The Role of Slag from the Combustion of Solid Municipal Waste in Circular Economy

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Slag formed in the processes of thermal degradation of the municipal fraction is classified in accordance with applicable regulations as waste with code 19 01 12. It is estimated that as a result of the combustion of municipal fractions, about 0.25 Mg of slag per 1 Mg of incinerated waste is formed. From the perspective of the circular economy, it is necessary to seek new applications for this type of material in the industry. New business models, in particular the recovery of by-products, are a chance for their optimal use. This concept assumes that waste from one process is a product for another process. Action requires a new look at the market and the development of previously non-existent industrial symbioses. As a result of reintroducing slag into circulation, a reduction in natural resource consumption can be achieved, resulting in both economic and environmental savings. The objective of the article is a preliminary assessment of the physical and chemical properties of slag from municipal waste incineration plants as an additive to concrete. For the purposes of evaluating the use of slag in construction, the following scenarios were analyzed: slag as a substitute for aggregate, sand, and cement. The tests were carried out on slag obtained from three different installations operating in Poland. The article presents the oxide and elemental composition of slags, and the obtained results are related to the requirements for using granulated blast furnace slag as a type II additive to concrete. The analyzed slags are characterized by a low content of chlorine (Cl<0.5%), the total sulfur content was at the level of 0.7%. The organic carbon content (TOC) of the tested slags was below the level of quantification. The obtained results confirm that the use of slag as an alternative aggregate or raw material in concrete does not pose a threat to individual elements of the natural environment.

Keywords: *slag, raw material, recycling, concrete*

1. Introduction

Continuous economic development, consumerism and a growth of social status contribute to an increasing amount of generated waste. According to Eurostat data, 505 kg of municipal waste per capita was generated in Europe in 2020. In Poland it was 346 kg per capita [1]. According to the Waste Act of 14 December 2012 [2], every activity related to waste must comply with the appropriate hierarchy of waste management, according to which it is recommended to prevent formation of waste in the first place. Secondly, the waste must be prepared for reuse, then it must be recycled or subjected to other recycling processes, including energy recovery. Final element of the waste management hierarchy is its disposal. Management of mixed municipal waste can be carried out using various methods. One of them is thermal degradation in the installations designed for this purpose [3-4]. Indicated solution on the one hand contributes to the optimal management of the combustible fraction, but on the other hand contributes to the formation of significant amounts of secondary waste, such as: slag, fly ash, etc. [5-6]. According to the Regulation of the Minister of the Environment of 27 September 2001 on the waste catalog [7], slag derived from municipal waste incineration plants is classified as waste with the code 19 01 12 – incineration ash and slag other than those mentioned in 19 01 11. It is estimated that thermal degradation of municipal waste produces about 250-300 kg of slag per 1 Mg of incinerated waste [8-9]. From a circular economy perspective, new possibilities of using this type of material in industry must be sought. New business models are a chance for their optimal use. Emphasis should be put on the circular model developed under the international R2π project. It consists of 7 business models covering 3 phases i.e. production, use and end of life. One of the models in the phase of production is the recycling of by-products. Foregoing concept assumes that waste from one process can be a raw material for another industry. This requires a fresh look at the market and development of previously non-existent industrial symbiosis [10-11]. Repurposing of slag can lead to lower consumption of natural resources, which are shrinking due to intensive exploitation. Additionally, this will lead to economic and environmental savings [12, 13].

Modern concept consistent with the idea of the circular economy assumes the use of slag from incineration of municipal waste in broadly understood construction [12, 14, 15, 16, 17]. Various concepts of slag application in construction are analysed for example as a replacement for aggregate, sand or a partial replacement for cement. The problems of application of slag originating in incineration of municipal waste in Circular Economy is well recognized in many countries [5, 6, 18, 19]. It should be emphasized that despite the knowledge of the subject, there is no universal method of reusing this type of slag. In Poland, the issue of the optimal and safe use of slag from incineration of municipal waste is a new issue that requires analysis. Variable composition of municipal fractions related to seasonality and different levels of recycling translate into slag properties. Slags from incineration

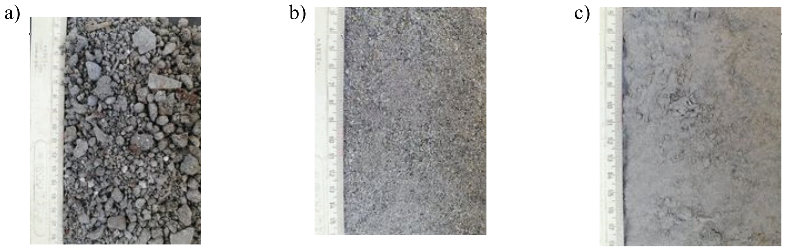

Fig. 1. Slag MSWI 1, a) granulated, b) sand fraction, c) cement fraction
Fig. 1. Żużel MSWI 1, a) granulowany, b) frakcja piaskowa, c) frakcja cementowa

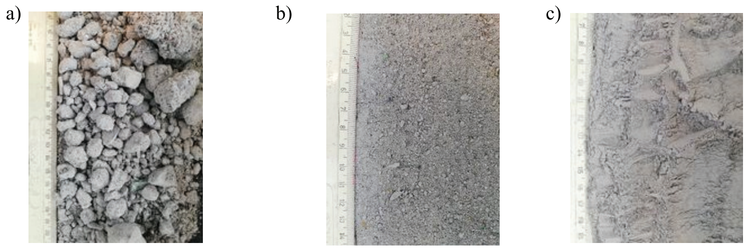

Fig. 2. Slag MSWI 2, a) granulated, b) sand fraction, c) cement fraction
Fig. 2. Żużel MSWI 2, a) granulowany, b) frakcja piaskowa, c) frakcja cementowa

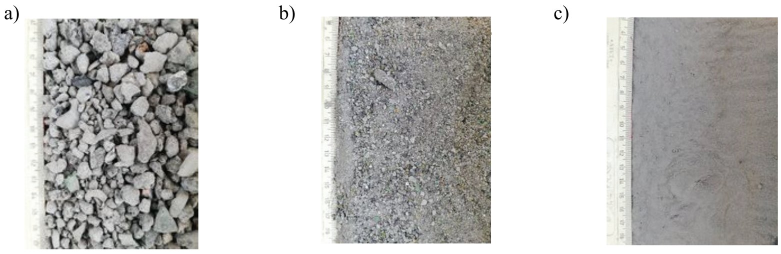

Fig. 3. Slag MSWI 3, a) granulated, b) sand fraction, c) cement fraction
Fig. 3. Żużel MSWI 3, a) granulowany, b) frakcja piaskowa, c) frakcja cementowa

of municipal waste require constant analyses, mainly regarding their chemical composition, on the basis of which it will be possible to make a decision regarding their potential use, for example for the production of concrete. The approach proposed in the article is pro-ecological, because waste is eliminated from the environment while maintaining a reserve of raw materials. The proposed solution is in line with the direction of climate neutrality and the circular economy.

The aim of the article is to initially assess the physical and chemical properties of slags from selected Municipal Waste Thermal Treatment Plants as an additive to concrete or alternative aggregate in road construction. Currently, there are no standards specifying the requirements for slag from incineration of municipal waste as a fully-fledged raw material for the construction industry. For the purposes of this article, the requirements for ground granulated blast furnace slag (GBFS), commonly used as a type II additive in the composition of concrete, were taken as a reference point for considerations.

2. Materials and Methodology

2.1 Materials

The material used in the research were slags, formed as by-products during thermal processing of mixed municipal waste. They mainly consisted of mineral (non-flammable) substances. According to the Catalog of Wastes [7], with the code 19 01 12 the slags are classified as bottom ash and slags other than those mentioned in 19 01 11). The analyzed slags came from three incineration plants. In order to facilitate their identification in the further part of the article, the following designations were adopted:

- Slag MSWI 1 – slag from a Municipal Waste Incineration Plant equipped with a sliding grate with an annual installation capacity of 220,000 Mg,
- Slag MSWI 2 – slag from a Municipal Waste Incineration Plant equipped with a sliding grate with an annual installation capacity of 210,000 Mg,
- Slag MSWI 3 – slag from a Municipal Waste Incineration Plant equipped with a reciprocating grate with an annual installation capacity of 94,000 Mg.

Slag MSWI 1 in the raw state did not exceed a fraction of 2 cm. It was characterized by a dark gray color. Numerous particles of glass and metals were visible. The slag was mechanically treated in order to obtain a fraction similar to sand and cement. Fig 1 shows slag MSWI 1 in the raw state and after the mechanical treatment.

Slag MSWI 2 in the raw state did not exceed the fraction of 3 cm. It was light-gray in color. Compared to the slag MSWI 1, slag MSWI 2 contained less glass and metal particles. In order to obtain a fraction similar to sand and cement, the slag was grinded. Figure 2 shows the slag MSWI 2 in the raw state and after the mechanical treatment.

Slag – MSWI 3 in the raw state, did not exceed the fraction of 1–2 cm. It was characterized by a gray color. It con-

Tab. 1. Basic technical properties of tested slags, expressed in % [*blq –values below the limit of quantification]

Tab. 1. Podstawowe właściwości techniczne badanych żużli, wyrażone w %

Properties	Symbol	Unit	Slag – MSWI 1	Slag – MSWI 2	Slag – MSWI 3	Standard requirement GBFS [26]
Moisture	M	%	1.19	0.70	4.84	≤ 1.0
Total carbon	C	%	1.44	2.26	1.88	-
Total organic carbon	TOC	%	blq	blq	blq	-
Sulfur	S	%	0.75	0.55	0.71	≤ 2.0
Chlorine	Cl	%	0.42	0.22	0.25	≤ 0.1

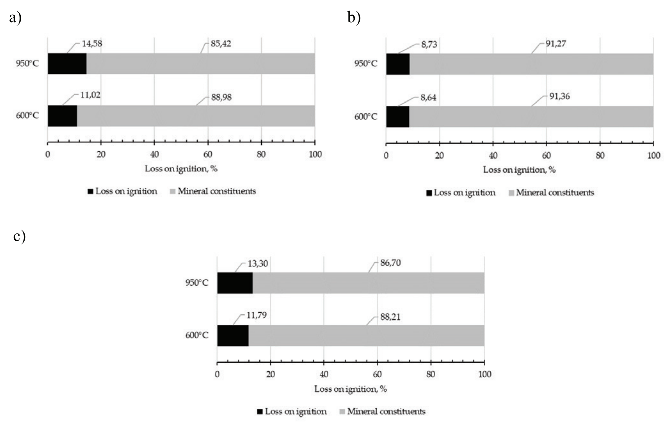

Fig. 4. Loss on ignition (LOI), a) slag – MSWI 1, b) slag – MSWI 2, c) slag – MSWI 3

Rys. 4. Strata przy zapaleniu (LOI), a) żużel – MSWI 1, b) żużel – MSWI 2, c) żużel – MSWI 3

Tab. 2. Content of oxides (%) in the tested materials

Tab. 2. Zawartość tlenków (%) w badanych materiałach

Properties	Symbol	Slag – MSWI 1	Slag – MSWI 2	Slag – MSWI 3	Standard requirement GBFS [26]
Silicon dioxide	SiO_2	50.50	57.90	54.50	37.63
Iron(III) oxide	Fe_2O_3	5.00	4.97	4.19	1.48
Aluminium oxide	Al_2O_3	11.30	10.80	6.53	6.84
Manganese(II,III) oxide	Mn_3O_4	0.11	0.12	0.13	-
Titanium dioxide	TiO_2	0.95	0.50	0.66	-
Calcium oxide	CaO	16.50	12.50	16.30	45.63
Magnesium oxide	MgO	1.77	1.73	1.80	5.33
Sulfur trioxide	SO_3	1.39	0.74	1.67	0.08
Phosphorus pentoxide	P_2O_5	1.12	0.74	0.99	-
Sodium oxide	Na_2O	4.16	6.61	5.62	0.55
Potassium oxide	K_2O	0.84	0.95	1.05	0.56
Barium oxide	BaO	0.14	0.14	0.12	-
Strontium oxide	SrO	0.04	0.06	0.06	-

Tab. 3. Properties of tested slags in relation to the standard requirements of PN-EN 197-1 [28]

Tab. 3. Właściwości badanych żużli w odniesieniu do wymagań normowych PN-EN 197-1 [28]

Requirements according to PN-EN 15167-2		Slag – MSWI 1	Slag – MSWI 2	Slag – MSWI 3	GBFS [28]
Glassy Phase	≥67,0%	-	-	-	
$CaO+MgO+SiO_2$	≥67%	68.77	72.13	72.60	89.00
$(CaO + MgO)/SiO_2$	≥ 1,0	0.36	0.25	0.33	1.18
CaO/SiO_2	1,3 ÷ 1,4	0.33	0.21	0.30	1.03
$(CaO+MgO)/(SiO_2+Al_2O_3)$	1,0 ÷ 1,3	0.30	0.21	0.30	0.98
$(CaO+1,4*MgO+0,56*Al_2O_3)/SiO_2$	≥1,65	0.50	0.36	0.41	1.36
$(CaO+MgO+Al_2O_3)/SiO_2$	≥1,0	0.58	0.43	0.45	1.21

Tab. 4. Heavy metal concentration, expressed in mg/kg

Tab. 4. Stężenie metali ciężkich, wyrażone w mg/kg

Properties	Symbol	Slag – MSWI 1	Slag – MSWI 2	Slag – MSWI 3
Zinc	Zn	2797.00	1621.00	2337.00
Copper	Cu	21608.00	1918.00	867.00
Lead	Pb	766.00	687.00	437.00
Nickel	Ni	73.60	81.00	211.00
Chrome	Cr	277.00	342.00	605.00
Cadmium	Cd	5.80	3.35	0.96
Arsenic	As	5.30	16.50	6.07
Vanadium	V	31.80	30.00	30.70
Thallium	Tl	<1.00	<1.00	-
Mercury	Hg	0.04	0.24	<0.01

tained significant amounts of glass and metals. The slag was mechanically treated in order to obtain a fraction similar to sand and cement. After grinding, no excessive dusting was observed, it was related to the higher humidity of the slag. Figure 3 shows the slag – MSWI 3 in the raw state and after mechanical treatment.

2.2 Methods

The first analytical step was to determine the total water content according to the PN-EN 15934: 2013 standard [20]. Then, the tested slags were mechanically ground using a ball mill in order to obtain an appropriate degree of homogenization for further analytics. The prepared samples were subjected to selected physicochemical analyzes. The determination of roasting losses was performed according to PN-EN 15935:2013-02 [21]. Then the slags were tested for the content of the following elements according to individual standards: carbon (C) - PN-EN 15407: 2011 [22], organic carbon (TOC) - PN-Z-15011-3: 2001 [23], sulfur (S) - PN-ISO 334: 1997 [24] and chlorine (CI) - PN-ISO 587: 2000 [25]. Optical emission spectrometry (ICP OES) was used to assess the oxide composition and heavy metal content in the dry mass of the samples.

3. Results and Discussion

Table 1 presents the basic physicochemical properties of the tested slags, which, in the absence of applicable requirements, have been referred to the requirements to be met by granulated blast furnace slag [26].

The total humidity of the tested slags (slag – MSWI 1 and slag – MSWI 3) was definitely higher than recommended in the norm (≤1.0%). Only slag – MSWI 2 meets the requirements. It is worth noting that increased humidity can affect pozzolanic activity. Undesirable components of a potential mineral additive include: too high content of sulfur compounds, chlorine and unburnt coal. The high content of unburned coal (C>5%) can increase water resistance and reduce the frost resistance of mortars or concrete with its participation. The content of chlorine, sulfur and organic carbon in the tested slags was below 1.0%.

Losses on ignition (LOI) for the tested slags are shown in Figure 4. LOIs were determined by heating the slag samples to a constant mass. A muffle furnace was used to heat the slag samples to a constant mass at two temperatures: 600°C and 950°C under an oxidizing atmosphere. In the case of slag – MSWI 1 and slag – MSWI 3, it was found that LOI at 600°C does not meet the criterion of allowing hazardous waste (LOI≤10%) to be disposed at a landfill. However, for slag – MSWI 2 this criterion was met [27]. The ignition losses for the tested slags were determined by roasting the samples at 950°C over an extended time of up to 1 hour. This parameter is important due to their use in construction. The permissible LOI limit for GBFS is ≤5% [28]. Slags with high ignition losses may cause concrete mixes to become less workable. In slag – MSWI 1 LOI was 14.58%, in the slag – MSWI 2 sample the value was 8.73%, and in the slag – MSWI 3 it was 13.30%.

Following the furnace slag testing, a chemical analysis was performed. Tables 2–4 present the results obtained from the analysis of the oxide composition and heavy metal content of MSWI slags. Table 2 shows the chemical composition of the tested slags and the ratio of individual oxides according to the requirements of the standard characterizing granular blast furnace slag (GBFS). The basic phase component of the studied MSWI was silica – SiO_2. High silica content (SiO_2 >50%) can result in high pozzolanic activity. The CaO content meets the requirements for ground granulated blast furnace slags.

Table 3 presents the properties of granular blast furnace slag in relation to the requirements of PN-EN 197-1 [28]. In accordance with the standard, construction slag should contain at least two-thirds of the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon oxide (SiO2). In the analyzed cases, the slag composition does not meet the required level. The mass ratio (CaO+MgO)/SiO_2 should be higher than 1.0%. The slags shows a lower value than required. Based on calculations, it can be concluded that the tested slags are not hydraulically active.

In the testing of heavy metal content in slags, most trace elements were found to be relatively high (Table 4). Tested slags from the incineration of municipal waste contain heavy metals in the following sequences:

- Slag MSWI 1 – Zn>Cu>Pb>Cr>Ni>V>Cd>As>Tl>Hg
- Slag MSWI 2 – Cu>Zn>Pb>Cr>Ni>V>As>Cd>Tl>Hg
- Slag MSWI 3 – Zn>Cu>Cr>Pb>Ni>V>As>Cd>Hg>Tl

Among the analyzed metals, the highest content for all tested samples was recorded for Cu in the range of 1867.0–21608.0 mg/kg and for Zn in the range of 1621.0–2797.0 mg/kg. The lowest value was recorded for mercury 0.01–0.24 mg/kg.

4. Conclusions

The slags that are generated from the incineration of municipal waste are not an easy raw material to use, but, if properly treated, they can be a good alternative to non-renewable natural resources. The obtained results give a chance for environmentally friendly use for slag from the incineration of municipal waste in construction, e.g. for the production of building materials or for roads. The issue under review may represent the best and cheapest long-term solution in line with the circular economy that could fill the market gap in the context of dwindling anthropogenic resources. During chemical tests, it has been shown that using slag from MSWI in concrete should not be harmful to the environment. However, it is important to note that the composition of the MSWI slag varies depending on the composition of the municipal waste stream sent to the incineration plant. It is necessary to conduct research on the variability of the chemical composition of the resulting slags thruought the year. In order to determine their optimal use in construction, a full set of data must be collected. The next research step will be to design concrete samples with different slag shares and test them under various environmental exposure classes according to PN EN 206. The search for mineral additives for concrete, as well as aggregate substitutes for the road industry is still a current and important topic.

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Rola żużla ze spalania odpadów komunalnych w gospodarce o obiegu zamkniętym

Żużel powstający w procesach degradacji termicznej odpadów komunalnych klasyfikuje się zgodnie z obowiązującymi przepisami jako odpad o kodzie 19 01 12. Szacuje się, że w wyniku spalania odpadów komunalnych powstaje około 0,25 Mg żużla na 1 Mg spalanych odpadów. Z perspektywy gospodarki o obiegu zamkniętym konieczne jest poszukiwanie dla tego materiału nowych zastosowań w przemyśle. Szansą na ich optymalne wykorzystanie są nowe modele biznesowe, w szczególności odzysk produktów ubocznych. Koncepcja ta zakłada, że odpad z jednego procesu jest produktem dla innego procesu. Działanie wymaga nowego spojrzenia na rynek i rozwój nieistniejących wcześniej symbioz przemysłowych. W wyniku ponownego wprowadzenia żużla do obiegu następuje redukcja zużycia zasobów naturalnych, co skutkuje oszczędnościami zarówno ekonomicznymi, jak i środowiskowymi. Celem artykułu jest wstępna ocena właściwości fizycznych i chemicznych żużla ze spalarni odpadów komunalnych jako dodatku do betonu. Na potrzeby oceny wykorzystania żużla w budownictwie przeanalizowano następujące scenariusze: żużel jako zamiennik do kruszywa, piasku i cementu. Badania przeprowadzono na żużlu pozyskanym z trzech różnych instalacji działające w Polsce. W artykule przedstawiono skład tlenkowy i pierwiastkowy żużli, a uzyskane wyniki odniesiono do wymagania dotyczące stosowania granulowanego żużla wielkopiecowego jako dodatku typu II do betonu. Analizowane żużle charakteryzują się niską zawartością chloru (Cl<0,5%), całkowita zawartość siarki kształtowała się na poziomie 0,7%. Zawartość węgla organicznego (TOC) w badanych żużlach był poniżej poziomu analitycznego. Uzyskane wyniki potwierdzają możliwość wykorzystania żużla jako alternatywnego kruszywa lub surowca do betonu. W wykorzystanie popiołów ze spalarni odpadów komunalnych do betonu nie stwarza zagrożenia dla środowiska naturalnego.

Słowa kluczowe: *żużel, surowiec, recykling, beton*