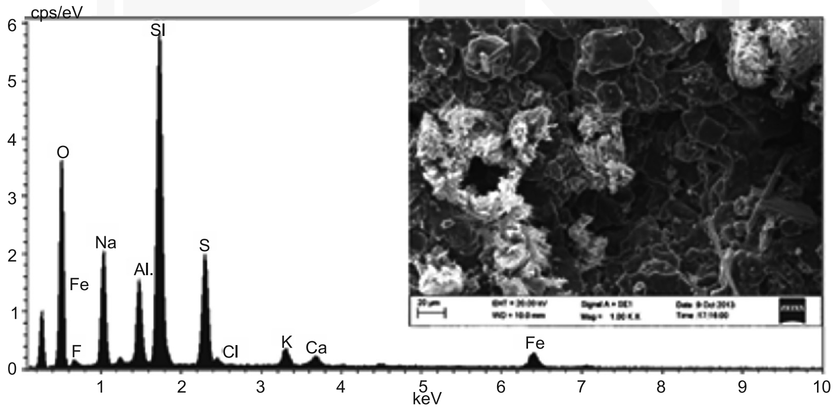

Fig. 6. Microstructure of ceramic brick and EDS analysis of the surface

analysis was performed. Sample images of the microstructure of damaged ceramic bricks, cement mortar and mineral wool observed in the SEM and EDS analysis are shown in Figs. 6–8.

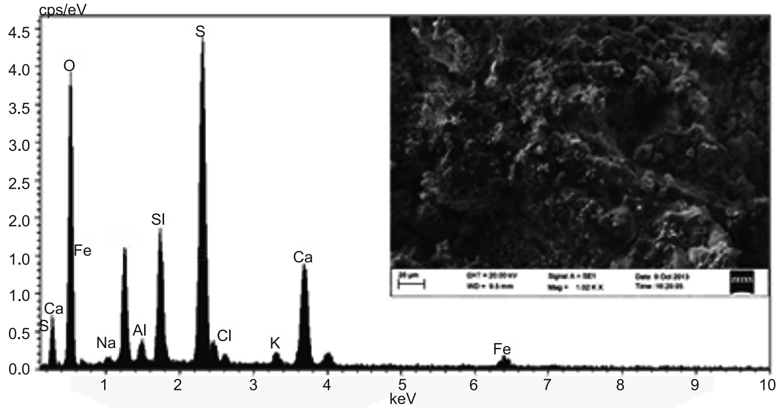

Fig. 7. Microstructure of cement mortar and EDS analysis of the surface

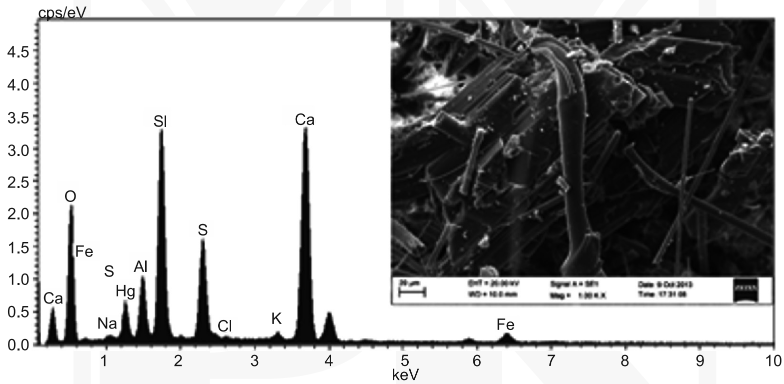

Fig. 8. Microstructure of thermal insulation and EDS analysis of the surface

Microstructural studies confirmed the presence of crystalline phases shown in *X*-ray crystallography studies. In addition, they revealed that the sulphate and chloride ions are incorporated in the form of ions in the structure of the aluminosilicate phases of ceramic bricks and in the CSH phase structure in the cement mortar. In the place of thermal insulation, numerous corrosive products containing sulphate and chloride ions in their compositions, were identified [19].

4.3. Results of quantitative and qualitative analysis

4.3.1. Content of weight of harmful substances

In the process of percolation from test materials, most of the substances which accumulated in the pores of materials were removed. On the basis of mass change before and after the process of percolation, the percentage loss of mass of the tested materials was calculated. The loss of weight obtained in this way stands for a quantitative (mass) content of substances which are a real threat to the environment, as they are leached out from the material when they come into contact with water. These are not permanently associated with any of the tested materials. The results are shown in Table 3.

Table 3

The percentage of soluble substances and the mass accumulated in the ceramic brick, cement mortar and mineral wool

Contamination \ Material	Ceramic brick	Cement mortar	Mineral wool
Amount of waste material	640 tons	213 tons	77 tons
Amount of harmful compounds that are susceptible to leaching	13.4 tons	19.6 tons	4.8 tons
Content of harmful chemical compounds susceptible to leaching	2.1% of mass	9.2% of mass	6.2% of mass

Studies have shown that most of the chemical compounds which are harmful to the environment are located in the cement mortar. Their content equals 19.6 tons. In turn, the content of these substances in ceramic brick is at a level of 13.4 tons. Additionally, in the mineral wool, which contains the smallest amount of this material, there are considerable amounts of harmful substances. This results from the fact that the space between the ceramic lining and the shaft of the chimney makes an ideal location for the accumulation of the components of discharged flue gases. When these compounds come into contact with moisture, it causes a condensation of acidic components from the flue gases to occur. As a result, it induces a strong destruction of the material in places where the so-called corrosive precipitates are formed – its main ingredients are substances considered harmful to the environment. In extreme causes, the spaces between the ceramic liners and the concrete shafts are completely filled with corrosive products.

4.3.2. Quantitative assessment of the content of sulphate and chloride ions

Solutions (extracts) obtained as a result of the percolation of brick, mortar and insulation were subjected to chemical analysis. The degree of contamination by harmful substances differentiated and depended on the material being tested. Respectively, for the ceramic bricks, mortar, and thermal insulation, are at the levels:

– 0.7%, 4.7% and 1% by weight of the material in the case of sulphate ions,
– 0.4%, 1.1% and 1% by weight of the material in the case of chloride ions.

The degree of contamination of the particular ions expressed as a percentage is relatively small, but in relation to the total weight of the liner and the insulation, gives a tremendous amount of sulphates and chlorides, which are observed into the demolished liner and the removed insulation. The results are presented in Table 4.

Table 4

The percentage and the mass of SO_4^{2-} and Cl^- ions in materials removed from the chimney

Harmful substances \ Materials	Ceramic brick	Cement mortar	Mineral wool
Mass of waste materials	640 tons	213 tons	77 tons
Content of ions SO_4^{2-}	0.7% of mass 4.5 tons	4.7% of mass 10.8 tons	1.0% of mass 0.8 tons
Content of ions Cl^-	0.4% of mass 2.6 tons	1.1% of mass 2.5 tons	1.0% of mass 0.8 tons

The ceramic bricks contain 4.5 tons of sulphate ions and 2.6 tons of chloride ions. In total, the bricks contain nearly 7.1 tons of the substances which carry a strong threat to the environment. However, in the mortar there is 10.8 tons of SO_4^{2-} and 2.5 tons of Cl^-, and this adds up to a total of more than 13 tons. The smallest pollution comes from the thermal insulation and is 0.8 tons for both substances. Thus, in the demolished liner and damaged insulation, the total sulphate content is 16.1 tons, while the chlorides measured 5.9 tons. These numbers appear due to the fact that 67% of the sulphates were built up in the mortar, 28% in the brick and 5% in the insulation. However, the chloride ions are in a comparable amount in both the mortar and brick and equal to 42% and 44%, respectively. In turn, the thermal insulation contains 14% of all chlorides. Figure 9 shows the percentage of the content of toxic substances depending on the type of a material.

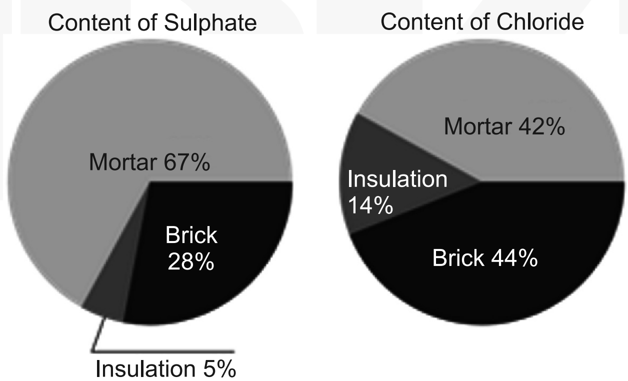

Fig. 9. Percentage of harmful chemical compounds in materials removed from the chimney

Taking into account the percentage of each ion, it was found that the most contaminated material that was removed from the chimney during the repair works is mortar – this contains 67% of sulphate and 42% of all of chloride ions. Although the binding material is almost three times less (by weight) than the brick, it is the greatest source of the pollution of hazardous substances to the environment.

4.4. Research results of the pore structure

One of the main factors determining the corrosive resistance of ceramics is its porosity. The relatively high porosity of the material (such as an ordinary ceramic brick which is more than 30%) makes it accessible to external media (including corrosion), which facilitates the penetration and removal of corrosive products. In addition to the volume fraction of pores, their size and shape are also very important [4, 18]. Additionally, the fact that in traditional ceramics the spaces between grains are filled with corrosive products means that the situation is only aggravated. As a result of the accumulation of harmful substances in the materials of the ceramic liner, evidence suggests that the structure of porosity changes. The purpose of this research was to determine the category of the pores forming a place of accumulation of harmful substances – results are presented below. For this purpose, the mercury porosimetry method was used to determine the porosity structure of contaminated mortar and ceramic brick. Then, using a percolation method, the accumulated substances were removed from test materials and the designation of structure of porosity was re-made. The obtained results are presented in the form of a population curves determined for each test material before and after the leaching process – these are displayed in Fig. 10.

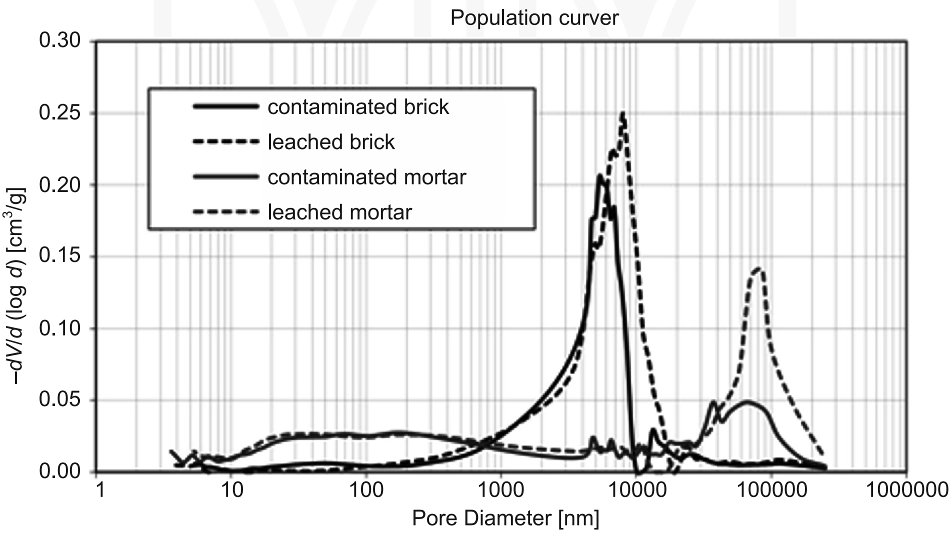

Fig. 10. Population curves of ceramic brick and mortar set before and after the process of percolation

All pores in the tested materials are categorised according to their diameters. This method of presentation of pore structure allows for the specification of the size of the pores which are dominant places for the accumulation of harmful substances in the brick and mortar. Division of the pores into categories according to their diameter are shown in Tables 5 and 6.

Table 5

Categories of pores in the ceramic brick

Ceramic brick	Leached	Contaminated
Total pore volume	0.1391 cm^3/g 100%	0.1104 cm^3/g 100%
Below 100 nm	0.0023 cm^3/g 1.7%	0.0069 cm^3/g 6.3%
100–9000 nm	0.1135 cm^3/g 81.6%	0.0924 cm^3/g 83.7%
9 000–20 000 nm	0.0158 cm^3/g 11.6%	0.0049 cm^3/g 4.5%
Above 20 000 nm	0.0075 cm^3/g 5.4%	0.0062 cm^3/g 5.5%

Table 6

Categories of pores in the cement mortar

Cement mortar	Leached	Contaminated
Total pore volume	0.1310 cm^3/g 100%	0.0971 cm^3/g 100%
Below 100 nm	0.0279 cm^3/g 21.3%	0.0258 cm^3/g 26.5%
100–50 000 nm	0.0578 cm^3/g 44.1%	0.0558 cm^3/g 57.5%
50 000–100 000 nm	0.0388 cm^3/g 29.6%	0.0139 cm^3/g 14.5%
Above 100 000 nm	0.0065 cm^3/g 5%	0.0015 cm^3/g 1.5%

As a result of the accumulation of various substances in the pores of ceramic bricks, porosity of the material has decreased by more than 20%. These changes relate primarily to the pores with diameters ranging from 100 to 100.000 nm. The accumulation of the substance leads to decrease of the pores. Thus, in the structure of ceramic brick, there is a greater quantity of smaller pores in comparison to the pore structure observed in the leached brick.

In the cement mortar, the process of accumulation of pollutant substances is also clearly visible. The porosity of the material at the time of the demolition was over 25% lower in comparison to the porosity of the material after leaching. From among all the categories of pores, the changes pertain primarily to pores having a diameter of 100 to 100 000 nm – this means that the process of accumulation of harmful substances occurs mainly in these pores.

5. Conclusions

As mentioned in the introduction, in the EU report there was a statement that of all the waste generated in the member states, 32% is as a result of activities of the construction and dismantling of buildings. They mainly consist of inert materials such as brick, ceramic tiles, asphalt, concrete, and to a lesser extent, wood, plastics and metals. Although they are characterised by relatively low levels of impact to the environment per unit of weight, construction waste is crucial in terms of waste management.

The results of research on industrial constructions presented in this paper refer to the last phase of the LCA of a building according to EN-15804. They show that the bricks, plastic, cement and mineral wool can be characterised by a high degree of pollution. It significantly hinder the process of utilization and effectively limit the directions of their reuse and disposal.

It should also be noted that demolition, which in this case is that of an industrial chimney, is inevitably associated with the production of large amounts of waste that are not neutral to humans and the environment. Because of this, it is particularly important to the development of an EU-wide market for the recycling of waste in pursuit of a closed loop economy, in which the new European standards for quality grades of recycled materials.

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