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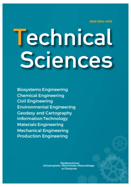

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IMMOBILIZATION OF ENVIRONMENTALLY HARMFUL ELEMENTS IN CONCRETE

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Abstract

Concrete is a material widely used in the construction industry. The possibility of waste immobilization generated by modern-day industry in concrete structures sets a viable alternative to conventional waste disposal methods. Most of the existing efforts in the field of waste disposal through introducing them to concrete blends face significant limitations. In this study, research was undertaken on the leachability of selected actual industrial waste, such as volatile ashes, sewage sludge, and water sludges, along with paints and varnish containing organic solvents. The research was undertaken undertaken on both crushed and uncrushed samples. The obtained leachability results for individual contaminants (elements and compounds) were compared with current regulatory standards.

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Introduction

Concrete is a commonly used material in the construction industry, including in hydrotechnical engineering (sewage treatment plants, road drainage systems, drinking water supply and discharge systems) (ULIASZ-BOCHEŃCZYK, MOKRZYCKI 2022). Concretes are divided among others into: cement concrete, resin concrete, asphalt concrete, and concrete based on other binding materials such as gypsum concrete or sulfur concrete. Cement concrete is the most commonly used type. Its classification is based on several criteria, such as composition, properties, production methods, transportation, applications, and the type of construction structure (KOHUTEK 2005). Waste management in Poland, the European Union, as well as most highly developed countries, is strictly regulated by national legislation, and the regulatory process is still ongoing. The various processes and methods of waste management are primarily based on environmental protection laws. In Poland, such legal acts include the Act of April 27, 2001 (*Ustawa z dnia 27 kwietnia 2001 r. – Prawo ochrony środowiska (Dz. U. z 2022 r. poz. 2556)*, 9 December 2022), allong with other national laws and regulations, and numerous normative acts of the European Union, including directives and regulations of the European Parliament and the Council, as well as directives and implementing decisions of the European Commission, all of which Polish legislation must comply with. The purpose of these regulations is to ensure state and institutional control over waste circulation. This applies to waste producers, intermediaries in waste trade, entrepreneurs involved in waste management processes, entities transporting waste, and other entities active in the field of waste management. As a result, waste management, including methods of waste utilization, is subject to specific rules and regulations characteristic of this area of economic activity. Research has been carried out to determine which elements or chemical compounds will have the best effect in the immobilization of environmentally harmful elements in concrete.

Waste database

The BDO (Database on Products, Packaging, and Waste Management) system is a registry designed to improve the traceability and control of waste management processes. Its main objectives are to tighten control over waste handling systems, enhance the effectiveness of combating the shadow economy and illegal landfills, and improve recycling rates.

The obligation to register in the BDO system and to maintain waste records and reporting applies to businesses that generate waste and are required to keep waste documentation. This also includes entities introducing packaged products into the domestic market, manufacturing or importing packaging, or purchasing it through intra-community transactions (from EU-based companies). Waste is classified in the waste catalogue, which organizes waste into 20 groups based on the origin of generation:

01 – Waste resulting from exploration, mining, physical and chemical treatment of minerals and other geological materials,
02 – Waste from agriculture, horticulture, hydroponics, fisheries, forestry, hunting, and food processing,
03 – Waste from wood processing and the production of panels and furniture, pulp, paper, and cardboard,
04 – Waste from the leather, fur, and textile industries,
05 – Waste from oil refining, natural gas purification, and pyrolytic treatment of coal,
06 – Waste from the manufacture, formulation, distribution, and use of inorganic chemicals,
07 – Waste from the manufacture, formulation, distribution, and use of organic chemicals,
08 – Waste from the manufacture, formulation, distribution, and use of coatings (paints, varnishes, ceramic enamels), sealants, adhesives, and printing inks,
09 – Waste from the photographic industry and photographic services,
10 – Waste from thermal processes,
11 – Waste from chemical surface treatment and coating of metals and other materials, and from non-ferrous hydrometallurgical processes,
12 – Waste from shaping and physical and mechanical surface treatment of metals and plastics,
13 – Waste oils and liquid fuels waste (excluding edible oils and wastes listed under groups 05, 12, and 19),
14 – Waste from organic solvents, refrigerants, and propellants (excluding groups 07 and 08),
15 – Packaging waste; absorbents, wiping cloths, filter materials, and protective clothing not otherwise specified,
16 – Wastes not otherwise specified in the catalogue,
17 – Construction and demolition waste (including soil and land from contaminated sites) [NOTE: changes effective from 2025].
18 – Medical and veterinary waste,
19 – Waste from waste management facilities, wastewater treatment plants, and water purification for drinking and industrial purposes,
20 – Municipal waste, including separately collected fractions (*Rozporządzenia Ministra Środowiska z dnia 27 września 2001*).

Waste management in Poland – processes, methods, terminology

The terms “utilization” and “recycling” of waste are colloquial expressions not found in the Environmental Protection Law Act, although they appear in other legal acts such as regulations of the European Parliament and Council. In waste management, the official terms are “landfilling” and “treatment” of waste. Therefore, when referring to a landfill, the correct term is a “waste disposal site.” In the case of recycling, it refers to treatment. According to current nomenclature, treatment may take the form of disposal or recovery. Waste treatment is carried out at facilities, where a “facility” may be either a waste disposal site, for example, for composting organic municipal waste, a thermal treatment plant (commonly referred to as a waste incineration plant), or a facility for physico-chemical stabilization of waste (colloquially: concrete batching plant). Waste disposal involves reducing the hazardousness of waste. This primarily concerns the limitation of the environmental impact of substances contained in waste. Typically, this impact involves the migration of harmful substances through leakage and infiltration into soil, odor emissions through evaporation or sublimation, dusting, hazardous radiation, etc. Due to the degree of hazardousness, waste in the Waste Database (BDO) is assigned six-digit codes. Some codes are marked with an asterisk. Such markings indicate hazardous waste. Disposal of waste marked with an asterisk should result in the production (through the disposal process) of a new waste substance that is no longer classified as hazardous, i.e., a non-hazardous or inert waste. Whether a given waste substance has lost its hazardous status is determined by an elemental leachability test, also known as a migration test. The Regulation of the Minister of Economy of 16 July 2015 on the criteria for acceptance of waste at landfills specifies permissible leachability levels for various elements and, depending on the test results (conducted by an accredited laboratory), allows the substance to be landfilled in an appropriate category of landfill or treated in an appropriate process or method. Waste recovery is a specific form of waste treatment. It consists of completely removing waste characteristics from a substance, meaning the total and permanent cessation of its environmental impact, particularly its influence on human and animal health. The recovery process always results in a new product that is reused in the economy. If the recovery process generates energy, it is referred to as “waste recycling”. This creates a so-called “closed-loop waste cycle,” which is the goal of highly developed countries, including EU member states, and is reflected in European Union directives. A good example of waste recovery is zeolite concrete, produced with the use of waste in various forms such as liquids, aggregates, sludges, and sediments. An example of recycling is municipal waste incineration, which generates thermal energy and, in parallel, electricity. In Poland, the Association of Energy Producers from Waste (SPEO) operates, bringing together municipal waste incineration plants located in various Polish cities. Several types of recycling are distinguished, including material (mechanical) recycling, which involves reprocessing waste into products with usable value. Raw material (chemical) recycling entails the recovery of raw materials used in the original product. Organic recycling (composting), which consists of the natural disposal of biodegradable waste through decomposition by microorganisms, producing compost, a natural fertilizer. Waste treatment methods are divided into processes and methods. The result of applying a given treatment determines the further classification of the processed product. Relevant regulations, followed by administrative decisions, determine whether particular waste types can be processed using a given method or in a particular process (*Rozporządzenie Ministra Gospodarki z dnia 16 lipca 2015 r. w sprawie dopuszczania odpadów do składowania na składowiskach (Dz.U. 2015 poz. 1277).* Each waste treatment process and method (disposal or recovery) is assigned a symbol: R for recovery processes and D for disposal methods. The list of waste treatment processes and methods is presented in Table 1 (ZĘBEK 2018).

Table 1

Waste treatment processes and methods

Recovery processes	Disposal methods
1	2
R1 Use principally as a fuel or other means of generating energy	D1 Deposit into or onto land (e.g., landfill, etc.)
R2 Solvent reclamation/regeneration	D2 Land treatment (e.g., biodegradation of liquid or sludge waste in soils, etc.)
R3 Recycling or reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)	D3 Deep injection (e.g., injection of pumpable waste into wells, salt domes, or naturally occurring repositories, etc.)
R4 Recycling or reclamation of metals and metal compounds	D4 Surface impoundment (e.g., placement of liquid or sludge waste into pits, ponds, or lagoons, etc.)
R5 Recycling or reclamation of other inorganic materials	D5 Specially engineered landfill (e.g., placement into separate sealed cells, covered and isolated from each other and the environment, etc.)
R6 Regeneration of acids or bases	D6 Release into a water body, except seas/oceans
R7 Recovery of components used for pollution abatement	D7 Release into seas/oceans, including sea-bed insertion
R8 Recovery of components from catalysts	D8 Biological treatment not specified elsewhere in this annex, which results in final compounds or mixtures that are disposed of through any of the operations numbered D1 to D12
R9 Oil re-refining or other reuses of oil	D9 Physico-chemical treatment not specified elsewhere in this annex, which results in final compounds or mixtures that are disposed of through any of the operations numbered D1 to D12 (e.g., evaporation, drying, calcination, etc.)

cont. Table 1

1	2
R10 Land treatment resulting in benefit to agriculture or ecological improvement	D10 Incineration on land
R11 Use of wastes obtained from any of the operations numbered R1 to R10	D11 Incineration at sea
R12 Exchange of wastes for submission to any of the operations numbered R1 to R11	D12 Permanent storage (e.g., emplacement of containers in a mine, etc.)
R13 Storage of wastes pending any of the operations numbered R1 to R12 (excluding temporary storage, pending collection, on the site where the waste is produced)	D13 Blending or mixing before submission to any of the operations numbered D1 to D12
	D14 Repackaging before submission to any of the operations numbered D1 to D13
	D15 Storage pending any of the operations numbered D1 to D14 (excluding temporary storage, pending collection, on the site where the waste is produced)

As indicated by the list of waste processing methods and operations, when referring to concrete mix produced with the participation of waste classified as waste intended for disposal at hazardous or non-hazardous waste landfills, this constitutes waste treatment by method D9. Conversely, when referring to zeolite concrete for which an opinion has been obtained confirming the loss of waste status and proving no impact on the natural environment, this constitutes waste recovery under process R5.

Recovery of hazardous industrial waste in concrete production

To date, most efforts in the field of waste processing by incorporating waste materials into concrete mixes have faced significant limitations. The first limitation concerns the type of waste. From a technological perspective, the most apparent candidates for use in concrete mixtures are ashes, dusts, and slags from the thermal treatment of fossil fuels, primarily coal, as well as from the combustion of sorted municipal waste and metallurgical processes. The second limitation is the effectiveness of the process – in most cases, the outcome is merely a reduction in the hazard level of the waste transformed into concrete. Such concrete remains classified as waste, albeit less hazardous than the original input material. The third limitation is the usability of such concrete. Since it remains waste, it cannot be marketed and must be deposited in appropriately classified landfills (GAWLICKI, SIEMIĄTKOWSKI 2018). In Europe, particularly in the Netherlands, research and trials over the past three decades have explored effective methods for neutralizing soil toxins resulting primarily from industrial accidents, transportation incidents, chemical spills, or waste landfill operations. The Netherlands has been a pioneer in ground stabilization through chemical modification of hydraulic binders, primarily cement (JÓŹWIAK, SIEMASZKO--LOTKOWSKA 2006). These experiences originated in road and hydro-engineering construction. Given the often unfavorable soil conditions in the Netherlands, such as peat, frost-susceptible, or organic soils that require replacement to ensure adequate load-bearing capacity and compressive strength, high groundwater tables further complicate soil replacement, leading to extended construction timelines and increased costs. Unfortunately, cement alone, as a hydraulic binder, cannot ensure the required compaction, plasticity, impermeability, and thus load-bearing capacity and stress resistance of organic soils. Even with excessive amounts of cement per cubic meter of stabilized soil, effectiveness remains uncertain (e.g., shrinkage-induced cracking in cement-soil composites), not to mention the costs. Dutch engineers, supported by strong research and development facilities, gradually succeeded in modifying cement properties through additives and admixtures (classified by their proportion relative to cement mass) to enhance their stabilizing effects. The PN-EN 206:2014 standard introduces a new approach to concrete mix design, production, and evaluation of its technical properties. The primary objective is to ensure adequate durability of concrete structures and elements under specified environmental conditions, with a designed service life of at least 50 years. This standard defines a concrete additive as a fine-grained inorganic material used to enhance specific properties or achieve special attributes. Among these are pozzolanic additives such as silica fume, fly ash, ground granulated blast furnace slag, and metakaolinite. Metakaolinite, produced by calcining natural kaolinite at 700–900°C, is a highly reactive pozzolanic material. Kaolinite is a two-layer phyllosilicate mineral with the crystallochemical formula $Al_4[Si_4O_{10}](OH)_8$, consisting of tetrahedral silicate and octahedral alumino-oxyhydroxide layers. Dehydroxylation of kaolinite begins at 550°C (BUNDYRA-ORACZ 2008). The properties of metakaolinite proved critical for soil stabilization, particularly its resistance to chloride (MIKUŁA, ŁACH, MIERZWIŃSKI 2017) and sulfate (COURARD et al. 2003) corrosion. Metakaolinite acts as a chloride diffusion inhibitor in mortars, including soil-cement composites. It also enhances mortar resistance to sulfate corrosion, particularly from $MgSO_4$. One of the effects of modified hydraulic binders was the sealing of stabilized soil in conditions of proper moisture, water pH, compaction, and curing. Stabilized layers demonstrated adequate load-bearing capacity (at relatively low thickness) and compressive strength, with water permeability reduced to below 5%. Further cement modifications tested natural and synthetic zeolites with equally favorable outcomes. Notably, zeolites immobilize heavy metals in contaminated soils. This property led to targeted research into using ion exchange to limit migration of elements from waste-derived substances in soil.

Zeolites and ion exchange

Zeolites are a group of aluminosilicate minerals (silicate class) with varying chemical composition, properties, and crystal forms. They are hydrated sodium and calcium aluminosilicates, sometimes also containing barium, strontium, potassium, magnesium, and manganese. Ion exchange occurs when an ion (an atom or molecule that has gained or lost electrons and thus carries an electric charge) is exchanged for a similarly charged ion attached to an immobile solid particle. The cation exchange capacity of traditional aluminosilicate zeolites stems from the isomorphic substitution of aluminum in tetrahedral coordination within their Si-Al structures, which imparts a negative charge ($Si^{4+} \rightarrow Al^{3+}$) balanced by cations located in the pores and channels (PYTEL 2005). Research by Dutch firms and institutions resulted in numerous patents for modifying Portland cement to produce silicate matrices during hydration that are highly effective in stabilizing soils previously unstabilizable with cement alone.

Polish experience in immobilizing harmful elements in concrete

Since Poland acceded to the European Union in 2004, numerous Polish companies – some with Dutch capital, but primarily with access to Dutch research, technology, and products – have emerged. Some Polish firms have not only applied Dutch stabilization technologies on local construction sites but also advanced them. One Poznań-based company began researching the use of ion-exchange zeolitic formulations to immobilize elements from waste substances, aiming for complete waste recovery. This involved analyzing and selecting suitable waste materials, as well as modifying concrete production technology. Work included adapting mix recipes, extensive formulation modifications, physical testing, and leaching studies of elements from concrete made with various waste types. This know-how underpinned the development of zeolite concrete technology (FABIARZ 2005). The characteristics and description of zeolite concrete are best presented through comparison with conventional concrete.

- **Chemical Differences**

Ordinary Concrete: Cement binder setting involves chemical and physical processes initiated when cement is mixed with water. Cement components react with water; tricalcium aluminate is the most reactive component in cement. In the presence of gypsum, it reacts with water to form ettringite $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$, this ettringite creates a layer on the surface of the aluminate that is impermeable to water. Once the gypsum is depleted, the remaining tricalcium aluminate rapidly reacts with water, forming hydrated aluminates. In contrast, the hydration of calcium silicates produces hydrated silicates and calcium hydroxide. The binding of the cementitious binder ultimately leads to a stable system where the hardened cement paste binds the aggregate particles together (PIETRAS, KONKOL 2021).

Zeolite Concrete: In parallel with the binding process of the cementitious binder, an ion exchange process occurs due to the presence of a suitable zeolite component. In this process, an ion (an atom or molecule that has gained or lost an electron and thus acquired an electrical charge) from a substance is exchanged with a similarly charged ion attached to a stationary solid particle. As a result of pozzolanic reactions, a silicate matrix is formed with a high number of durable bonds, often referred to as perovskite-like structures (ŁUKOWSKI 2014).

- **Physical Differences**

Ordinary Concrete: in ordinary concrete, cement undergoes a change of state under the influence of water during the hydration process, initially transitioning into a gel and subsequently into a solid. The cement paste binds the aggregates in a manner that does not affect the migration of elements contained within the mixture. The functionality of cement is ensured solely when mixed with inactive components, such as natural aggregates, water, and optionally, products of natural hydrocarbon combustion. Upon crushing, it releases the elements contained within its structure (GRABOWSKA 2016).

Zeolite concrete, in which the elemental compositions lead to the physico-chemical stabilization of the mixture, possesses the following advantages:

– Permanent immobilization of elements at the molecular level.

– Ability to stabilize chemically active substances, e.g., ashes and dusts from the incineration of industrial and municipal waste, liquids, sludges, and others.

– High elasticity coefficient.

Crucially, upon crushing, it does not release the elements contained within its structure (NOCUŃ-WCZELIK, CZAPIK 2010).

- **Functional Differences**

Ordinary Concrete: A construction material. It does not contain zeolites. No ion exchange occurs.

Zeolite Concrete: A product of waste recovery processes. It contains zeolites, and ion exchange occurs.

The applications are similar, although due to the use of ion-exchange composites, zeolite concrete is more impermeable and corrosion-resistant (MIKUŁA 2014).

- **Innovation**

Current State: Solidification and stabilization of waste represent a physico-chemical method for waste treatment. The primary objective of this process is the chemical transformation of waste to prevent the leaching of harmful soluble compounds. Additionally, where feasible, it aims to modify certain physical parameters of the waste to enhance its mechanical strength, reduce water absorption, and increase frost resistance, among other properties. This immobilization process is most commonly applied to inorganic hazardous wastes (or those containing minor amounts of organic compounds) from which soluble chemical compounds of metals, posing environmental threats, can leach. Examples include: slags, ashes, and dusts from thermal processes (e.g., iron and steel metallurgy, non-ferrous metal metallurgy, waste incineration plants), industrial dusts and sludges, ashes, dusts, and sludges from gas treatment processes, and waste from galvanic processes (ROSIŃSKA, KARWOWSKA, MADEŁA 2022). (For instance, in the case of slags from primary and secondary production (BDO code 10 04 01*), arsenic compounds are particularly hazardous). Beyond the aforementioned applications, zeolite concrete offers the potential for effective physicochemical stabilization not only of the waste types listed above but also of wastes containing higher concentrations of organic compounds (e.g., DOC/RWO), liquid wastes, and sewage sludges with significant water content (63–75%), soil contaminated with petroleum products, and other waste substances. (Ongoing research continues to expand the catalog of successfully stabilized substances (WASIAK, RÓŻALSKA 2003)). “Effective stabilization” in this context refers to the permanent immobilization of elements that pose an environmental threat.

Research results

Control tests were carried out on the leachability of a number of elements and harmful substances from the obtained zeolite concrete containing various types of waste. The obtained results were verified to see if they fit into the applicable legal standards and meet the permissible values contained therein.

– Waste from Thermal Waste Treatment Plants (TWTP): Waste codes: 19 01 05* (filter cakes, e.g., filter cake from exhaust gas treatment), 19 01 07* (solid waste from exhaust gas treatment), 19 01 13* (fly ash containing hazardous substances), 19 01 15* (boiler dusts containing hazardous substances).

– Sludges: Waste codes: 03 03 11 (sludges from on-site effluent treatment other than those mentioned in 03 03 10), 19 01 05 (filter sludges, e.g., filter cake from exhaust gas treatment), 19 08 05 (stabilized municipal sewage sludges).

– Slimes: Waste codes: 08 01 11* (waste paints and varnishes containing organic solvents or other hazardous substances), 08 01 13* (sludges from paint and varnish removal containing organic solvents or other hazardous substances), 08 01 15* (aqueous sludges containing paints and varnishes containing organic solvents or other hazardous substances), 08 03 12* (waste printing inks containing hazardous substances).

– Current research focuses on reducing the leachability of heavy metal elements present in slags from primary and secondary production (10 04 01*) as well as bottom ash and fly ash (19 01 12).

Sample preparation and leachability test conditions

Concrete samples containing waste were prepared, and leachability tests were conducted in accordance with standard PN-EN-12457-4-2006.

1. Crushing and homogenization of the sample to a fraction of <10 mm.
2. Determination of dry residue content.
3. Calculation of the water quantity required for 0.090 kg of sample, based on dry mass, with a liquid-to-solid ratio of 10:1.
4. The prepared container with the sample and water was mixed on a roller mixer for 24 hours at room temperature 20°C±5°C.
5. Care was taken to avoid excessive attrition that could lead to over-grinding of the sample.
6. The water used adhered to the standard's requirements: distilled, demineralized, deionized, or water of equivalent purity ($5<pH<7.5$) with conductivity <0.5 mS/m, conforming to purity grade 3 as per EN ISO 3696. Water with a pH of 7.00 was specifically used.
7. After 15 minutes of suspension sedimentation, the entire mixture was filtered through a 0.45 µm filter.
8. Subsequently, the filtrate was analyzed for the content of individual parameters.

The results of the conducted tests are presented below.

Sample description: A solid product incorporating waste with code 08 01 15* (aqueous sludges containing paints and varnishes, or other hazardous substances) was tested, named: zeolite concrete.

Test results and evaluation

A series of tests were carried out in accredited laboratories. The obtained samples of various types of hazardous waste after immobilization in cement mortars were tested for leachability immediately after the concrete mixes had matured (according to the standard, 28 days after the mix was produced). Table 2 presents the results of the study on the leachability of elements from zeolite concrete: boiler dusts containing hazardous substances, with a detailed breakdown of the determined parameters.

Heavy metal leachability tests conducted in an accredited laboratory showed that concrete samples containing only waste ash and ordinary cement

Table 2

Results of the study on the leachability of elements from boiler dust containing hazardous substances (sample 062/71/02/2023 and modified zeolite concrete: boiler dusts containing hazardous substances (19 01 15*) – sample 0D17/09/24**

No.	Laboratory sample code:		062/71/02/2024	0D17/09/24
	Parameter determined	MoE Regulations	Unmodified sample	Sample modified with zeolite
			[mg/kg d.m.]	
1.	Dry residue	–	100	100
2.	Chlorides	800	50000	<200
3.	Dissolved organic carbon (DOC)	500	5,1	<5,0
4.	Total dissolved solids (TDS), substances dissolved at 105°C	4000	222000	810
5.	Sulphates (VI)	1000	34500	74
6.	Fluorides	10	16	<3,0
7.	Antimony	0,06	<0,5	0,01
8.	Arsenic	0,5	<0,5	<0,01
9.	Selenium	0,1	1,36	<0,01
10.	Copper	2	2,08	<0,01
11.	Zinc	4	45	<0,02
12.	Barium	20	33	0,2
13.	Molybdenum	0,5	6,5	<0,01
14.	Nickel	0,4	<0,2	<0,03
15.	Chromium	0,5	14	<0,05
16.	Cadmium	0,04	0,18	<0,05
17.	Lead	0,5	725	<0,01
18.	Mercury	0,01	0,00328	0,000139
19.	Phenol index	1	–	<0,05

MoE – requirements according to the Regulation of the Minister of Economy of 16 July 2015 (Journal of Laws of 2015, item 1277, Annex No. 2).

**The binary statement of conformity with requirements is based on the simple acceptance rule (following ILAC-G8:09/2019). The client agrees to accept a result as compliant if its value is below the acceptance limit. The risk of false acceptance is up to 50% for results close to the acceptance limit and is considered where appropriate. The client agrees to accept a result as non-compliant if its value is above the acceptance limit. The risk of false rejection is up to 50% for results close to the acceptance limit and is considered where appropriate. For results presented as < or > a specified value, the laboratory has provided a statement of conformity as an opinion and interpretation by referring directly to the lower or upper value of the range, respectively, while using the symbols cited in the report (Z or N) for the assessment.

were unable to meet the standards for most of the parameters tested. After appropriate formulation with the addition of zeolites, the concrete samples were subjected to repeated tests for metal leachability. Appropriately modified with zeolites, cement mortars containing harmful waste allow for obtaining a final product that meets high standard assumptions (Table 1–3). Two aqueous extract samples of the aforementioned product (one crushed sample, one intact sample) were subjected to testing. The tests were performed in an accredited laboratory. The test results from December 22, 2024, are compiled in Table 3 and evaluated according to the Regulation of the Minister of Economy of July 16, 2015, concerning the admissibility of waste for landfilling. All tested samples were assessed positively.

Table 3

Results of the study on the leachability of elements from modified zeolite concrete: Aqueous sludges containing paints and varnishes with organic solvents or other hazardous substances (08 01 15*)

No.	Parameter determined	Test result (from report no. 41/12/2024)		Permissible values*
		Crushed sample	Whole sample	
		[mg/kg d.m.]		
1.	Chlorides	115	157	800
2.	Fluorides	<4,00	<4,00	10
3.	Sulphates(VI)	<50,0	<50,0	1000
4.	Total dissolved solids (TDS)z)	16100	18600	4000**
5.	Dissolved organic carbon (DOC)	281	414	500
6.	Antimony	<0,010	<0,010	0,06
7.	Arsenic	<0,500	<0,500	0,5
8.	Barium	9,97	12,7	20
9.	Molybdenum	<0,200	<0,200	0,5
10.	Nickel	<0,200	<0,200	0,4
11.	Chromium	0,098	<0,050	0,5
12.	Cadmium	<0,0100	<0,0100	0,04
13.	Copper	0,295	<0,100	2
14.	Lead	<0,500	<0,500	0,5
15.	Zinc	0,718	1,31	4
16.	Mercury	<0,00010	0,00012	0,01
17.	Selenium	<0,050	<0,050	0,1
18.	Phenol index	0,35	<0,05	1
19.	Total organic carbon	309	442	30000
20.	Benzene, toluene, ethylbenzene and xylenes (BTEX)	<0,032	<0,032	6
21.	Petroleum hydrocarbons C10-C40 fraction	<0,50	<0,50	500
22.	Polycyclic aromatic hydrocarbons (PAHs) – sum of 16 PAHs	0,0192	0,0152	1
23.	Sum of 7 PCBs	<0,000073	<0,000073	1

*Permissible values based on the Regulation of the Minister of Economy of 16 July 2015 on the admission of waste to landfills.

**The values for total dissolved solids (TDS) may be used interchangeably with the values for sulphates and chlorides.

A study of the leachability of elements from zeolite concrete with boiler dust containing hazardous substances was also carried out. Using a sample for testing the leachability of elements from zeolite concrete: boiler dust containing hazardous substances (19 01 15*). The sample was taken A cylinder containing waste (sample code 006_190115_10,01_IC-_08.24_3) with a diameter of 10 cm and a height of 12 cm. Zeolite concrete produced with the participation of waste with code 19 01 15* (Boiler dust containing hazardous substances). Sample prepared on 24.08.2023. Leachate test (liquid/solid ratio 10 l/kg). The sample was of the waste type. It was delivered to the laboratory on 22.09.2024, tests started on 26.09.2024. completed on 04/10/2024. A sample intended for testing the leachability of elements from zeolite concrete was also described: Stabilized municipal sewage sludge (19 08 05). Concrete sample with the addition of waste

Table 4

Results of element leachability from zeolite concrete:
stabilised municipal sewage sludge (19 08 05) – 0D17/09/24**

Laboratory sample code: 0D17/09/24			
No.	Parameter determined	MoE Regulations	Test result
		[mg/kg d.m.]	
1.	Dry residue	–	99,9
2.	Chlorides	800	<200
3.	Dissolved organic carbon (DOC)	500	95,3
4.	Total dissolved solids (TDS), substances dissolved at 105°C	4000	1710
5.	Sulphates (VI)	1000	865
6.	Fluorides	10	<3,0
7.	Antimony	0,06	0,01
8.	Arsenic	0,5	<0,01
9.	Selenium	0,1	<0,01
10.	Copper	2	0,65
11.	Zinc	4	<1,0
12.	Barium	20	0,122
13.	Molybdenum	0,5	0,041
14.	Nickel	0,4	0,11
15.	Chromium	0,5	<0,05
16.	Cadmium	0,04	<0,005
17.	Lead	0,5	<0,01
18.	Mercury	0,01	0,00034
19.	Phenol index	1	<0,05

MoE – requirements according to the Regulation of the Minister of Economy of 16 July 2015 (Journal of Laws of 2015, item 1277, Annex No. 2).

code 19 08 05 + phosphogypsum (20.07.2024), Batch from 20.07.2024 – testing 90 days after the preparation of the mixture (10x10x10 cm), leachate testing (liquid/solid ratio 10 l/kg). The sample was of the sewage type. It was delivered to the laboratory on 17.10.2024, testing started on 17.10.2024. completed on 01.11.2024. All tested samples were assessed positively. A detailed breakdown of the determined parameters, data, and their conformity with standards is presented in Table 4.

Summarizing Tables 2–4, it can be stated that VanStab's many years of research have already led to the immobilization of industrial waste in cement plants by combining various devices with appropriate zeolites. More detailed technological solutions are currently being developed, and relevant patent procedures are underway.

Conclusions

The possibility of permanent immobilization and use of hazardous industrial waste with zeolite additives in concrete matrices can be highly effective. This type of technology is also relatively cheap. Harmful waste such as fly ash, sewage sludge and water sludge containing paints and varnishes – even those with organic solvents – can be effectively immobilized in concrete structures. The conducted studies have shown that both intact and crushed samples meet the current, rigorous normative requirements regarding the leachability of individual elements and compounds in the aquatic environment, thus changing the classification of toxic waste to non-hazardous waste, which facilitates safe storage and even secondary use in road construction.

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