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DEFINING OF EAF STEEL SLAG APPLICATION POSSIBILITIES IN ASPHALT MIXTURE PRODUCTION

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Abstract. Electric arc furnace (EAF) steel slag, generated from carbon steel production process, is the most interesting from the asphalt technology point of view. This paper aims to explore the feasibility of utilizing steel slag as aggregates in asphalt mixtures. Characterization of EAF slag was carried out through examination of its physical and chemical properties with special emphasis on chemical and structural characteristics. Optical Microscopy (OM), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Energy Dispersive Spectrometry (EDS) and γ-spectrometric analysis were employed to study the texture, morphology and composition of steel slag. Volume properties of steel slag were also evaluated as compared to those of natural aggregates. For this purpose the specimens of EAF slag were taken from the regular production processes in CMC Sisak, Croatia, Steel mill. The results which were obtained by testing geometric, physical-mechanic properties, as well as the properties of duration on the specimen of electric furnace steel slag of CMC Sisak, when compared to steel slag properties of other steel producers (Acroni, Jesenice, Slovenia and Štore Steel, Štore, Slovenia) and with properties of natural aggregates, have satisfied the conditions for manufacturing mixtures of the tested steel slag and natural stone, which can be used in asphalt production. In comparison to the natural aggregates, which are used in asphalt mixtures on highways and roads with heavy traffic, the examined steel slag has equally good physical and mechanical properties, while it is significantly better when it comes to resistance to polishing. Special attention has been given to the free CaO and free MgO, which can cause volume instability, thus limiting the use of steel slag in road construction.

Keywords: metallurgical waste; steel slag; road construction; asphalt.

1. Introduction

Of the total amount of all types of waste produced in the electric-furnace process of steel production, steel slag is definitely the most significant in amount, for its amount ranges from 60 to 263 kgt^{-1} of raw steel (Integrated… 2008). Two types of steel slag are produced in electric furnaces; the so-called black steel slag when re-melting unalloyed steel waste and the white steel slag, which is created during the re-melting of alloyed steel waste. These two types of steel slag differ one from another by their chemical and consequentially mineral composition.

The application of steel slag from steel mills was not very popular until the late 1990s, for there were vast amounts of blast-furnace steel slag available, while the steel slag from steel mills was used for the manufacture of chemical fertilizers, where only the so-called Thomas steel slag, a by-product of steel production from phosphorous raw iron, was used. Nowadays, due to a relatively high stake of electric-furnace steel in the total amount of steel produced throughout the world, thus also the growth of available amounts of this type of waste i.e. reduced production of iron in blast furnaces, steel slag is becoming increasingly important, while the application of steel slag is also rapidly growing in the developed countries.

The development of steel slag application was further slowed down by the high level of steel drops in its composition, which was returned into electric furnaces after the separation, and the slag was in most cases disposed of in factory scrap-yards (landfill) for non-hazardous industrial waste.

Taking into consideration that in Croatia we expect a significant increase in steel production via procedures in electric arc furnaces, it is vital to pay more attention to the issue of disposal of most highly represented waste, i.e. by-products, which is EAF steel slag. Even though EAF steel slag has been classified as non-hazardous waste by its physical and chemical characteristics, and is possible to be disposed of at provided disposal sites without danger to the environment, this is rarely applied, because the permanent disposal of steel slag is highly expensive and requires a great area, and the valuable ingredients of steel slag are lost forever. Therefore, it is indispensable to consider the electric furnace steel slag as a by-product and not classify it as metallurgic waste, but to examine it in detail and, in accordance to final results, apply it as a valuable raw material in other industries.

This paper presents the results of testing basic physical and chemical characteristics of water-cooled steel slag with the purpose of its characterization as the type of waste, i.e. by-product of electric furnace processes of

producing carbon steel intended for recycling in other industries. Special attention has been directed at investigating the possibilities of it being used as substitute for natural mineral aggregates when producing asphalt mixtures. Results of analyses usually conducted when testing physical and chemical characteristics of natural mineral aggregates intended for the same purpose are also presented.

2. Methods

The testing has been conducted on steel slag generated during the production of carbon steel by electric furnace process in Steel Mill of CMC Sisak, Croatia. Liquid steel slag was, cooled with water and subjected to the following procedures: grinding, magnetic separation in order to remove leftover particles of the cooled steel melt, fragmentation and sieving. In this way an average specimen of steel slag was created, as well as specimens of granulometric fractions (0/4, 4/8, 8/16 and 16/32 mm).

In order to determine the basic mineralogical and chemical characteristics of the water-cooled steel slag, a mineral analysis was conducted by Optical Microscopy (OM), Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-Ray Diffraction Analysis (X-RDA). The presence of radionuclides and their activity was determined by γ-spectrometry.

As the objective and purpose of this paper were to test the suitability of electric furnace slag for its application in the manufacture of asphalt mixtures, analyses were conducted, which are common when testing physical and chemical properties of natural mineral aggregates intended for the same purpose. A chemical analysis was done according to the standard EN 196, granulometric composition was determined by the wet sieving method according to the standard EN 933-1, the shape of the particle was determined using the flakiness index according to the standard EN 933-3, and the shape index was established according to the standard EN 933-4. Furthermore, resistance to wear was determined according to the standard EN 1097-1, resistance to fragmentation – via Los Angeles method according to the standard EN 1097-2, density and water absorption was determined according to the standard EN 1097-6, polished stone value – according to the standard EN 1097-8, resistance to freezing and thawing –according to the standard EN 1367-1, magnesium sulfate test was conducted according to the standard EN 1367-2, volume stability EN 1744-1 as well as the determination of resistance – to thermal shock according to the standard EN 1367-5.

3. Results and discussion

3.1. Mineralogical analysis of steel slag

Analysis specimens were prepared in the phase of preparation by grinding, which were for identification of certain mineral stages etched by a 1% NH_4Cl solution and 1% borax solution. In order to prevent the hydration of some minerals in slag, ethanol was used for preparations of samples instead of water.

Analysis of water-cooled slag (average sample) preparation identified wustite (FeO), dicalcium and tricalcium silicates ($2CaO.SiO_2$, C_2S i $3CaO.SiO_2$, C_3S), brownmillerite ($Ca_2(Al, Fe)_2O_5$, C_4AF) and mayenite ($12CaO.7Al_2O_3$, $C_{12}A_7$), as showed in Fig. 1.
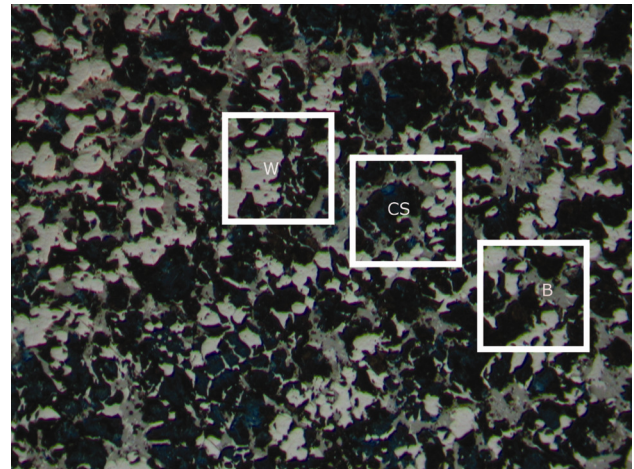
Fig. 1. The optical microscopic analysis of slag depicting the main components: wustite (W), calcium silicates (CS) and brownmillerite (B) (reflected light, magnification 60 x)

The slag is well crystallised, and has a comparatively homogenous structure. The borders and common points of the particles are clearly visible as well as the transfers of one mineral particle into another mineral.

The analysed slag does not contain the glassy phase. The presence of chromites has not been identified, nor free CaO or MgO. The porosity is partially macroscopic, visible by plain sight, with round, oval and xenomorphic pores, average size between 10 and 180 μm. Micro cracks are rare and mostly thin, sometimes outspread, ending in the pores or interconnecting. The average width of the cracks is 30 μm. The characteristic microtexture and slag mineral components are showed in Fig. 2.
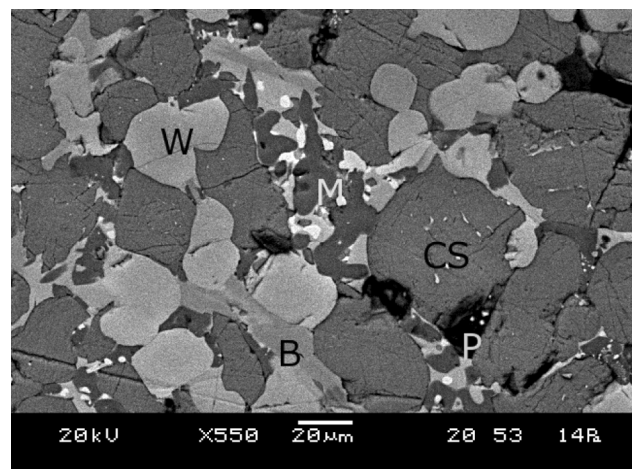
Fig. 2. Scanning electron micrograph (SEM) – characteristic slag microtexture: wustite (W), calcium silicate (CS), brownmillerite (B), mayenite (M), pores (P) and inclusions of iron (white)
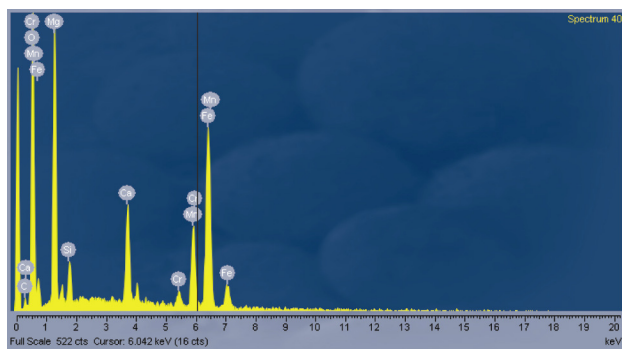
Fig. 3. EDS spectrum of wustite

The chemical composition of particular components was also analysed, first and foremost for the purpose of testing the phase, into which the potentially present chrome was tied. It was determined that chrome, apart from Mg, Mn, Ca and Si, was tied in the wustite structure, which was then confirmed by the X-ray spectrometric analyses of the particle identified as W (Fig. 3).

The microtexture of different steel producers of black steel slag (Fig. 4) is more or less identical, the only significant difference being related to the particle size. The most characteristic minerals are the following: wustite (FeO), which is well crystallized into round and oval-shaped particles, similarly crystallized lamellar larnite with some allite ($C_2S + C_3S$), both of which are embedded in a microcrystalline matrix of brownmillerite (C_4AF), and mayenite ($C_{12}A_{14}O_{33}$).

3.2. X-Ray diffraction analysis of steel slag

The mineral composition of the electric furnace steel slag depends on the very process of steel production, and the basic parameters influencing the slag composition directly are the following: the quality of produced steel, i.e. the quality and composition of steel scrap used as raw material, non-metal supplements and their mass portion in the electric furnace heat (lime, dolomite, bauxite, fluorite), used types and amounts of ferroalloy (Fe-Mn, Si-Mn, Fe-SI, Fe-Cr, etc.), as well as other technological parameters such as amounts of oxygen added, temperature regime of the furnace, manner and dynamics of slag separation, etc.

One of the most important factors influencing their usability is the mineral composition. To be more precise, slag is by its properties quite similar to natural mineral materials, insofar as we pay attention to that in the very process of its creation. Otherwise, it may contain undesired mineral stages, which diminish the required properties, i.e. its usability.

Due to their mineral composition, steel slag from the process of production of unalloyed steel are otherwise known as black steel slag, and they represent a mixture of oxides of a relatively complex chemical composition. They mostly contain calcium and iron oxides, followed by (according to representation) magnesium, silica and aluminium oxides (Motz and Geiseler 2001; Akin Altun and Yilmaz 2002; Khan *et al.* 2002; Bradaškja *et al.* 2004; Frias Rojas and Sanchez de Rojas 2004; Agostina-
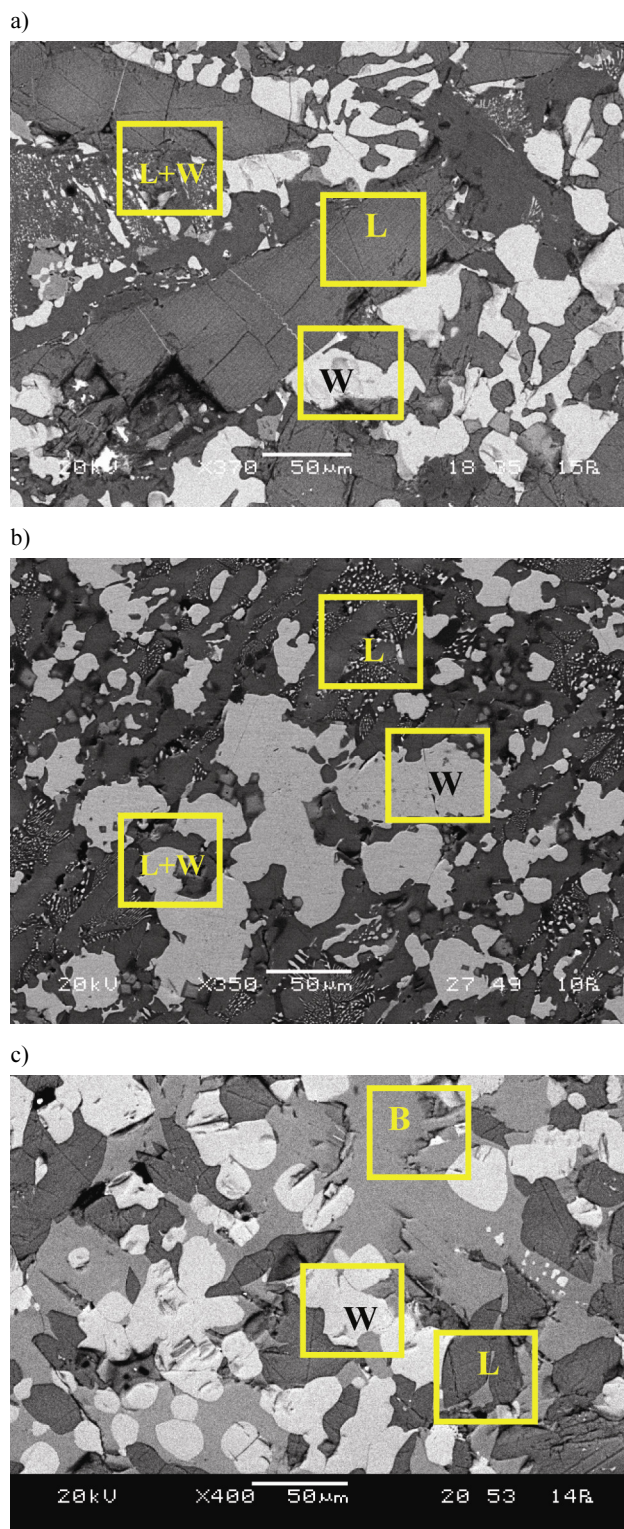

Fig. 4. Scanning electron micrograph (SEM) of the slag: a) Store steel slag, b) Acroni steel slag and c) CMC Sisak steel slag; larnite (L), wustite (W) and brownmillerite (B)

cchio and Olita 2005; de Oliveira Polese *et al.* 2006; Diener 2006; Gomes and Pinto 2006; Shuguang *et al.* 2006; Bernardo *et al.* 2007; Chaurand *et al.* 2007; Cioroi and Nistor 2007; Diener *et al.* 2007; Engström 2007; Kumar 2007; Tossavainen *et al.* 2007; Venkateswaran *et al.* 2007; Wu *et al.* 2007; Lekakh *et al.* 2008; Tsakiridis *et*

al. 2008; Ahmedzade and Sengoz 2009). The structure of steel slag is based on two- and three-component compositions of the type CaO-SiO_2, CaO-FeO, CaO-SiO_2-MnO, CaO-Al_2O_3, CaO-FeO-SiO_2 and CaO-SiO_2-FeO-MgO (Lamut *et al.* 1992; Lamut and Gontarev 1994; Cioroi and Nistor 2007), and the most highly represented minerals in slag are dicalcium and tricalcium silicates, while different aluminates and silicates are likely to appear as well (Šelih *et al.* 2004).

Identification of the present mineral phases has been conducted on the basis of recorded diffractogram (Fig. 5) obtained by recording a rotating slag specimen on the diffractometer device Philips, PW 1830 in the angle area of 5 to 70 $^\circ/2\Theta$ with applying $CuK\alpha$-radiation. The voltage of the X-ray tube was 40 kV, anode electricity totalled 40 mA, and an analyser crystal created out of graphite was used, as well as a proportional counting mechanism. Diffraction data were processed by the computer program Philips X'Pert Software, and specific recorded relative intensities of X-ray diffraction lines were compared to values found in other expert texts on the same topic. The following mineralogical components resulted from X-Ray diffraction analysis of slag: wustite FeO; calcium ferrite $CaFe_2O_4$/(CF); srebrodolskite $Ca_2Fe_2O_5$/(C_2F); larnite Ca_2SiO_4/(C_2S); alite Ca_3SiO_5/(C_3S); mayenite $Ca_{12}Al_{14}O_{33}$/$C_{12}A_7$; brownmillerite $Ca_2(Al,Fe)_2O_5$ /C_4AF. The recorded spectrograms of analysed samples of slag point to the possibility of calcium ferrite $CaFe_2O_4$ (CF) and rankinite $Ca_3Si_2O_7$ (C_3S_2) stages as well.

3.3. Chemical analysis

Chemical analysis of the examined slag (average sample) was conducted according to the standard EN 196-2 intended for cement analysis in order to encompass the analysis of more aggregates in comparison to the standard EN 1744-1 intended for analysis of aggregates.

On the basis of data from previously published work on the chemical composition of steel slag (Motz and Gei-

seler 2001; Akin Altun and Yilmaz 2002; Khan *et al.* 2002; Bradaškja *et al.* 2004; Frias Rojas and Sanchez de Rojas 2004; Agostinacchio and Olita 2005; de Oliveira Polese *et al.* 2006; Diener 2006; Gomes and Pinto 2006; Shuguang *et al.* 2006; Bernardo *et al.* 2007; Chaurand *et al.* 2007; Cioroi and Nistor 2007; Diener *et al.* 2007; Engström 2007; Kumar 2007; Tossavainen *et al.* 2007; Venkateswaran *et al.* 2007; Wu *et al.* 2007; Lekakh *et al.* 2008; Tsakiridis *et al.* 2008; Ahmedzade and Sengoz 2009), one can reach the conclusion that the representation of certain oxides ranges within comparatively broad limitations, which, of course, is the consequence of the quality of steel produced, i.e. the quality and composition of steel scrap used as raw material, type and share in the heat of specific non-metallic supplements, type and amount of ferroalloys, as well as other technological parameters. Thus, CaO ranges from 18.4 to 60%, FeO (2.5–41.2%), Fe_2O_3 (1–31.2%), SiO_2 (6.5–35%), MgO (1.3–31.27%), Al_2O_3 (1–13.44%), MnO (0.60–12%), Na_2O (0.06–0.5%), K_2O (0.02–0.2%), P_2O_5 (0.01–1.8%).

Chemical analysis of investigated slag has determined that CaO content was 33.2%, Fe_2O_3 29.64%, SiO_2 10.08%, MgO 13.09%, Al_2O_3 1.66%, MnO 6.18%, Na_2O 0.02% and K_2O 0.06%, sulphide 0.12%, chloride 0.02%, insoluble residue in HCl and Na_2CO_3 4.18% and insoluble residue in HCl and KOH 0.64%.

3.4. Environmental impact

It is of vital importance to be familiar with the technical significance of the secondary application of waste materials, as well as with their possible environmental effects because some waste materials might contain increased concentrations of substances harmful to human health or the environment, especially to the water (Ettler *et al.* 2003; Narimantas *et al.* 2008; Shams *et al.* 2009; Jaskelevicius and Lynikiene 2009; Venkatesan and Swaminathan 2009).
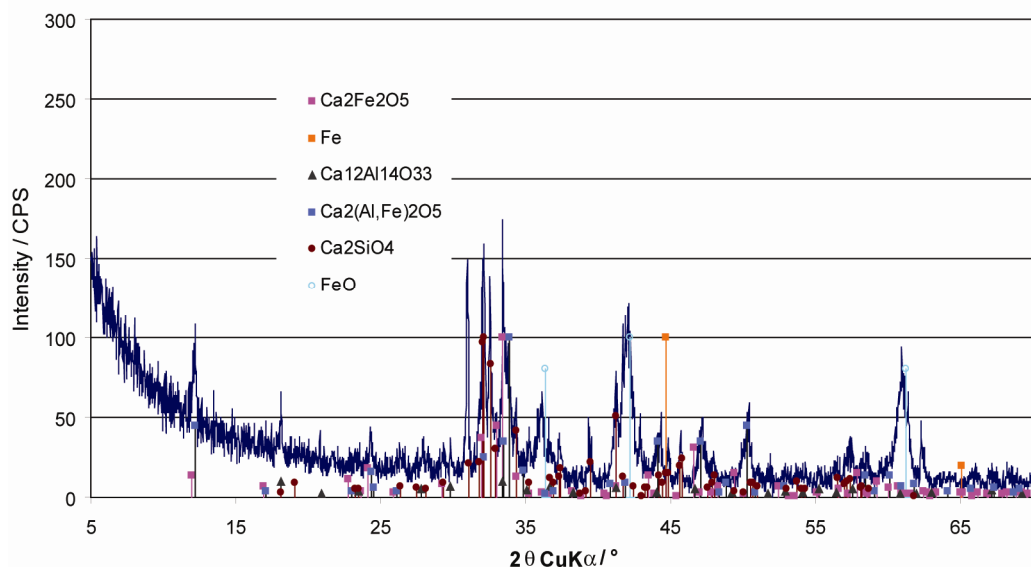

Fig. 5. XRD patterns of investigated slag

The environmental conformity of slags has been investigated for years, which normally should be judged by their leachability. Due to the very low solubility of the most mineral phases of the EAF steel slags in water, the EAF steel slags do not affect the environment.

All the methods, procedures, determination tests and eco-toxicity reviews used nowadays have been developed from the earliest method of elution by distilled water according to the norm DIN 38414-S4 (German standard methods for the estimation of water, waste water and sludges, soils and sediments-group S, 1984), where the solid–liquid ratio is 1/10, and the period of mixing is 24 hours.

Slag specimen was tested in accredited laboratory, and with the purpose of determining physical and chemical characteristics of slag waste for permanent disposal, according to valid regulations (Ordinance... 2007). The final results of determining physical and chemical characteristics of the eluate, presented in Table 1, show that steel slag satisfies the prescribed conditions, according to which it is allowed to permanently dispose of it at disposal sites of categories I and II.

In terms of the chemical composition of the steel slag, and especially if it is regarded as material, which could also be applied in the construction industry, i.e. road-construction, a vital parameter is the amount of free oxides of calcium and magnesium. More precisely, the constituent amount of free CaO and free MgO is one of the most significant parameters when estimating the possibility of using steel slag in the construction industry, and it is reflected in the so-called volume stability.

Results of slag expansion determined according to the standard EN 1744-1 are presented in Table 2.

To define EAF steel slag application possibilities in asphalt mixture production, it was necessary to prove its volume stability (according to Item 19.3 of the standard EN 1744-1). The volume stability test results, on average 2.9%, have shown that steel slag aggregates are applicable for use in asphalt mixture production.

Table 1. Results of measuring parameter values of slag (average sample) eluate intended for permanent disposal according to Croatian Regulations for waste disposal

Parameters	Method	mg/kg of dry substance	
		Limiting value of eluate parameter *T/K = 10 l/kg	Measured value of eluate parameter
Arsenic / As	EN ISO 11969	2	<0.1
Barium / Ba	Standard Methods 3111D, 3113 – Ba. 19th Edition 1995	100	<15.9
Cadmium / Cd	ISO 8288	1	<0.1
Total chromium/Cr	EN ISO 11885	10	<0.5
Copper / Cu	ISO 8288	50	<1
Mercury / Hg	EN 1483	0.2	<0.05
Molybdenum / Mo	ISO 15586	10	<0.628
Nickel / Ni	ISO 8288	10	<1
Lead / Pb	ISO 8288	10	<1
Antimony / Sb	Standard Methods 3113/PE Apl. note – Sb. 19th Edition 1995	0.7	<0.05
Selenium / Se	ISO 9965	0.5	<0.05
Zink / Zn	ISO 8288	50	<1
Chlorides / Cl–	ISO 10304-1	15 000	133
Fluoride / F–	DIN 3845-D4	150	0.411
Sulphates / SO42–	EN 10304-1	20 000	17.4
Dissolved organic carbon – DOC / C	EN 1484	800	25.4
Total dissolved substances	DIN 3845-H1-2	60 000	6800

*L/S = *liquid/solid*

Table 2. Results of determining slag expansion to EN 1744-1

Specimen mark	Slag specimen volume (cm^3)	Specimen volume mass (mg/m^3)	Amount of pores in the specimen (vol %)	Change in specimen height (mm)	Specimen expansion (vol %)	Average expansion (vol %)	Differences among specimens (vol %)	Standard deviation (vol %)
1	1572	2.78	25.31	1.19	2.62	2.9	–0.54	0.39
2	1579	2.77	25.60	1.44	3.16			

3.5. Determining activities of ^{40}K, ^{232}Th (^{228}Ra), ^{226}Ra and ^{238}U

Data from previous works (Lubenau and Yusko 1995, 1998; Sofilić *et al.* 2004) indicate the appearance of radionuclide in the waste from steel production processes, and the most common radionuclides are the following: ^{137}Cs, ^{60}Co, ^{226}Ra, ^{192}Ir, ^{241}Am, ^{232}Th and ^{90}Sr, which are distributed among the melt, slag and electric arc furnace dust during the technological process of steel production, depending on their chemical and physical properties (Lubenau and Yusko 1995, 1998). In line with the said, and according to valid Croatian regulations (Ordinance on the conditions, methods and terms for systematically research and monitoring of types and activities of radioactive substances in air, soil, see, rivers, lakes, underground waters, solid and liquid rainfalls, drinking water, food and stuff of commonly usage, 2008), in order for the electric furnace slag to be used as supplement in the production of construction material, it is essential to be familiar with the composition and amount of radionuclide in such a material, which is exactly why it was exposed to a γ-spectrometric analysis. Quantity determination, i.e. calculating the activity of particular radionuclide, was done on a specimen of electric furnace slag by applying a γ-spectrometric method.

The presence of radionuclides and their activity was determined by using a Canberra γ-spectrometric system with a Ge-detector connected to a 4096 channel analyser by the same manufacturer.

Measurement conditions were set so that the energy difference between the two channels amounted to ~0.50 keV, and the time period of the measurement was 100 000 to 200 000 seconds. In this manner, the presence of natural isotopes ^{40}K, ^{232}Th (^{228}Ra), ^{226}Ra and ^{238}U was determined in the specimens of electric furnace slag, as presented in Table 3.

In detail, in order for the electric furnace slag to be used as supplement in the production of construction materials it is essential to fulfil the prescribed Croatian maximum limit of radioactivity in construction material, which should not exceed the following concentration of activities: 300 Bqkg^{-1} for ^{226}Ra; 200 Bqkg^{-1} for ^{232}Th and 3000 Bqkg^{-1} for ^{40}K, so that this condition is met:

$$(C_{Ra}/300) + (C_{Th}/200) + (C_K/3000) \leq 1,$$

where: C_{Ra}, C_{Th} and C_K are the concentrations of appropriate radionuclide in Bqkg^{-1}.

The calculated values of radioactivity in the analysed electric furnace slag lead to the conclusion that the analysed slag can be used as supplement in the production of construction materials, because the calculated index values of present radionuclides were <1 i.e. smaller than the maximum allowed limit.

3.6. Determination of the mechanical characteristics of electric furnace slag

For the purpose of determining suitability of slag for usage in the production of asphalt mixtures, it was exposed to the testing of its geometric, physical and mechanical properties, as well as durability, Table 4–9. The results of those tests have been compared to natural aggregates commonly used in the manufacture of asphalt mixtures. Geometric properties of the slag in terms of shape index and flakiness index (FI_{10}; SI_{15}) satisfy the highest criteria.

Granulometric composition of 0/4 mm fraction meets the G_A85 criterion, and the ratio of small particles is 6.6%; fractions 4/8, 8/16 mm, according to their granulometric

Table 3. Results of γ-spectrometric analysis of the steel slag

Granulometric fraction (mm)	Activity, Bqkg^{-1}				$(C_{Ra}/300) + (C_{Th}/200) + (C_K/3000)$
	^{40}K	^{232}Th (^{228}Ra)	^{226}Ra	^{238}U	
0/4	22.0±2.8	14.4±0.9	24.0±0.8	24.1±2.8	0.159
4/8	<8.42	11.0±2.09	13.4±1.93	9.05±3.68	<0.110
8/16	14.2±6.22	9.66±2.07	16.9±2.21	13.2±4.40	0.109
16/32	14.1±6.81	10.2±2.12	14.8±2.04	13.3±4.53	0.105

Table 4. Resistance to wear 'micro-Deval' according to EN 1097-1

Classification class of the specimen tested and the type of testing	Fraction size of the test portion of the specimen (mm)	Micro-Deval coefficient for every specimen M_{DE}	Median value of micro-Deval coefficient $\overline{M}_{DE}$	Class (EN 13043) M_{DE}
8/16 mm	10/11.2 (30–40%)	7.8	8	$M_{DE}10$
Wet	11.2/14 (70–30%)	7.3		

Table 5. Resistance to fragmentation via 'Los Angeles' method according to EN 1097-2

Tested fraction size (mm)	Tested fraction portion (mass %)	Los Angeles coefficient LA	Class (EN 13043) LA
10/11.2	30	13	LA_{15}
11.2/14	70		

Table 6. Determining resistance to thermal shock according to EN 1367-5

Type of aggregate Tested fraction *di/Di*	Loss of mass after the thermal shock	Method determining hardness EN 1097-2 Los Angeles		Loss of hardness after the thermal shock (resistance to thermal shock) ($V_{LA} = LA_2 - LA_1$)
		LA_1 Coefficient without heating	LA_2 Coefficient after the thermal shock	
Slag 10–14 mm	0.4%	12.8	14.1	1.3

Table 7. Polishing testing according to EN 1097-8

Respective values of the polishing quality of the test aggregate / PSV	Median value of the polishing quality of the test aggregate / S	Respective values of the polishing quality of the control aggregate PSV	Median value of the polishing quality of the control aggregate C	Median value of the polishing quality of the aggregate PSV PSV=(S+52.5-C)	Class (EN 13043) PSV
72.0		54.7			
73.0	71.6	54.3	54.5	70	PSV_{68}
71.0		55.0			
70.3		54.0			

Table 8. Determining density via water absorption method according to EN 1097-6

Fraction (mm)	Portion of test fraction in total specimen (mass %)	Dry test specimen mass (g)	Density (Mg/m^3)			Water absorption WA_{24}, (%)
			ρ_{ssd}	ρ_{rd}	ρ_a	
0/4	100	1041.2	3.49	3.41	3.69	2.2
4/8	100	1103.9	3.65	3.59	3.82	1.7
8/16	100	2083.7	3.73	3.68	3.88	1.5
16/32	100	5080.4	3.64	3.57	3.82	1.8

Table 9. Comparison of physical properties of slag and natural aggregates

Characteristic	CMC Sisak slag	Store Steel slag	Acroni Steel slag	Diabaz Croatia	Bazalt Austria	Filit Slovenia
Resistance to fragmentation (LA)	13	17	16	15	15	20
Resistance to abrasion (micro-Deval)	8	7	8	8	8	10
Frost resistance (Mg$_2$SO$_4$, % by weight)	1.0	0.2	0.3	0.0	0.0	0.0
Frost resistance, freezing and thawing (% by weight)	0.4	0.0	0.0	0.0	0.0	0.0
Fines (% by weight)	0.5	0.6	0.1	0.5	0.5	0.7
Water absorption (% by weight)	1.3	0.5	0.5	0.4	0.6	0.5
Bulk density (Mg/m^3)	3.4	3.7	3.7	2.8	2.8	2.9
Volume stability (% V/V)	2.9	1.6	1.3	NR	NR	NR

NR- not relevant

composition satisfy the highest criterion **G$_C$ 90/10**, while fraction 16/32 mm has been classified as (**G$_C$ 90/15***)*; small particles ratio in 0.063 mm on 8/16 and 16/32 mm fractions is smaller than 0.5%, which puts them in the highest class **f$_{0,5}$**, whereas fraction 4/8 mm has a 0.9% ratio, classifying it as **f$_1$**. The obtained results showed that slag resistance to wear in the wet state meets the requirements of the highest class (**M$_{DE}$10**), Table 4. Resistance of slag to fragmentation via the 'Los Angeles' method places it to the highest class (**LA$_{15}$***)*, and after the thermal shock, the decrease in hardness is a minor 1.3,

which makes it enter the highest class in this category as well, Tables 5 and 6. The obtained polishing value is very high, satisfying the highest criteria (**PSV$_{68}$**), Table 7. The determined densities are high, which was to be expected considering aggregate origin, Table 8. The water absorption on tested fractions is more than l%, the durability via testing by magnesium sulphate and by freezing and thawing method. The final results have met the highest criteria. Affinity of aggregate to bituminous binder is very good (>90%).

Due to similarities in the mineral composition of the observed slag from CMC Sisak and those from steel mills of Store Steel and Acroni, Slovenia, their similarities in mechanical characteristics, as showed in Table 9, were to be expected. When comparing the mechanical characteristic of the tested slag with the same characteristics of natural aggregates, a comparative similarity was noted, as presented in Table 9 as well.

4. Conclusion

On the basis of tested mechanical, physical and chemical properties of electric furnace slag created as by-product during the production of electro-steel in the steel mill of CMC Sisak, Croatia, and with the purpose of determining its suitability for partial or complete replacement of natural aggregates when producing asphalt mixtures, it has been concluded that:

- Wustite (FeO), dicalcium and tricalcium silicates ($2CaO.SiO_2$, C_2S i $3CaO.SiO_2$), brownmillerite ($Ca_2(Al,Fe)_2O_5$) and mayenite ($12CaO.7Al_2O_3$) are the most highly represented mineral phases;
- Apart from the said mineral stages, which are more or less represented in the previous research, reflected in available work, the recorded spectrograms of the analysed steel slag specimens indicate the possibility of the presence of the following stages: $CaO.Fe_2O_3$ and $CaO.2Fe_2O_3$;
- The analysed steel slag does not contain the glassy phase, the presence of chromites has not been identified, and the low representation of CaO or MgO fulfils the prescribed requirements of volume stability when estimating the slag in terms of its application in the construction industry;
- Chemical analysis has determined that CaO content is 33.2%, Fe_2O_3 29.64%, SiO_2 10.08%, MgO 13.09%, Al_2O_3 1.66%, MnO 6.18%, Na_2O 0.02% and K_2O 0.06%.
- Determination of waste eco-toxicity intended for permanent disposal or some other phase of disposal has been conducted by examining the composition of its eluate received by simulating the sieving of water through the waste, and the final results showed that the slag does not contain constituent, which might in any way affect the environment harmfully, thus that it can be disposed of at non-hazardous waste disposal site;
- Quantity determination, i.e. calculating the activity of particular radionuclide was done on a specimen of electric furnace slag and the presence of radionuclides and their activity showed that the analysed slag can be used as supplement in the production of construction materials, because the calculated index values of present radionuclides are smaller than the maximum allowed limit;
- All results of the tested geometric, physical and mechanical properties as well as durability indicate that steel slag fulfils the conditions required for aggregates used for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas (EN 13043:2002/AC:2004).

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ELK PLIENO ŠLAKO PANAUDOJIMO GAMINANT ASFALTO MIŠINĮ GALIMYBĖS

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S a n t r a u k a

Nagrinėjamos plieno šlako panaudojimo asfalto mišiniui gaminti galimybės. Šis šlakas susidaro elektros lanko krosnyje (ELK) anglies plieno gamybos procese. Nagrinėjamos fizikinės bei cheminės šlako savybės, pateikiamos cheminės ir struktūrinės charakteristikos. Plieno šlako tekstūra, morfologija ir sudėtis nustatyta taikant optinę mikroskopiją (OM), rentgeno spindulių difrakciją (RSD), skenuojančiąją elektroninę mikroskopiją (SEM), energijos dispersinę spektrometriją (EDS) bei spektrometrinę analizę. ELK šlako mėginiai buvo paimti iš plieno gamyklos *CMC Sisak*, Kroatijoje. Šių mėginių geometrinės, fizikinės ir mechaninės bei patvarumo savybės buvo lyginamos su kitų šlakų (*Acroni, Jesenice*, Slovėnija ir *Store steel*, *Štore*, Slovėnija) ir natūralių agregatų savybėmis. Gauti rezultatai patvirtino tirto plieno šlako bei natūralaus akmens panaudojimo gaminant asfaltą galimybes. Natūralūs agregatai, naudojami asfalto mišiniuose tiesiant greitkelius ir intensyvaus eismo kelius, bei tiriamas plieno šlakas turi panašių gerų fizikinių bei mechaninių savybių, tačiau ELK šlakas yra atsparesnis glūdinimui. Daug dėmesio buvo skirta laisviesiems CaO ir MgO, lemiantiems medžiagos nepatvarumą. Šie oksidai yra pagrindinis veiksnys, ribojantis plieno šlako naudojimą asfaltui gaminti.

Reikšminiai žodžiai: metalurgijos atliekos, plieno šlakas, kelių tiesyba, asfaltas.

ВОЗМОЖНОСТИ ПРИМЕНЕНИЯ СТАЛЬНОГО ШЛАКА ИЗ ДУГОВОЙ СТАЛЕПЛАВИЛЬНОЙ ПЕЧИ ДЛЯ ПРОИЗВОДСТВА АСФАЛЬТОВОЙ СМЕСИ

Т. Софилич, А. Младенович, У. Софилич

Р е з ю м е

В статье ставилась цель исследовать возможности применения стальных шлаков, образующихся в процессе производства стали в дуговой сталеплавильной печи (ДСП), для производства асфальтовой смеси. Исследовались физические и химические свойства шлака из ДСП. Текстура, морфология и состав стального шлака определялись с использованием оптической микроскопии, дифракции рентгеновских лучей, электронной микроскопии, энергодисперсной спектрометрии и γ-спектрометрического анализа. Образцы шлака из ДСП были взяты на заводе по производству стали в Хорватии. Геометрические, физико-механические и прочностные свойства образцов сравнивались со свойствами других шлаков (из Словении) и с натуральными материалами. Полученные результаты подтвердили возможность применения шлака исследованной стали и натурального камня для производства асфальтовой смеси. Натуральные материалы, применяемые в асфальтовых смесях при строительстве магистралей и дорог с интенсивным движением, и исследованный стальной шлак обладают приблизительно одинаковыми хорошими физико-механическими свойствами, однако шлак из ДСП более устойчив при шлифовании. При анализе большое внимание также уделялось свободным CaO и MgO, вызывающим нестабильность материала. Эти оксиды являются основным фактором, лимитирующим применение стального шлака при производстве асфальта.

Ключевые слова: отходы металлургического производства, стальной шлак, строительство дорог, асфальт.

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