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USE OF WASTE IN THE PRODUCTION OF CONCRETE STRUCTURES

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Abstract

The article describes the possibilities of managing and neutralizing industrial and municipal waste in concrete production, recycling, and forming processes. These possibilities relate to the immobilization of contaminants by creating durable systems using hydraulic binders. This is achievable by converting soluble compounds into insoluble forms through the precipitation of salts, oxides, and toxic metals into sparingly soluble hydroxides, sulfides, or phosphates. A classification of concretes according to their potential areas of structural application has been presented. The strength of this material has been defined based on adopted standards, and potential environmental risks associated with its production have been identified. The processes of leaching heavy metals into the environment have also been addressed. Concrete itself may exhibit varying levels of radioactivity. However, appropriate modification of concrete allows for effective containment of hazardous radioactive waste.

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By using fine-grained, inorganic additives such as silica fume, fly ash, ground granulated blast furnace slag or metakaolinite it is possible to improve certain properties of concrete or even obtain special properties. Possible types of municipal waste have been defined, and potential methods of utilizing industrial and municipal waste in concrete production have been presented. The share of recycled substances used during concrete formation has been analysed. Agricultural waste represents a separate waste category with considerable potential for utilization in concrete and cement mortars.

Introduction

The immobilization of various types of waste within cement structures offers an alternative to other methods of disposal and management of numerous problematic industrial and municipal waste products. Diverse analytical methods for building materials are an integral part of research, enabling the monitoring of several crucial parameters, such as the leaching of heavy metals – including Ba, Cd, Cr, Cu, Ni, Pb, Zn, As, Sb, Se, Mo, and Hg – from concrete systems into the environment. The stabilization process of different types of industrial waste is particularly important, especially for waste containing heavy metals that may migrate to water intake sources (Augustyniok et al. 2007, Varinca, Gönüllü 2011, Bajorek et al. 2014, Wichowski et al. 2017).

Modern waste management methods enable the effective immobilization of ashes and slags from waste incineration plants within concrete structures through innovative technologies, including binding technologies and geopolymerization processes. In these processes, binding occurs in highly alkaline aqueous solutions where reactive aluminosilicates dissolve, followed by polycondensation processes that link forming $[SiO_4]_4$ and $[AlO_4]_5$ tetrahedra into amorphous or subcrystalline three-dimensional aluminosilicate structures. This technology can be applied, for instance, to secure landfill sites, where the resulting high resistance to environmental conditions can serve as an effective impermeable and isolating barrier between the waste and the environment (Mikuła et al. 2017).

High temperatures have a minimal effect on the release of heavy metals from concrete into aquatic environments, with chromium being a notable exception, as its leachability increases with temperature. The addition of ashes to cement mortars does not significantly contribute to the migration of heavy metals from concrete structures into the aquatic environment. Research results have demonstrated that, regardless of the type of cement used, the level of heavy metal emissions from concrete into the water environment remains very low (Król, Jagoda 2008, Wichowski et al. 2017).

Construction waste should be utilized as extensively as possible in the production of new products, thus reducing costs and mitigating environmental burdens. Member states of the European Union display varied approaches to the management of municipal solid waste and biowaste. The energetic use of biomass from municipal waste and other alternative fuels in cement production is becoming increasingly significant, as cement manufacturing is the most energy-intensive industrial sector. In Poland, the use of alternative fuels in cement production has exceeded 70%, making Polish cement plants among the most modern in Europe (Król 2006, Kondej 2008, Bieniek et al. 2011, Butmankiewicz et al. 2012, Siemiątkowski 2012, *Guide* *de l'élimination des déchets*... 2012, ZAJĄC, GOŁĘBIOWSKA 2014, KWAŚNIEWSKI et al. 2018, HERNÁNDEZ MORENO, LERMA GÓMEZ 2017, SZCZUCKA-LASOTA et al. 2018, PORANEK et al. 2021).

Concrete offers considerable potential for the incorporation of waste materials (e.g., ashes, silica dust, slag), which can integrally become part of the hardened materials structure. It is possible to obtain a stable final product that undergoes minimal erosion and leaching processes. The construction industry annually consumes approximately 20 billion tons of aggregate, 1.5 billion tons of cement, and 800 million tons of water. Wastes that can be used in concrete production include: car tires, plastics, textiles, wood scraps, sawdust, paper, cardboard, expired fats, used oils and greases, paraffin residues, post-refinery waste, used paints, paint sludge and solvents, dewatered sewage sludge, and combustible materials from the dismantling of scrapped vehicles. Waste management is a civilizational necessity, but it must also be economically viable. The introduction of any new type of waste into the technological process should be preceded by comprehensive and reliable research (BUNDYRA-ORACZ 2008, ULIASZ-BOCHEŃCZYK, MOKRZYCKI 2022).

Types of concrete, its applications and production scale

The general classification of concrete based on the type of binder used includes:
- cement concretes;
- resin concretes;
- asphalt concretes;
- concretes based on other binding materials (e.g., gypsum concretes, sulfur concretes).

Cement concretes are the most commonly used. Their classification criteria include:
- components (aggregate fractions 0/8, 0/16: type of aggregate – gravel or crushed aggregates);
- properties:
  - Density,
  - Strength,
  - frost resistance,
  - water tightness,
  - production and transportation methods;
- applications:
  - bridge concretes,
  - road concretes,
  - hydraulic engineering concretes,
  - flooring concrete.

Concrete is a ubiquitous material, often overlooked and treated as something obvious, perceived as always having been present and expected to remain so in the future. It is widely used in (LATOSIŃSKA, ŻYGADŁO 2007):

– foundations;
– load-bearing walls;
– floors;
– ceilings;
– architectural elements;
– concrete furniture;
– road infrastructure;
– sustainable construction – using concrete with recycled materials helps reduce the consumption of natural resources and CO_2 emissions;
– prefabrication, which allows quality control at every stage of production;
– hydraulic engineering structures;
– artistic projects.

Given this broad range of applications, it follows that concrete is produced in large quantities, and the market is worth several billion zlotys. The production value of concrete in Poland, which has been steadily increasing, is presented in Figure 1 (Spectis 2024). Approximate conversions from PLN to US dollars and euro, in accordance with the exchange rate: 1 PLN ≈ 0.25 USD, 1 PLN ≈ 0.22 EUR, show that in 2011 the value of production amounted to approx. PLN 5 billion, which corresponds to USD 1.25 billion and EUR 1.10 billion. In the years 2012-2015, production remained at a stable level of approx. PLN 5-6 billion (i.e. approx. USD 1.25-1.5 billion and EUR 1.1-1.3 billion). Since 2016, production has increased significantly. In 2017, the value of PLN 7.5 billion was

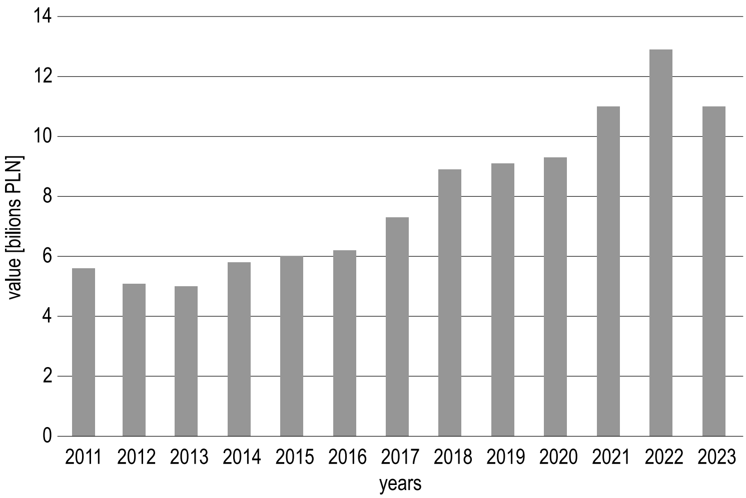

Fig. 1. The concrete products market in Poland in the years 2011-2023
Source: based on Spectis (2024).

exceeded (approx. USD 1.9 billion, EUR 1.65 billion), and in 2018 it reached PLN 9 billion (approx. USD 2.25 billion, EUR 1.98 billion). In 2021, the value increased to PLN 11 billion, which is: USD 2.75 billion and EUR 2.42 billion. The record year was 2022, when the production value reached PLN 13 billion, which is USD 3.25 billion and EUR 2.86 billion. In 2023, a slight decrease was recorded to PLN 11 billion, which is: USD 2.75 billion and EUR 2.42 billion.

Concrete production and its associated environmental risks

The primary parameter characterizing concrete is its strength, which depends on the so-called concrete class. According to Polish standards, the strength of concrete is determined by considering the permissible load on a concrete cube with sides measuring 15 cm. Strength is measured over a period of 28 days, as this is the timeframe during which the concrete undergoes its maturation process. Based on this criterion, various concrete classes are distinguished, for example:

– Concrete class B20 – its minimum strength is maintained at the level of 20 MPa

– Concrete class B25 – its minimum strength is maintained at the level of 25 MPa.

The possible concrete classes according to standards applied in Poland and Europe are presented in Table 1.

Concrete production primarily involves the extraction and use of significant quantities of natural aggregates, water, and the production and application of the necessary amount of cement. Such activities may lead to negative environmental impacts. Consequently, industrial and municipal waste is increasingly being used in concrete production. Examples of such practices include the use of granulated blast furnace slag, fly ash, and silica dust, which are by-products of the metallurgical and energy industries. There are significant concerns regarding the leachability of heavy metals, as well as radioactivity and the environmental impact of these phenomena, since the European standards system does not specify permissible concentrations of heavy metals in concrete (KOHUTEK 2005). Table 2 presents the content of selected heavy metals in concrete components, with particular attention to slag cement and Portland cement. Slag cement is mainly used in foundation works, as well as in hydraulic and underground construction, whereas Portland cement is used to produce concrete for reinforced structures such as ceilings, columns, and lintels (KOHUTEK 2005).

It should be noted that each concrete class has different applications. For example, classes of ready-mix concrete translate into its use for constructing specific structural elements. Concrete classes B10 to B15, corresponding to C8/10 to C12/15 according to European standards, are used for foundations. They are

Table 1

Concrete Classes B According to the Former Polish Standard and the Currently Applicable New European Standard – Concrete Classes C

PN-88/B-06250	PN-EN 206-1
B7.5	–
B10	C8/10
B12.5	–
B15	C12/15
B17.5	–
B20	C16/20
B25	C20/25
B30	C25/30
B35	–
–	C30/37
B40	–
B45	C35/45
B50	C40/50
B55	C45/55
B60	C50/60
–	C55/67
–	C60/75
–	C70/85
–	C80/95
–	C90/105
–	C100/115

Source: based on KOHUTEK (2005).

Table 2

Content of Selected Heavy Metals in Concrete Components

Heavy Metal	Slag Cement – Heavy Metal Content [% by weight]	Portland-Slag Cement – Heavy Metal Content [% by weight]
Nickel	0.00032	0.00035
Cadmium	0.00031	0.0006
Lead	0.0022	0.0044
Chromium	0.0017	0.0030

Source: based on KRÓL (2006).

also employed for ground stabilization or flooring finishes but are not suitable for the construction of structural elements. In contrast, concrete classes from B20 to B30 (C16/20) are ideal construction materials for walls, stairs, and similar elements, while B35 and B40 (C30/37) meet bridge construction standards. However, single-family housing most commonly uses concrete up to class B30. Thus, it can be concluded that each concrete class is used in accordance with its designated purpose specified in the standards. This provides engineers and architects with a wide range of choices to select the best type of concrete for their projects. The European standard recommends applying an appropriate strength reserve for concrete, allowing concrete produced according to the two norms listed in the table to be considered equivalent products. The strength of concrete (as adopted by the standard) refers to its ability (under specified operating conditions) to maintain its properties at an appropriate level for approximately 50 years (BUNDYRA-ORACZ 2008).

Another important parameter is the level of radioactivity of concrete and its components. Using the so-called activity indices *f*1 and *f*2, the content of natural radioactive isotopes present in industrial waste materials used in construction is determined:

– *f*1 – It is a dimensionless index that determines the content of natural radioactive isotopes (considering the concentrations of potassium, radium, and thorium).

– *f*2 – It indicates the content of radium Ra-226; the unit of the index is Bq/kg.

The permissible values of the indices are as follows: $f1 < 1.2$ and for *f*2, the limit value is 240 Bq/kg.

The values of these indices must not exceed 20% of the content of (KRÓL 2006):

– *f*1=1 and *f*2 = 200 Bq/kg – with reference to building materials and raw materials used in concrete production that are applied in structures intended for the occupancy of humans and other living organisms;

– *f*1=2 and *f*2 = 400 Bq/kg – with reference to industrial waste used in construction projects located in built-up areas;

– *f*1 = 3,5 and *f*2 = 1000 Bq/kg – with reference to industrial waste used in the above-ground parts of construction structure,

– *f*1 = 7 and *f*2 = 2000 Bq/kg – with reference to industrial waste used in the underground parts of construction structures.

On the other hand, researchers from the Lodz University of Technology have developed sulfur-organic copolymers that can be used to produce more durable sulfur concretes. The modified concretes will enable the disposal of radioactive waste. The developed technology facilitates better management of waste sulfur, phosphogypsum, and various types of high-tonnage technological waste, such as ashes and slags from combined heat and power plants, rubber recycling products, and biomass. Sulfur, at an appropriately high temperature of 160°C, undergoes spontaneous polymerization; however, such polymer systems are unstable and relatively quickly recrystallize, thereby deteriorating their mechanical properties. To stabilize the polymer structure of sulfur, unsaturated organic compounds can be added to stabilize the resulting copolymer. In the synthesis of sulfur-organic copolymers, alongside the most commonly used dicyclopentadiene, renewable substances of natural origin, such as turpentine, furfural, furfuryl alcohol, or oil obtained from the pyrolysis of waste rubber and polyolefins, can also be used. In polymer concretes with sulfur copolymers as the binder, industrial waste such as phosphogypsum, ashes, and slags from combined heat and power plants can also be incorporated. The proposed sulfur-organic copolymers as binders allow for the production of special concretes, increasing chemical resistance even to seawater, which enables their application, for instance, as quay elements in ports. The developed sulfur concretes create possibilities for the safe disposal of hazardous radioactive waste from nuclear power plants, which can be securely stored in shelters made of sulfur concrete, as radionuclides will not be released from such barrier. The developed technology is currently available on a laboratory scale. Efforts are underway to adapt the production of the developed sulfur concretes to a large industrial scale (*szu/ hgt/.* 2018).

Global concrete production has steadily increased from 3,000 million m^3 in 1990, to 5,000 million m^3 in 2000, and 6,000 million m^3 in 2005. Currently, more than 8,500 million m^3 of concrete are produced worldwide, with Poland accounting for approximately 26 million m^3 annually. It is estimated that around 20,000 people are currently employed in the concrete industry, which includes as many as 600 manufacturers. Thus, the scale is immense. Concrete production from 1930 to 2020 is presented in Figure 2 (Szczucka-Lasota et al. 2018).

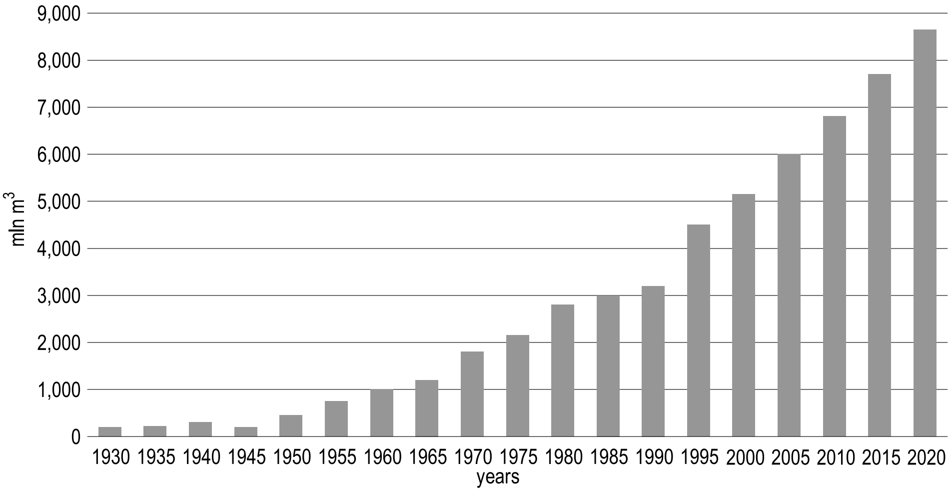

Fig. 2. Global scale of concrete production from 1930 to 2020
Source: based on Szczucka-Lasota et al. (2018).

Management of municipal and industrial waste

Industrial waste is defined as waste generated as a result of economic activity. Consequently, it is often not possible to completely avoid its production. Municipal waste refers to all solid waste and substances, excluding wastewater, that result from human activities in various areas of life, such as households or the service sector. The division of waste into municipal and industrial categories is as follows (KONDEJ 2008):

– Municipal Waste:
  - metals,
  - plastics,
  - textiles,
  - glass,
  - paper,
  - cardboard,
  - cans,
  - used hygiene products,
  - clothing,
  - documents,
  - fertiilizer residues;
– Industrial Waste:
  - mining wastes,
  - metalgical waste,
  - energy sector waste,
  - waste generated at construction sites,
  - waste generated in automative workshop.

In Poland, vast amounts of waste (both municipal and industrial) are generated each year, posing a major problem and challenge for modern civilization. Of the 129 million tons of waste produced in Poland in 2022, over 10% consisted of municipal waste. Among this, nearly 44% of the waste was collected selectively, representing an increase of over 10% compared to the previous year.

The average Polish citizen generates approximately 350 kilograms of waste annually. The amount of municipal and non-municipal waste generated in various years is presented in Figure 3. Municipal waste, compared to other types of waste produced by humans, constitutes a significantly smaller portion of the total annual waste production.

The scale of industrial waste generated in Poland from 2010 to 2023 is presented in Figure 4. Until 2015, the trend in waste generation was increasing. After 2022, it stabilized at a level of 110 million tons annually.

In the interest of environmental protection, proper waste management should be pursued. This can be achieved, for example, through recycling and the neutralization of waste that can be repurposed for other uses. Various types

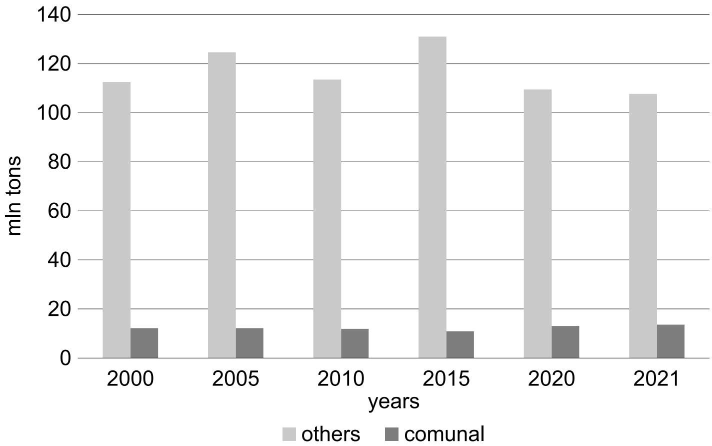

Fig. 3. Structure of waste generated in Poland in million tons in the years 2000-2021
Source: based on *Wytwarzanie odpadów w Polsce* (2023).

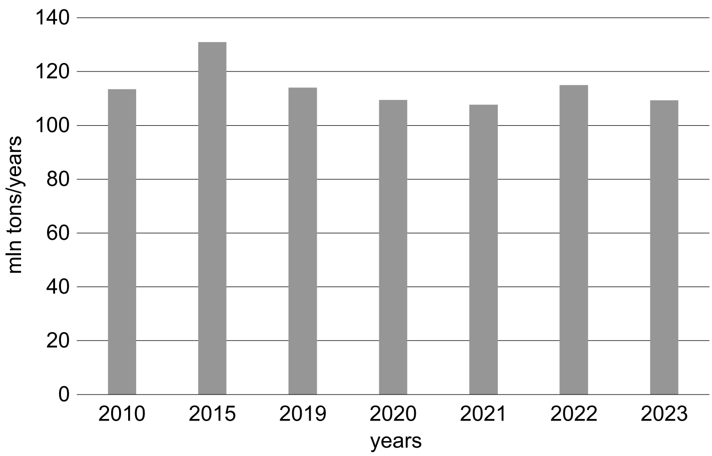

Fig. 4. Industrial waste generated in Poland in the years 2010-2023
Source: based on ZĘBEK (2018).

of waste can be managed in many ways. It should be noted that the concrete industry has been utilizing waste as a raw material for cement production for many years (ULIASZ-BOCHEŃCZYK, MOKRZYCKI 2022). The method of their management depends, among other factors, on the quality of the waste (MICHALSKI 2015). The use of waste in the building materials industry, however, should not (ULIASZ-BOCHEŃCZYK, MOKRZYCKI 2022):

– lower the quality of the manufactured products;
– pose a threat to workers and the natural environment;
– create risks for users of such products.

Areas where industrial waste can be utilized include, for example:

– ceramics – the production of bricks using, among others, sewage sludge derived from municipal wastewater treatment mixed with waste from coke plants, galvanic wastewater, and waste polymers;

– aggregates – the use of municipal sewage sludge for the production of expanded clay aggregate. Sewage sludge, a by-product of wastewater treatment, contains between 30–85% organic matter (in dry mass), which positively affects the increase in the porosity of the expanded clay aggregate. The expanded clay obtained through this method can be used in the production of lightweight concretes. Aggregates can also be produced from construction waste (as so-called recycled aggregates, i.e., processed reinforced concrete rubble, asphalt, brick, or concrete debris). Recycled material has been described as a building material that can substitute for many natural raw materials, such as gravel, limestone, or sand.

– binders, e.g., cement – cement is a building material for which demand increases year by year. Its production requires specific conditions, such as very high temperatures during the manufacturing process. Cement production is linked to the recycling of industrial waste, which can be used as alternative fuels. These wastes include:

- rubber waste (including used tires),
- used oils,
- solvents,
- paints,
- ashes,
- energy slags.

Management of plastic waste

The amount of various types of plastic waste is constantly increasing, leading to a range of ecological and economic problems. This is due to the very low biodegradability of polymer materials. Such waste poses a threat to all components of the environment, including the land, hydrosphere, biosphere, and atmosphere. Proper waste management should be one of the priority directions in the broader field of environmental protection. Research on the management of polymer waste is being conducted at numerous centers and primarily focuses on the following types of plastic waste (GARBACIK, GIERGICZNY 2014):

– ABS plastics;

– polyurethane foams;

– polyethylene;

– polypropylene;

– polystyrene;

– poly(vinyl chloride) (PVC);
– poly(ethylene terephthalate) (PET);
– carpet coverings containing polyamide;
– fibers and powders from used tires;
– shredded electric cables;
– melamine-formaldehyde resins.

The modification of concrete using polymers offers significant possibilities for shaping the properties of the resulting material. Such additives can often improve the physicomechanical properties of concrete. Studies have shown that with an increase in polymer content in concrete, the depth of chloride ion penetration may also decrease, due to the reduction in the volume of large pores in modified mortars. The main disadvantage of these polymer additives is their high cost. Therefore, the possibility of utilizing waste plastics is particularly important. Poly(ethylene terephthalate), abbreviated as PET, is an example of a plastic material that is massively landfilled. It is used in the production of packaging and is characterized by high mechanical strength and resistance to atmospheric factors. It can operate across a wide temperature range from –40°C to 110°C. Due to the short service life of PET bottles, they quickly become problematic waste. Although plastic waste can be incinerated for energy recovery, polymers are too valuable as raw materials to be disposed of in this manner. Thus, the building materials industry presents a promising opportunity for the large-scale management of these wastes. For several years, research has been conducted on the possibility of using PET bottles. Waste PET can be processed into unsaturated polyester resins, which are then used as a binder in the production of polymer concrete. Unsaturated polyesters from waste PET bottles are obtained in two stages. The first involves depolymerization through glycolysis, while the second consists of introducing unsaturated bonds into the main polymer chain via a reaction of the first-stage products with maleic anhydride. Additionally, cut PET bottles, in the form of flakes or fibers, can serve as a valuable composite component in concrete production (WILIŃSKI 2012).

Used rubber tires also represent a significant waste problem. Although they can be partially recycled, they often end up in landfills or, worse, are burned in individual heating sources.

It is possible to replace some of the sand or gravel with ground-up tires. The resulting concrete can even be harder than traditional concrete, because the rubber particles in it allow it to bend under pressure and thus avoid cracking. In 2022, researchers from the Royal Melbourne Institute of Technology (RMIT University) presented a form of concrete in which traditional aggregate was entirely replaced with rubber obtained from tires. The final product demonstrated significant improvements in compressive, flexural, and tensile strength. Importantly, due to the use of rubber, the concrete was considerably lighter than traditional concrete. Additionally, concrete produced using waste personal protective equipment showed noticeable reinforcement of its structure. Medical waste such as gowns, face masks, and rubber gloves, once shredded, was incorporated into concrete in various proportions. Any addition of this type of medical waste to concrete not only did not deteriorate its properties, but even improved the quality of the final product. It was shown that rubber gloves increased compressive strength by 22%, face masks by 17%, and shredded gowns improved compressive strength by 15%, flexibility by 12%, and resistance to bending stresses by 21% (JAKUBIEC 2022).

Management of agricultural waste

In the interest of environmental protection, research over recent decades has focused on finding alternative solutions for cement and aggregates. Various types of geopolymers and lime-clay cements are often used as substitutes for traditional cement. Alternative solutions for mineral building aggregates are also being sought. It is worth noting that the use of agricultural waste as a substitute for building aggregates is currently on the rise. The application of agricultural waste in concrete production can not only enhance the ecological profile of the final product but may also become a necessary solution due to the growing scarcity of natural aggregate resources.

Implementations that use agricultural waste as a replacement for cement, aggregates, or as reinforcement of the cement matrix with plant-derived fibers hold considerable, yet untapped, potential. Ash from agricultural waste is frequently used, as many types of plant waste ash are applied either as a partial substitute for cement or as a filler aimed at improving the performance of cementitious concrete (HORSZCZARUK, OLCZYK 2023).

An interesting idea was proposed by Australian scientists in 2024, who, for the first time in the world, used coffee grounds in concrete production. They demonstrated that replacing up to 15% of the sand, traditionally used in concrete, with coffee grounds resulted in a 30% increase in strength. Organic waste added directly to concrete may decompose over time, weakening the material. Therefore, a low-energy process was developed in which coffee grounds are heated to 350°C without air access to produce biochar. This innovative production method not only reduces reliance on sand, a non-renewable resource, but also decreases the amount of organic waste ending up in landfills, thereby reducing their contribution to greenhouse gas emissions.

This allows the required cement content to be reduced by up to 10% in the final product (*Położono pierwszy na świecie…* 2024).

Management of hazardous industrial waste

One of the methods for neutralizing waste is waste stabilization. The aim of this process is to chemically transform the waste to limit the leaching of harmful substances present as soluble compounds, and, where possible, to alter some physical parameters of the waste to improve its mechanical strength, reduce water absorption, and increase frost resistance. The stabilization process is most often applied to hazardous inorganic waste (or waste containing small amounts of organic compounds) from which soluble chemical compounds of metals, harmful to the environment, are leached. These include slags, ashes, and dusts from thermal processes (such as iron and steel metallurgy, non-ferrous metal metallurgy, waste incineration plants, etc.), industrial dusts and sludges, ashes, dusts and sludges from gas cleaning processes, and waste from galvanic processes. In addition to the applications mentioned above, the effectiveness of physicochemical stabilization has also been extended to waste containing higher amounts of organic compounds (e.g., DOC/RWO), liquid waste, and sewage sludge with a high degree of hydration (63-75%), as well as soils contaminated with petroleum-derived waste and other waste substances (research is ongoing, and the catalog of substances effectively stabilized continues to expand). The hydraulic binder used for stabilization is cement. While appropriately dosed cement can provide the expected mechanical parameters for concrete containing non-standard components (waste), it does not guarantee the prevention of harmful element migration into the environment. Thus, concrete produced with waste where cement alone is the binder remains classified as waste. This situation created a need for research into the use of zeolite-based additives to modify cement, aiming to immobilize elements from waste substances and ultimately achieve full recovery of the waste. This required not only the analysis and selection of waste substances suitable for processing but also modifications to the concrete production technology itself. The work involved adjusting concrete mix formulations, countless modifications and testing of successive concrete mortars, physical property testing of the produced concretes, and leachability studies of elements from concretes incorporating various types of waste. The resulting know-how became the foundation for the zeolite concrete technology.

Ion exchange occurs when an ion (an atom or molecule that has lost or gained an electron, thus acquiring an electric charge) from a substance is exchanged for a similarly charged ion attached to an immobile solid particle. The cation exchange properties of traditional aluminosilicate zeolites result from the isomorphic positioning of aluminum in tetrahedral coordination within their Si/Al structures. This substitution imposes a negative charge on the framework ($Si^{4+} \rightarrow Al^{3+}$), which is balanced by cations held within the cavities and channels. The experience of companies and research institutions in the Netherlands has resulted in a series of patents for formulations that modify Portland cement in such a way that the silicate matrices formed during the hydration process become highly effective in stabilizing soils contaminated mainly with petroleum-based waste, which previously could not be stabilized using cement alone. Thanks to the expertise of Dutch engineers and strong research and development facilities, successes were gradually achieved in modifying cement to alter its stabilizing properties by introducing additives and admixtures (classified according to the proportion of the modifier relative to the mass of cement). According to the PN-EN 206:2014 standard, an additive for concrete is defined as a fine-grained inorganic material used to improve certain properties of concrete or to achieve special properties. Among these are additives exhibiting pozzolanic activity, including silica dust, fly ash, ground granulated blast furnace slag, and metakaolinite. Metakaolinite is an efficient material with pozzolanic activity. It is a mineral produced by calcining natural kaolinite at a temperature of 700-900°C. Kaolinite belongs to the group of layered clay minerals with a two-layer structure. The crystallochemical formula of the kaolinite unit is $Al_4[Si_4O_{10}](OH)_8$, and its structural element consists of a silicon-oxygen tetrahedral layer and an aluminum-oxygen-hydroxyl octahedral layer. Dehydroxylation of kaolinite begins at a temperature of about 550°C, and this process can be described by the following reaction equation (KONKOL, PYRA 2014, PIETRAS et al. 2020):

$$\underset{\text{kalonite}}{AI_2O_3 \cdot 2SiO_2 \cdot 2H_2O} \xrightarrow{\text{in } 500°C} \underset{\text{metakalonite}}{Al_2O_3 \cdot 2SiO_2} + 2H_2O$$

The key properties of metakaolinite proved to be crucial. Among them is its resistance to chloride-induced corrosion (COURARD et al. 2003) and sulfate-induced corrosion (PYTEL 2005). This refers to the positive effect of metakaolinite as an inhibitor of chloride diffusion in mortars. Moreover, it has been proven that the addition of metakaolinite increases the resistance of mortars to the corrosive action of sulfates, particularly $MgSO_4$. Subsequent attempts to modify cement included experiments with natural and synthetic zeolites, which also yielded very good results. Zeolites are a group of aluminosilicate minerals (belonging to the silicate group) with various chemical compositions, properties, and crystal forms. They are hydrated aluminosilicates of sodium and calcium, and to a lesser extent, barium, strontium, potassium, magnesium, and manganese. However, the introduction of zeolites was found to have an additional beneficial effect-heavy metals were permanently immobilized. Demonstrating this property provided the impetus for targeted research into the use of ion exchange to limit the migration of elements derived from waste substances.

A number of reports indicate the possibility of using or disposing of many types of industrial waste. Thanks to appropriate treatment and quality control, tev waste can be safely incorporated into the production of concrete or other building materials. Table 3 provides a list of the most important types of waste, their characteristics and the conditions they must meet in order to be safely managed or disposed of.

Table 3

Waste for management and disposal in cement systems (own work)

Type of waste	Properties and effects on concrete	Stabilization
Ceramics and glass	possibility of replacing natural aggregate, improving thermal insulation	after crushing, they become ceramic aggregate that is easy to manage
Fly ash	the presence of a number of toxic metals	stabilization with Portland cement with pozzolanic additives
Galvanic sludges	hydration disruption, low pH	lowering the pH to neutral, additional complexing with chelating agents
Plastics	poor adhesion, possibility of delamination	as a filler, preferably in small fractions
Tire rubber	increases porosity, compression reduction	stabilization possible in asphalt and lightweight concrete
Contaminated soil (hydrocarbons, metals)	difficult to mix homogeneously, VOC emissions	thermal or chemical cleaning recommended before adding to concrete
Chlorides and sulphates in the rubble	corrosion of reinforcement, weakening of the structure	use of sulphate-resistant cements, recommended addition of corrosion inhibitors
Biological waste	possibility of decomposition, gas emission and loss of concrete integrity	difficult to stabilize, specialist additives (e.g. metakaolin), alternative is biogas plant and composting
Medical waste	variable composition, infectivity, toxicity	Prior chemical or thermal sterilization required
Radioactive waste	radiation emissions and their long-term control	high density barrier concretes, bentonite addition, siarkobeton, wall thickness control

Conclusions

Municipal and industrial waste, generated on a massive scale as a result of human activity, presents a significant problem. These wastes are harmful to the environment; therefore, proper disposal or recycling must be ensured. Cement production alone accounts for approximately 8% of global carbon dioxide emissions, so even minor improvements can help reduce such environmental impacts. The use of waste materials in the production of building materials is becoming increasingly common. Many types of waste can be successfully incorporated into the production of concrete mortars, although this can sometimes lead to a reduction in the mechanical strength of the resulting concrete. Concrete is often used, for example, as a base aggregate in road infrastructure development. The leaching of heavy metals from concretes into aquatic environments is relatively low and should not pose a significant environmental issue. This is mainly due to the alkaline nature of concrete, which causes heavy metals to be bound in the form of insoluble hydroxide and basic salt precipitates, effectively immobilizing and protecting them from leaching. Agricultural production waste, which is a by-product, can also be successfully used in concrete production, offering environmental benefits. The types of agricultural waste used depend on regional availability. Currently, with such a large variety of waste, a given type of waste must be adapted to a specific technology of management in cement systems. This requires strict quality control and compliance with environmental and construction standards. Another important aspect may be the change of hazardous waste status due to immobilization in concrete to the creation of another type of waste, this time to non-hazardous waste. A smaller carbon footprint and a reduction in the problem of waste disposal and storage are undoubtedly the advantages that the creation of unconventional building materials brings. Currently, we have to wait for the popularization of these and other solutions in concrete production technology. In conclusion, the application of concrete for the management of various types of waste can effectively protect the environment from the effects of many harmful substances, and current concrete technologies offer a wide range of opportunities for incorporating waste into building materials.

References

AUGUSTYNIOK B., JAGODA D., KRÓL A., ROSZCZYK-WALCZAK R. 2007. *Release of heavy metals from concrete as a results of impact of high temperature*. Proceedings of ECOpole.

BAJOREK G., KALUKIN B., KIERNA-HNAT M. 2014. *Instrumentalne metody analiz chemicznych materiałów budowlanych w ujęciu normatywnym*. Instytut Śląski, Warszawa–Opole.

BIENIEK J., DOMARADZKA M., PRZYBYSZ K., WOŹNIAKOWSKI W. 2011. *Wykorzystanie paliw alternatywnych na bazie wyselekcjonowanych frakcji odpadów komunalnych i przemysłowych w Cementowni Górażdże*. Acta Agrophysica, 17(2): 277-288.

BUNDYRA-ORACZ G. 2008. *Różnice między PN-88/B-06250 Beton zwykły i PN-EN 206-1:2003 Beton.* Część 1. *Wymagania, właściwości, produkcja i zgodność*. Prace Instytutu Techniki Budowlanej, 2(146): 3-26.

BUTMANKIEWICZ T., DZIUGAN P., KANTOREK M., KARCZ H., WIERZBICKI K. 2012. *Thermal disposal of municipal waste on a grid-is it a proper technology?* Archives of Waste Management and Environmental Protection, 14(2): 13-28.

COURARD L., DARIMONT A., SCHOUTERDEN M., FERAUCHE F., WILLEM X., DEGEIMBRE R. 2003. *Durability of mortars modified with metakaolin*. Cement and Concrete Research, 33: 1473-1479.

GARBACIK A., GIERGICZNY Z. 2014. *Cementy specjalne – nowe kryteria klasyfikacji, wymagań i oceny zgodności*. Przegląd Budowlany, 85(5): 28-30.

Guide de l'élimination des déchets de chantier vers les filières de traitement recommandations à destination des professionnels. 2012. Travail collectif. Niort.

HERNÁNDEZ MORENO A., LERMA GÓMEZ A. 2017. *Documento No6: Gestion de residuos (proyecto de trazado y construcción: mejora de enlace en la carretera n-340. tramo: pk 1+081,5. t.m. amposta clave: 31-t-3840 documento n o 6).* Ministerio de Fomento, Madrit.

HORSZCZARUK E., OLCZYK N. 2023. *Możliwości wykorzystania odpadów z produkcji rolniczej jako składników betonu*. Konferencja „Dni betonu", 9-11 października 2023, Wisła.
JAKUBIEC M. 2022. *Beton ze starych opon i zużytych maseczek – odpady jako składnik betonu*. Termomodernizacja. Retrieved from https://termomodernizacja.pl/beton-ze-starych-opony-i-zuzytych-maseczek-odpady-jako-skladnik-betonu/ (22.04.2025).
KOHUTEK Z.B. 2005. *Norma PN-EN 2006-1 – nowy wymiar jakości betonu*. Górnictwo i Geoinżynieria, 29(3/1): 265-274.
KONDEJ D. 2008. *Odpady komunalne i przemysłowe – charakterystyka, zagrożenia*. Bezpieczeństwo Pracy: Nauka i Praktyka, 1: 16-19.
KONKOL J., PYRA M. 2014. *Wybrane właściwości betonów modyfikowanych zmiennym udziałem dodatku metakaolinitu*. Journal of Civil Engineering, Environment and Architecture JCEEA, 61(31): 287-296. https://doi.org/10.7862/rb.2014.95
KRÓL A. 2006. *Beton i jego składniki w aspekcie wymagań środowiskowych*. Budownictwo, Technologia, Architektura, 1: 53-56.
KRÓL A., JAGODA D. 2008. *Metody oceny oddziaływania betonu na środowisko*. Konferencja „Dni betonu", 13-15 października, Wisła.
KWAŚNIEWSKI K., GRZESIAK P., KAPŁAN R. 2018. *Ocena efektywności ekonomicznej procesu zgazowania odpadów komunalnych i przemysłowych*. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi Polskiej Akademii Nauk, 107: 5-18. https://doi.org/10.24425/123722
LATOSIŃSKA J., ŻYGADŁO M. 2007. *Gospodarka odpadami a produkcja materiałów budowlanych*. Materiały Międzynarodowego Forum Gospodarki Odpadami „Efektywne zarządzanie gospodarką odpadami", p. 563-572. Kalisz-Poznań.
MICHALSKI W. 2015. *Szkodliwe reakcje zachodzące w betonie*. Drogownictwo, 7: 215-223.
MIKUŁA J., ŁACH M., MIERZWIŃSKI D. 2017. *Utilization methods of slags and ash from waste incineration plants*. Ecological Engineering & Environmental Technology (EEET), 18(3): 37-46. https://doi.org/10.12912/23920629/68331
PIETRAS M., ISKRA-KOZAK W., KONKOL J. 2020. *Wykorzystanie zeolitów naturalnych jako dodatku do zapraw i betonu*. Izolacje, 7/8: 50-53.
Położono pierwszy na świecie „beton kawowy". 2024. MM Magazyn Przemysłowy Online. Retrieved from https://magazynprzemyslowy.pl/artykuly/polozono-pierwszy-na-swiecie-beton-kawowy (22.04.2025).
PORANEK N., ŁAŹNIEWSKA-PIEKARCZYK B., PIKOŃ K., CZAJKOWSKI A. 2021. *Ocena możliwości zagospodarowania odpadów wtórnych z ITPOK*. Nowa Energia, 4: 8-13.
PYTEL Z. 2005. *Resistance of cement mortars with the metakaolinite to chemical corrosion*. Cement Wapno Beton, 10(6), 330-338. Retrieved from https://www.cementwapnobeton.pl/pdf-177737-98316?filename=Resistance%20of%20cement.pdf
Spectis. 2024. *Rynek wyrobów betonowych w Polsce warty 11 mld zł*. Spectis. Construcion Market Expert. Retrieved from https://spectis.pl/news/459/5/Rynek-wyrobow-betonowych-w-Polsce-warty-11-mld-zl (20.12.2024).
SIEMIĄTKOWSKI G. 2012. *Zagospodarowanie zmieszanych odpadów komunalnych w Polsce– strategiczne kierunki i dostosowanie prawodawstwa na tle innych państw Unii Europejskiej*. Prace Instytutu Ceramiki i Materiałów Budowlanych, 5(10), 15-56, (in Polish).
SZCZUCKA-LASOTA B., WOLNIAK R., WĘGRZYN T. 2018. *Logistics in the management of municipal waste*. Scientific Papers of Silesian University of Technology. Organization and Management Series, 116(1995): 109-119. https://doi.org/10.29119/1641-3466.2018.116.8
szu/ hgt/. 2017. *Polski beton może posłużyć m.in. do utylizacji odpadów radioaktywnych*. Polska Agencja Prasowa. Retrieved from https://www.pap.pl/aktualnosci/news%2C935939%2Cpolski-beton-moze-posluzyc-min-do-utylizacji-odpadow-radioaktywnych.html (22.04.2025).
ULIASZ-BOCHEŃCZYK A., MOKRZYCKI E. 2022. *The use of waste in cement production in Poland – the move towards sustainable development*. Mineral Resources Management, 38(3), 67-81. https://doi.org/10.24425/gsm.2022.142791

VARINCA K., GÖNÜLLÜ M. 2011. *Solidification/Stabilization of Treatment Sludge Contains Heavy Metals*. Conference: EurAsia Waste Management Symposium, İstanbul, Türkiye.

WICHOWSKI P., NOWAK P., RUTKOWSKA G. 2017. *Wymywanie wybranych metali ciężkich z betonów zawierających popiół z termicznego przekształcania osadów ściekowych*. Acta Scientiarum Polonorum, Architecture Construction, 16, 43-51. https://doi.org/10.22630/ASPA.2017.16.1.05

WILIŃSKI D. 2012. *Zastosowanie odpadowego PET do wzmacniania betonu*. Materiały Budowlane, 5: 22-24.

Wytwarzanie odpadów w Polsce. 2023. Portal Statystyczny. Retrieved from https://portalstatystyczny.pl/wytwarzanie-odpadow-w-polsce/ (19.12.2024).

ZAJĄC B., GOŁĘBIOWSKA I. 2014. *Zagospodarowanie odpadów budowlanych*. Inżynieria i Aparatura Chemiczna, 6: 393-395.

ZĘBEK E. 2018. *Zasady gospodarki odpadami w ujęciu prawnym i środowiskowym*. Kortowski Przegląd Prawniczy Monografie, Olsztyn.