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Modern trends in waste recycling technologies of incinerators

Abstract: In 2021, the Government of the Russian Federation set the executive authorities the task of decarbonizing Russian industry and developing an action plan for the transition to carbon regulation and sequestration of carbon dioxide emissions. One of the directions of carbon dioxide sequestration is mineral carbonation. The idea of the work is to use mineral carbonation, as an alternative to natural mineral raw materials, slags from the combustion of solid non-combustible waste. The technology of carbon sequestration by mineral carbonation of technogenic raw materials is at the research stage, therefore it is necessary to assess the potential of using waste incinerators. To solve the tasks, the material composition of the slags of one of the incinerators was studied in detail. The possibility of slag enrichment with the production of copper-containing preconcentrate has been established. The content of minerals capable of participating in carbonation was determined, and the carbonation potential was estimated based on the calculated values. The requirements for man-made waste for their use as raw materials for carbonation are formulated. The factors that have a restraining effect on the introduction of mineral carbonation technologies are highlighted.

Keywords: incinerators, slag from incineration of non-combustible waste, carbon sequestration, carbonation potential, extraction of copper from technogenic raw materials.

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Introduction

The increase in the level of consumption, and as a result, the formation of a huge amount of industrial and household waste, has global consequences for the environment. The world annually produces more than two billion tons of household waste (MSW) that requires placement and disposal. In Russia, the area of landfill territories is about 13 million hectares (Gunich et al., (2018)). Despite the efforts being made, the problem of increasing the volume of waste has not yet been solved. One of the solutions to this problem, at this stage of society's development, is the construction of plants for sorting and incineration of solid waste.

Today there are two incinerators operating in Russia and it is planned to build another one. When burning garbage, 70-75% of MSW components are burned. Unburned solid residues – slags and ash, are exported and stored in dumps that are a source of pollution of the atmosphere and groundwater. Waste incineration slag is a silicate raw material, the composition of which varies widely. The composition of the slag depends on the composition of solid waste and the technological parameters of incinerators. According to the federal classifier of waste in Russia, waste incinerators belong to the 3-4 hazard class. However, slags contain compounds of eco-controlled metals in quantities exceeding the established maximum permissible concentrations (MPC) for soils, and the amount of some metals is comparable to their content in industrial deposits (Hungarian et al., 2018; Bagryantsev, 2016).

Slag processing schemes include crushing the material to a size of less than 50 mm, separation into fractions of 0 – 3 mm, 3 – 8 mm, and 8 – 50 mm, and magnetic separation (Fig. 1). The fraction of 0 – 3 mm and the tailings of processing material larger than 3 mm are sent to landfills for storage (Kolodezhnaya et al., 2022). Waste incinerator slag sorting tails contain compounds of non-magnetic metals: copper, zinc, lead, and aluminum. The development of technology for the recovery of copper from slags will reduce their negative impact on the environment and obtain additional products - polymetallic concentrate. Slag enrichment tailings can be used as raw materials for the production of building materials.

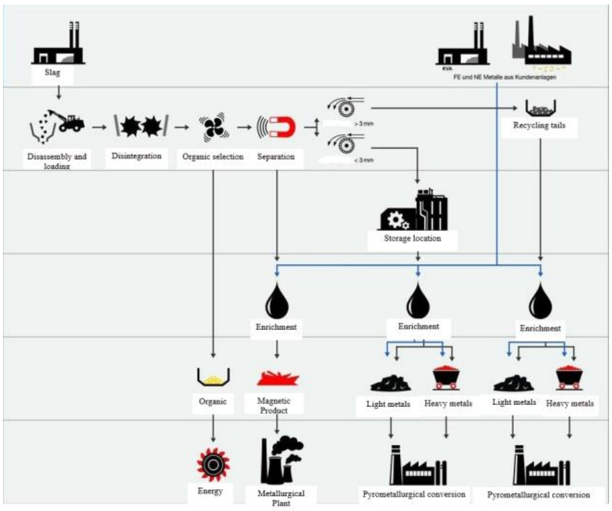

Figure 1. Scheme of dry mechanical treatment of slag from garbage incineration

Blast furnace slags are used and disposed of in concrete technology, for example, in the production of binders. One of the constraining factors in the way of using slag enrichment tailings from garbage incineration in the production of products and structures is the presence (in addition to metals) of free calcium and magnesium oxides, which cause an uneven change in volume during hardening and low strength of the slag binder without an activator. One of the possible ways to solve this problem may be the artificial carbonation of slags by emissions from industrial enterprises (Voronin et al., 2017; Huijgen & Wouter, 2005).

In 2021, the Government of the Russian Federation set the executive authorities the task of decarbonizing Russian industry and developing an action plan for the transition to carbon regulation and sequestration of carbon dioxide emissions (Decree of the Government of the Russian Federation No. 3052-r dated October 20, 2021, Special Report “Global warming by 1.5°C” accessed 15 October 2021). The task of reducing the dangerous anthropogenic impact on the environment remains a priority, I do not look at global economic and geopolitical challenges. The development of the scientific foundations of the technology of sequestration of industrial emissions is an urgent scientific and technical task. There are demonstration pilot plants for carbon dioxide capture and sequestration (Annual report of the International Energy Agency “On the prospects of World Energy up to 2050” (World Energy Outlook, 2022; Moazzem et al., 2012; Olajire, 2013). Figure 2 shows the main technological routes of priority sequestration technologies.

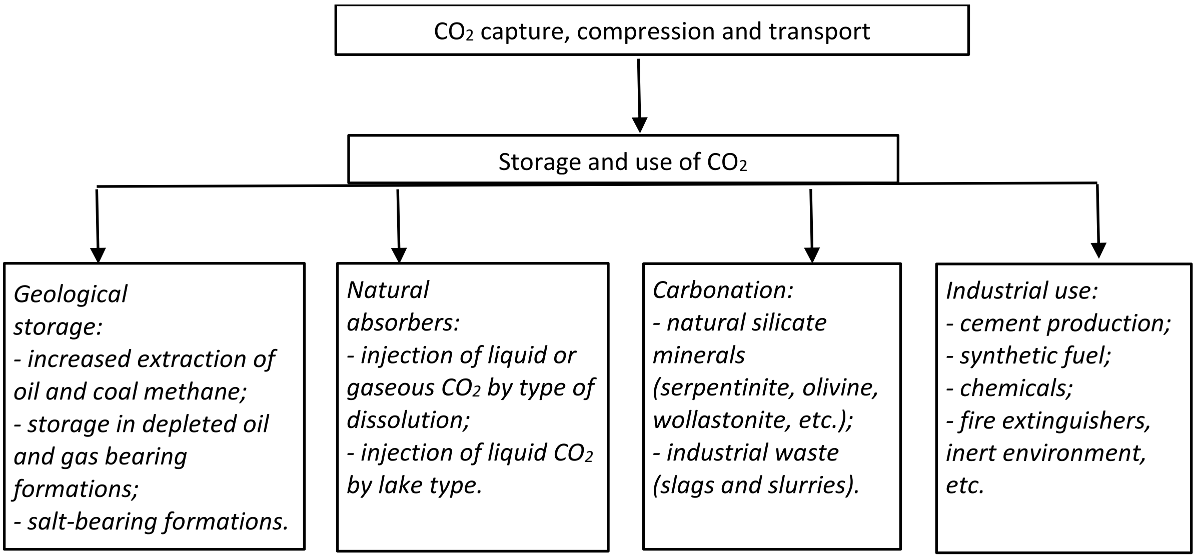

Figure 2. Scheme of application of CO_2 capture, storage and use technologies

One of the directions of carbon dioxide sequestration is mineral carbonation in industrial installations. In the process of mineral carbonation, carbon dioxide interacts with natural minerals to form stable solid carbonates. The most responsive components for mineral carbonation are oxides of divalent metals calcium and magnesium (Ca2+, Mg2+), which occur in the form of silicates, aluminosilicates, and hydroxides: serpentinite ($Mg_3Si_2O_5(OH)_4$), olivine ($(Mg,Fe)_2SiO_4$), wollastonite ($CaSiO_3$), etc. The mineral carbonation process will require 3.2 – 7.4 tons of pure natural silicates to bind $1m^3$ CO_2.

At the same time, the content of calcium and magnesium ions in soluble compounds capable of hydration in technogenic raw materials is crucial. The presence of elements such as Fe, Pb, Cr, Al, and metallic impurities adversely affects the carbonation process, therefore, the use of slags as raw materials for carbon sequestration is possible only after the recovery of metallic impurities. The described technologies are at the research stage and at the moment it is important to assess the possibility of enrichment and the potential for carbonation of slag from garbage incineration.

Research Methods

Analysis of the literature data confirms the presence of phases required for mineral carbonation in waste incineration slags. The carbonation potential is the required amount of man–made waste (in units of mass) to bind $1m^3$ of carbon dioxide [12]. The applicability of the slags was evaluated on the basis of the material and granulometric composition.

The objects of the study are 4 samples of waste sorting tailings from garbage incineration, selected from different points of the technological process. The results of the determination of granulometric, elemental, and phase compositions of 4 samples of tailings of slag processing from garbage incineration are presented.

The determination of the granulometric composition of slag was carried out according to the Russian standard GOST 8735 – 88 «Sand for construction works. Test methods».

The chemical composition of slag samples was determined by the X-ray fluorescence method on the ARL QUANT'X X-ray energy dispersion spectrometer of Thermo Scientific. A feature of the XFA method is the possibility of quantitative analysis of the composition of elements in complex multicomponent mixtures.

The phase composition of the slag was determined using the defractometer "D2 PHASER" and the licensed version of the program "Diffrac.Eva.V2.1", the database on mineralogy «PDF-2». Qualitative analysis was carried out using the licensed version of the program "Topas 4.2".

Research experiment

The granulometric composition of the slags is presented in Table 1.

Table 1. Particle size distribution of an input material

Marking of the sample	Total residue on sieves with a cell, mm, %						
	1.0	0.5	0.315	0.2	0.1	0.04	>0.04
1	0.0	0.0	17.8	33.5	77.6	97.1	100.0
2	46.7	65.4	78.2	84.4	93.6	98.5	100.0
3	49.7	65.4	76.7	83.6	93.5	98.3	100.0
4	0.0	0.0	3.3	10.5	67.9	91.4	100.0

Samples «2» and «3» are dry, loose material with a size of up to 1 mm. The content of particles smaller than 0.1 mm is 6.4 – 6.5%, which ensures reduced dusting of the material. Samples «1» and «4» are dust products with a size of less than 0.315 mm. The moisture content of the starting material was 0.2%, and the bulk density was 920 kg/m^3. During the magnetic analysis of the material, 9.2% of the magnetic fraction was isolated. The results obtained show the heterogeneity of slag processing tailings. A particle size of less than 1 millimeter is preferable for raw materials entering mineral carbonation, as this will ensure a sufficient contact surface and permeability of the material layer.

The analysis of the elemental composition (Table 2) showed the presence of up to 25% calcium and 1-2% magnesium in the sample material. The specific features of the slag formation of incinerators determine the silicate structure of calcium and magnesium-containing phases. Copper, lead, and zinc are also present in the material. To determine the possibility of slag enrichment, it is necessary to establish the form of separation of metal-containing phases.

Table 2. The chemical composition of an input material

Marking of the sample	**Mass concentration (%) chemical element**															
	Si	Ca	Fe	Mg	Al	Ti	P	Zn	Mn	Cu	Cr	Pb	K	Cl	SO_3	Mass loss during calcination
“1”	20.5	14.8	10.0	1.9	5.1	0.6	0.3	0.6	0.2	0.6	0.1	0.1	0.7	0.2	1.0	1.9
“2”	11.6	24.9	7.6	0.7	3.7	1.2	0.6	0.8	0.1	0.5	0.1	0.2	0.9	1.1	4.9	8.2
“3”	7.1	19.0	23.5	0.0	2.9	0.7	0.2	0.7	0.3	0.3	0.1	0.1	0.6	1.0	4.3	7.9
“4”	8.3	20.6	4.5	0.8	12.9	0.7	0.0	2.0	0.2	1.3	0.1	0.2	0.8	1.2	4.3	10.1

The studied material contains up to 20% of amorphous phases. The presence of melilite in the samples is (5 – 12%), anhydrite (1-3%), calcium silicates (4-7%), okermanite (9-11%), and glass phase (up to 20%), having weakly hydraulic properties, it allows us to consider slag processing tailings as raw materials for the production of building materials. In samples “2”, “3”, and “4” the presence of ettringites (up to 11%) was established, which, apparently, is due to the technology of their cooling. The presence of metallic aluminum (1-5%) in the material of samples “1” and “2” was found. The evaluation of the material composition showed the presence of slags of 21-39% (depending on the size) of phases capable of participating in CO_2 binding.

Iron in the material is represented by magnetite (up to 15%), hematite (1 – 5%), wustite (2 – 3%), as well as mackinawite (up to 1%) and is part of cuprospinel and franklinite.

Copper and zinc are present in the form of cuprospinel (1 – 2.5%) and franklinite (1-2%), and can also be part of both amorphous phases and present as alloying elements in other crystalline phases.

When enriching the material of the 0-0.315mm fraction on the concentration table, a heavy fraction with a mass fraction of copper of 13-16% was obtained. The yield of this product was up to 10%. To increase the mass fraction of copper, the concentrate was re-cleaned. The obtained data on the material composition of materials and the degree of their gravitational enrichment can be used in the development of technical solutions and recommendations for the enrichment of slags and the reduction of eco-controlled metals in slags sent for storage.

When slag interacts with the environment, the process of hydration of the active phases occurs: tricalcium silicate (Ca_3SiO_5), bicalcium silicate (β -Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$), single-calcium aluminate ($CaAl_2O_4$), mayenite ($Ca_{11.3}Al_{14}O_{32.3}$). The hydration products of these phases are bound by carbon dioxide (Table 3).

Table 3. Carbonation reactions of slag phases of incineration plants

Reaction equation	**ΔG, kJ/mol**
$Ca(OH)_2+CO_2(gas) \rightarrow CaCO_3(solid)+ H_2O(liquid)$	-74,92
$1/3(3CaO\cdot Al_2O_3\cdot 6H_2O)(solid)+CO_2(gas) \rightarrow CaCO_3(solid)+2/3Al(OH)_3(solid)+H_2O(liquid)$	-79,11
$1/3(3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 31H_2O)(solid)+CO_2(gas) \rightarrow CaCO_3(solid)+CaSO_4\cdot 2H_2O(solid)+2/3\,Al(OH)_3(solid)+22/3H_2O(liquid)$	-72,57
$CaO\cdot Al_2O_3\cdot 10H_2O+CO_2(gas) \rightarrow CaCO_3(solid)+2Al(OH)_3(solid)+7H_2O(liquid)$	-97,83

The carbonation potential of slag from garbage incineration calculated by size classes is presented in Table 4. To bind 1 m^3 of carbon dioxide, 7.9 – 37 kg of slag will be required, depending on the size of the slag, the data obtained can be used in the development of technical solutions and the design of carbon capture and burial plants.

Table 4. Carbonation potential of slags from garbage incineration

Fraction		**Carbonation potential, kg of slag per 1 m^3 of CO_2**
Slag of the current process	8 – 32mm	28.5
	1 – 8mm	18.6
	0 – 1mm	18.0
Slag from the dump	8 – 32mm	27.7
	1 – 8mm	37.0
	0 – 1mm	7.9

Conclusions

The conducted studies have shown that Cu, Zn, and Pb are present in waste incineration slags as independent metal phases and alloys, and are part of iron oxides and silicates. Reduction of Cu, Zn, and Pb content in the starting material can be achieved by enrichment by gravity methods in an aqueous medium on a concentration table. The separation of metals into separate products is due to the high density of copper-zinc alloys and lead. As a result of technological tests, a concentrate with a mass fraction of copper up to 16% was obtained and its yield will be 10-12%.

The presence of 21-39% of phases capable of participating in CO_2 binding in the slags has been established. Waste incineration slags can be used as an alternative to natural sources of raw materials for carbon dioxide sequestration. The carbonation potential of the slag was 7.9 – 37 kg per 1 m^3 of CO_2. Binders from waste incineration slags can be used for the manufacture of light inorganic building materials in the production of concrete and ceramic bricks.

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