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STEEL SLAG INSTEAD NATURAL AGGREGATE IN ASPHALT MIXTURE

ŻUŻEL STALOWNICZY, JAKO ZAMIENNIK KRUSZYW NATURALNYCH STOSOWANYCH W MIESZANCE ASFALTOWEJ

Even though electric arc furnace (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.

The purpose of this paper was to improve the management of this type of non-hazardous industrial waste. Alongside with reducing the area intended for its disposal and increasing the technological benefit of re-using waste material, the final results of these tests should ensure the economic profit of producers, as well as achieve a sociological-ecological benefit due to the reduction of expenditure of natural mineral aggregates, simultaneously enhancing the sustainable development policies in metallurgy.

A part of this research examines the possibilities of using EAF slag in other industries, with a special focus on using the slag as substitute for natural mineral aggregates in the production of asphalt mixtures in road construction. The paper presents the results of testing physical and mechanical properties of EAF slag coming from the regular production of unalloyed carbon steel in CMC Sisak, Croatia with the application of prior processing encompassing cooling the liquid slag by air, as well as quenching by water, grinding, magnetic separation, fragmentation and granulometric fractioning for the purpose of its application in technologies of producing asphalt mixtures.

Comparison of test results between specimens of water- and air-cooled EAF slag and natural aggregates used in asphalt mixtures on highways and other top-class traffic load roads has demonstrated that the examined slag has equally good physical and mechanical properties, while it is significantly better in terms of resistance to polishing.

Keywords: steel slag, waste, aggregates, road construction, asphalt

Pomimo faktu, że żużel z elektrycznych pieców łukowych (EAF) do wytopu stali został sklasyfikowany jako odpad inny niż niebezpieczny w oparciu o charakterystykę fizyczną i chemiczną, i możliwe jest jego składowanie na odpowiednich składowiskach bez zagrożenia dla środowiska naturalnego, jest to rzadko stosowane, ponieważ stałe składowanie żużla jest bardzo kosztowne i wymaga dużych powierzchni, a cenne składniki żużla są tracone na zawsze.

Celem pracy była poprawa zagospodarowania tego rodzaju odpadów przemysłowych. Wraz ze zmniejszeniem powierzchni przeznaczonej na składowanie żużla i zwiększeniem korzyści technologicznych z ponownego wykorzystania odpadów, ostateczne wyniki tych badań powinny zapewnić osiągnięcie zysku producentów, jak również osiągnięcia korzyści społeczno-ekologicznych ze względu na zmniejszenie zużycia naturalnych kruszyw mineralnych, a jednocześnie wzmocnienie polityki zrównoważonego rozwoju w hutnictwie.

Część tych badań analizuje możliwości wykorzystania żużla EAF w innych gałęziach przemysłu, ze szczególnym naciskiem na wykorzystanie żużla jako substytut naturalnych kruszyw mineralnych w produkcji mieszanek mineralno-asfaltowych w budownictwie drogowym. W artykule przedstawiono wyniki badań fizycznych i mechanicznych właściwości żużla EAF pochodzącego z regularnej produkcji stali węglowej niestopowej w CMC Sisak, Chorwacja z zastosowaniem uprzedniego przetworzenia obejmującego chłodzenia ciekłego żużla w powietrzu, jak również chłodzenia wodą, rozdrabniania, separacji magnetycznej, rozdrobnienia i frakcjonowania w celu jego stsowania w technologii produkcji mieszanek mineralno-asfaltowych.

Porównanie wyników badań próbek żużla chłodzonego wodą i chłodzonego powietrzem oraz kruszyw naturalnych stosowanych w mieszankach asfaltowych na autostradach i innych drogach o dużym obciążeniu ruchem wykazało, że badany żużel ma równie dobre właściwości fizyczne i mechaniczne, a jednocześnie jest znacznie lepszy pod względem odporności na ścieranie.

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1. Introduction

Steel mills, just as most metallurgical plants, influence the environment directly with their activities. Alongside with air and water pollution, they further burden the environment with their by-products, i.e. various hazardous and non-hazardous technological wastes, which are most commonly disposed of at their inadequate scrap-fills. The most common technological waste inadequately disposed of in the said manner is: unprocessed steel slag, used refractories, metal scrapings, various sludge, dust from smoke, mill scale, etc.

Of the total amount of all types of waste created 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 as presented in IPPC Directive document [1].

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 demonstrates the results of testing physical and chemical characteristics of water and air cooled steel slag with the purpose of its characterization as the type of waste, i.e. by-product of electric furnace processes of producing unalloyed carbon steel intended for reusing 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 demonstrated.

2. Exsperimental

The testing has been conducted on steel slag created during the production of EAF low carbon steel in Steel Mill of CMC Sisak, Croatia. Liquid steel slag was, after being poured out of the electric furnace cooled with air and water, after which it was 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 (0/4mm, 4/8mm, 8/16mm i 16/32mm).

In order to determine the physical and chemical characteristics of the air and water-cooled steel slag, a mineral analysis was conducted by optical microscopy, Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-Ray Diffraction Analysis (X-RDA). Considering that in Croatia steel slag is mainly disposed at non-hazardous waste disposals, an examination of its physical and chemical properties was also conducted in order to prove that this kind of disposal at disposal sites of the said type does not present the danger of pollution to the environment.

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 EN 196 norm, the shape of the particle was also determined using the flakiness index according to the EN 933-3 norm, shape index according to the norm EN 933-4. Furthermore, resistance to wear was determined according to the norm EN 1097-1, resistance to fragmentation via Los Angeles method according to the norm EN 1097-2, density and water absorption was determined according to the norm EN 1097-6, polished stone value according to the norm EN 1097-8, resistance to freezing and thawing according to the norm EN 1367-1, magnesium sulfate test was also conducted according to the norm EN 1367-2, as well as the determination of volume stability according to the norm EN 1744-1.

3. Results and discusion

3.1. Mineralogical analysis of steel slag

Analysis specimens were prepared in the form 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 microscope preparations instead of water.

Analysis of water-cooled slag preparation identified wustite (FeO), dicalcium and tricalcium silicates ($2CaO \cdot SiO_2$, C_2S and $3CaO \cdot SiO_2$, C_3S), brownmillerite ($Ca_2(Al, Fe)_2O_5$, C_4AF) and mayenite ($12CaO \cdot 7Al_2O_3$, $C_{12}A_7$), as demonstrated in Figure 1.

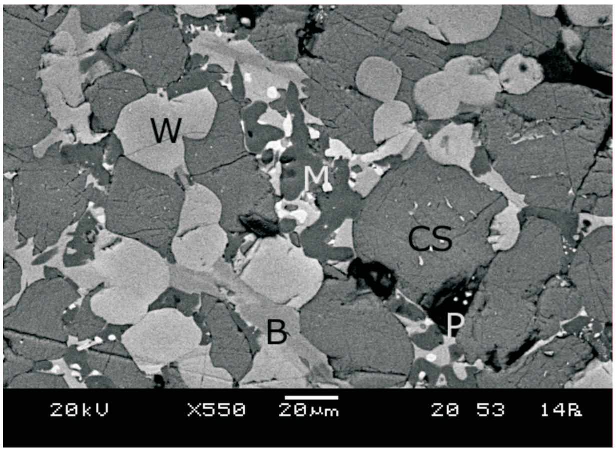

Fig. 1. Scanning electron micrograph (SEM) – wustite (W), calcium silicate (CS), brownmillerite (B), mayenite (M), pores (P) and inclusions of iron (white)

Wustite grains (FeO) are shaped round or oval, with the size of up to 100 µm, which are touching or combining, thus creating larger grains. Dicalcium and tricalcium silicates ($2CaO \cdot SiO_2$, C_2S and $3CaO \cdot SiO_2$, C_3S) appear after etching as blue and brown grains of prismatic and xenomorphic shape with characteristic cracks, reaching the size of up to 100 µm. Brownmillerite ($Ca_2(Al, Fe)_2O_5$, C_4AF) is not etched and is a shade darker than the wustite. It fills the interstition space among the grains of wustite and calcium silicates. Sometimes it has a round shape. The present mayenite ($12CaO \cdot 7Al_2O_3$, $C_{12}A_7$), just as the brownmillerite fills the space between the crystallized grains, and the melted iron (Fe) appears in the shape of larger inclusions, reaching the size of up to 1mm, or as microscopic inclusions of round, oval or xenomorphic shape of size up to 20 µm.

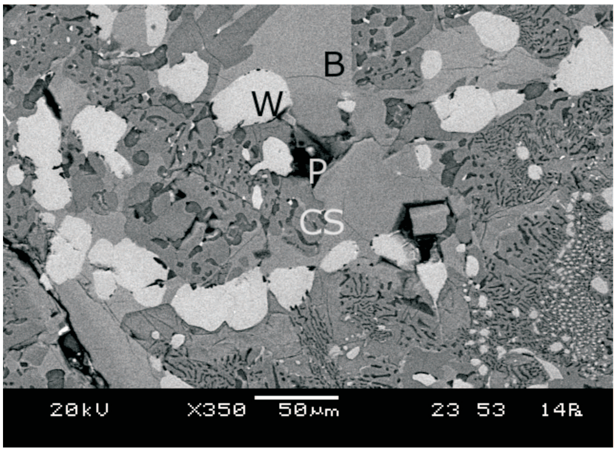

Fig. 2. Scanning electron micrograph (SEM) – wustite (W), calcium silicate (CS), brownmillerite (B), and pores (P)

The results of mineral analysis of air-cooled slag specimens are similar to the results obtained from the analysis of water-cooled slag, as demonstrated in Figure 2, i.e. wustite (FeO), dicalcium and tricalcium silicates ($2CaO \cdot SiO_2$, C_2S and $3CaO \cdot SiO_2$, C_3S), brownmillerite ($Ca_2(Al, Fe)_2O_5$, C_4AF) and mayenite ($12CaO \cdot 7Al_2O_3$, $C_{12}A_7$) have been identified. The great similarity in the mineral composition is indicated by the results of quantitative mineral analysis, as seen in Table 1.

The basic difference in the mineral composition of air-cooled slag when compared to the mineral composition of water-cooled slag is reflected in the fact that, apart from wustite, dicalcium and tricalcium silicates, brownmillerite, mayenite and melted iron (Fe), another mineral appears in the form of drop-shaped cluster and small inclusions in calcium silicates, and which contains significant amounts of manganese, Figure 3.

TABLE 1

Results of quantitative mineral analysis of slag

Mineral	Vol %	
	Water-cooled slag (WCS)	Air-cooled slag (ACS)
FeO	37	42
C_2S and C_3S	53	40
C_4AF	7	15
$C_{12}A_7$	2	1
Fe - metal	1	1
Mn - mineral	–	1

Due to a very expressed small-grain quality this mineral was not to be completely identified, however it might be vogtite $Ca(Fe,Ca,Mn)(Si_2O_6)$, or some of the minerals from the monticellite/merwinite series.

The water-cooled slag is well crystallized, with a considerably homogenous structure. The limits and touching points among a grains are clear, mostly very sharp and noticeable, as well as the transitions of one mineral's grain into another mineral. The analyzed slag specimens do not have the glass stage, therefore the presence of chromite, as well as free CaO or MgO has not being identified. The porosity is partly macroscopic, visible by naked eye, and partly microscopic, with round, oval and xenomorphic pores, average size from 10 to 180 µm. Micro-cracks are rare and mostly very thin, sometimes branched out, ending in pores or interlinking.

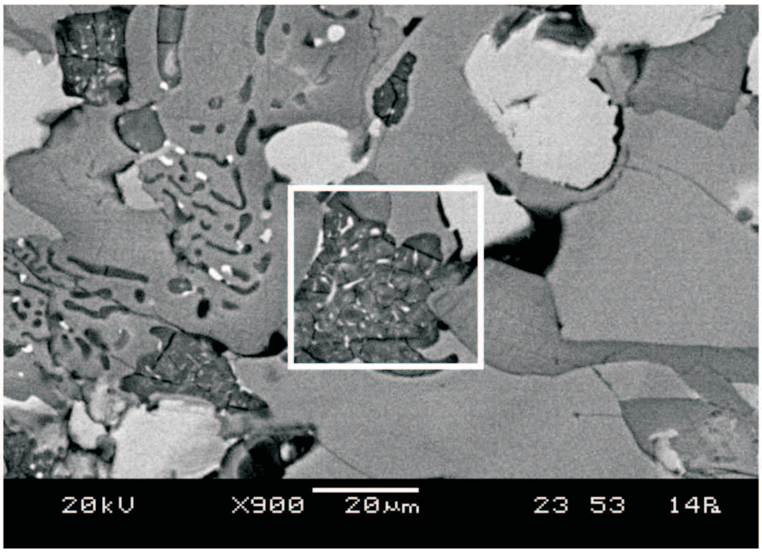

Fig. 3. Scanning electron micrograph (SEM) – the dark grain in the middle of the image is the Mn- mineral

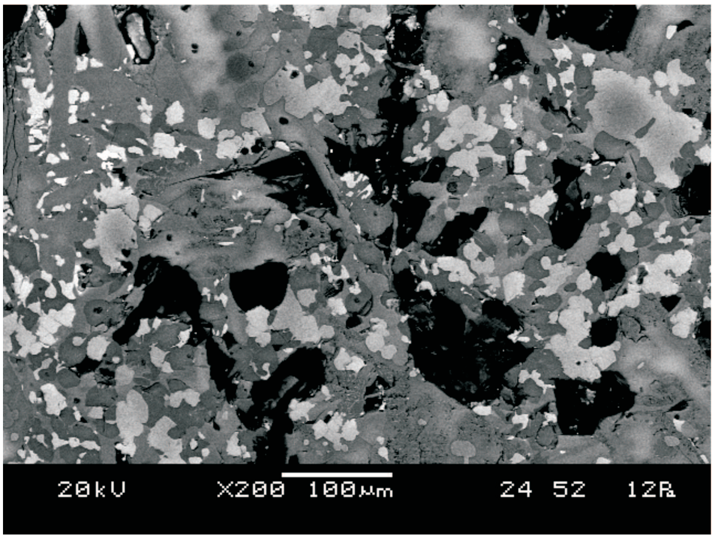

Fig. 4. Scanning electron micrograph (SEM) – high porosity of air cooled slag

The thin cracks are 30 µm wide on average. The microstructure in the air-cooled slag specimen is more heterogeneous and displaying the quality of more micro-porosity, as demonstrated in Figure 4.

For the purpose of determining the possible presence of ecologically very dangerous constituents in the slag specimens, the chemical composition of respective identified components in the observed specimens has also been analyzed, first and foremost in order to examine the forms into which the potentially present chromium is tied, Figure 5. It was determined that chromium, apart from Mg, Mn, Ca and Si is tied in the wustite structure, which has been confirmed by X-ray spectrometric analysis of wustite grain.

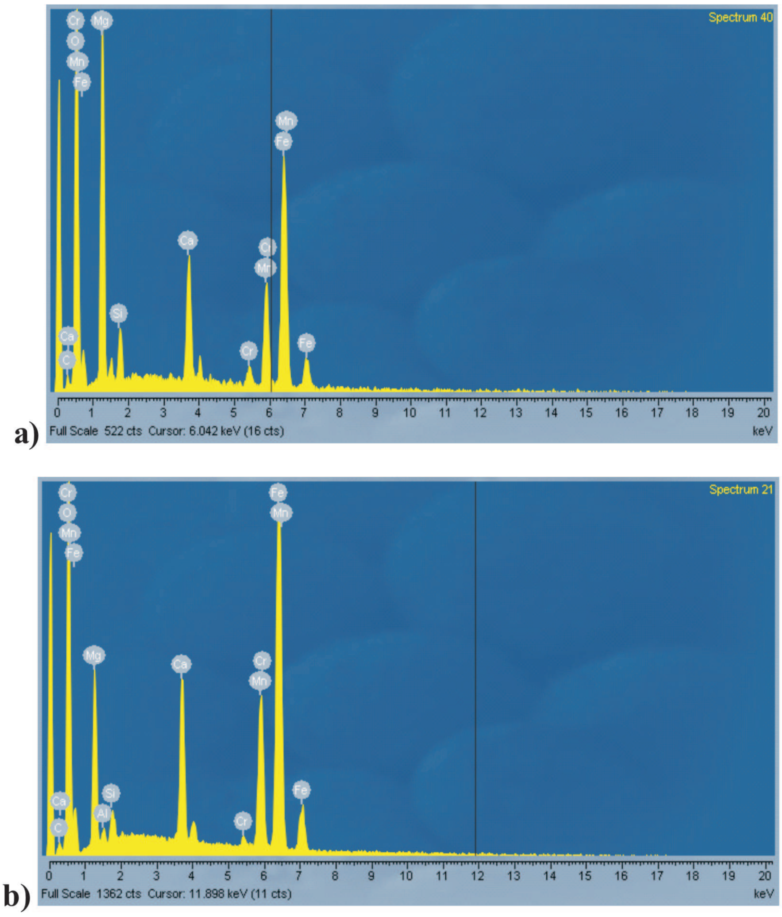

Fig. 5. EDS spectrum of wustite a) in water cooled slag and b) in air cooled slag

3.2. X-Ray diffraction phase analysis of slag

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 magnesium, silica and aluminium oxides. According to literature data [2-14] 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, and the most highly represented minerals in slag are dicalcium and tricalcium wustite silicates, while different aluminates and silicates are likely to appear as well.

Identification of the present mineral phases has been conducted on the basis of recorded diffractogram, Figure 6, obtained by recording a rotating slag specimen on the diffractrometric device Philips, PW 1830 in the angle area of 5 to 70°/2Θ with applying CuKα-radiation. The voltage of the X-ray tube was 40 kV, current intensity was 40 mA, and an analyzer 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.

X-Ray diffraction phase analysis of air (ACS) and water-cooled slag (WCS) identified wustite (FeO), srebrodolskite i.e. dicalcium ferrite ($2CaO\cdot Fe_2O_3$, $Ca_2Fe_2O_5$), larnite and alite i.e. dicalcium and tricalcium silicates ($2CaO\cdot SiO_2$ and $3CaO\cdot SiO_2$), brownmillerite ($Ca_2(Al, Fe)_2O_5$) and mayenite ($12CaO\cdot 7Al_2O_3$). The recorded spectrograms of analyzed samples of steel slag point to showed the possibility of calcium ferrite ($CaO\cdot Fe_2O_3$) and rankinite ($CaO\cdot 2Fe_2O_3$) as well.

3.3. Chemical analysis

Chemical analysis of the examined slag was conducted according to the norm EN 196-2 intended for cement analysis in order to encompass the analysis of more aggregates in comparison to the norm EN 1744-1 for mineral aggregates analysis.

Chemical analyses have determined that CaO ranges in water cooled slag and air cooled slag are 33.22 and 38.48%, Fe_2O_3 29.64 and 24.20%, SiO_2 10.86 and 11.01%, MgO 13.09 and 10.22%, Al_2O_3 1.66 and 8.67%, MnO 6.18 and 5.47%, Na_2O 0.02 and 0.07%, K_2O 0.06 and 0.04%.

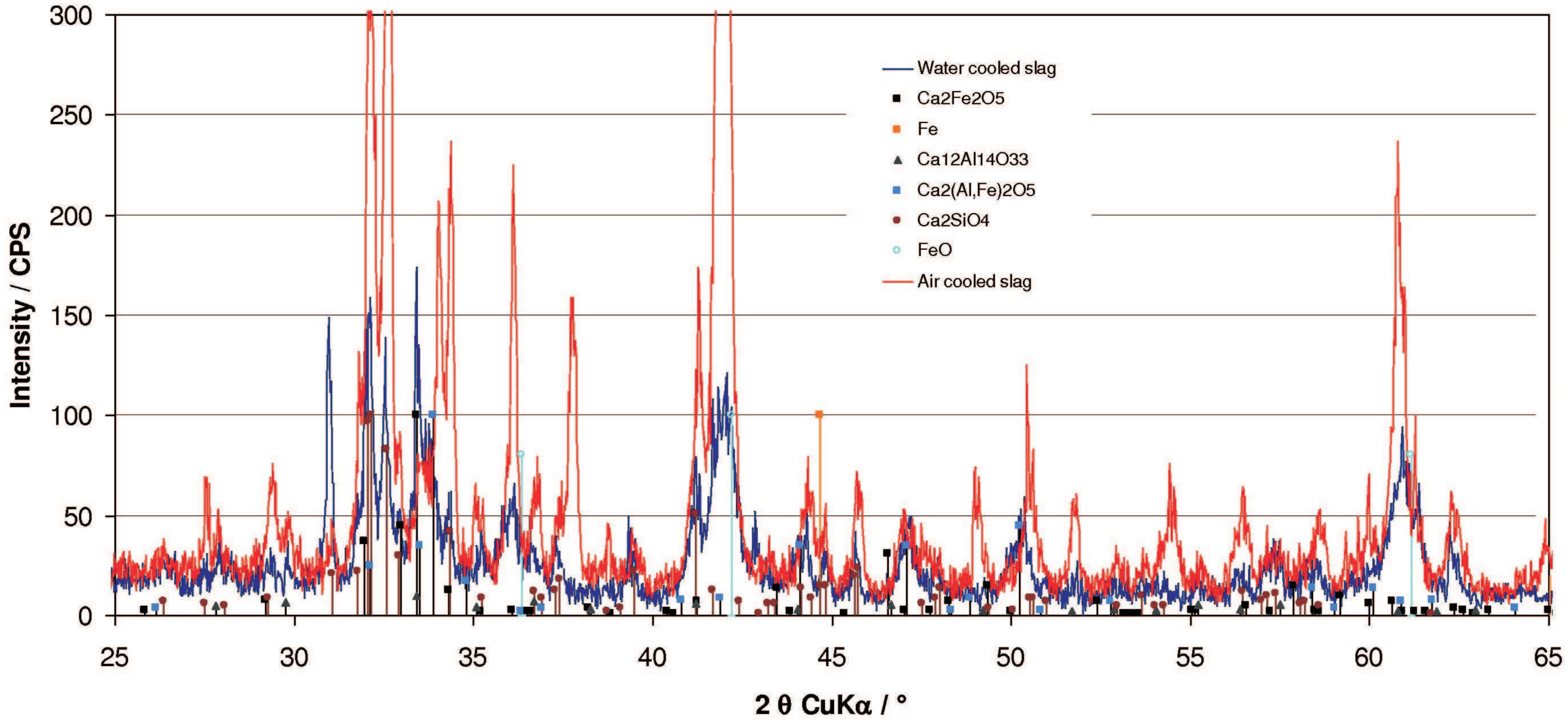

Fig. 6. XRD patterns of the phases with the largest mass shares in air- and water cooled slag

TABLE 2

Chemical analysis of slag specimen in comparison to chemical analysis data in previously published researches

Oxide	W (%)				
	WCS	ACS	Huijgen et al. [14]	Ahmedzade and Sengoz [15]	Motz and Geiseler [16]
CaO	33.22	38.42	31.7	47-55	25-40
Fe_2O_3	29.64	24.20	35.5	–	–
FeO	–	–	–	–	–
SiO_2	10.86	11.01	9.1	7.5-15	10-17
Al_2O_3	1.66	8.67	1.6	1.1-1.7	4-7
MgO	13.09	10.22	6.0	1.3-1.5	4-15
MnO	6.18	5.47	3.4	3.5-5.3	< 6
Na_2O	0.02	0.07	–	–	–
K_2O	0.06	0.04	–	–	–

Reference data [13-24] imply that the prevailing elements in steel slag vary in concentration: CaO 18.15-55%; Fe_2O_3 1.59-35.5%; SiO_2 2.74-35%; MgO 1.3-19.23%; Al_2O_3 1.2-9.8%; MnO 0.6-5.3%; Na_2O 0.06-0.5%; K_2O 0.02-0.2%.

Results of defining the representation of specific oxides in the examined slag specimen are showed in Table 2 in comparison to data on the representation of the same oxides in previously investigated steel slag from some of available published work [12-24].

Slag specimen was tested in a acreditated laboratory, and with the purpose of determining physical and chemical characteristics of slag waste for permanent disposal, according to the norm DIN 38414-S4 [25] and valid regulations [26]. The final results of determining physical and chemical characteristics of the eluate, demonstrate that steel slag satisfies the prescribed conditions according to which it is allowed to permanently dispose of it at disposal sites for nonhazardous waste.

3.4. Determination the mechanical characteristics of electric furnace slag

As the most typical area of usage for slags is the construction industry, its requirement system should be considered as well. Static and dynamic forces and the environmental strains like rain, heat, freeze and thaw require adequate long-term behaviour under these conditions for all constructions which are built. Therefore, the technical properties of processed aggregates which are used as construction material are of fundamental importance [16]. The most important properties are: volume stability; bulk density; shape; resistance to fragmentation (resistance to impact and crushing); water absorption; resistance to freezing and thawing and resistance to abrasion and polishing as well.

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-building, 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. The present free CaO and MgO in the slag cause volume instability which is the consequence of the following reactions:

$$CaO + H_2O \Leftrightarrow Ca(OH)_2 \tag{1}$$

$$Ca(OH)_2 + CO_2 \Leftrightarrow CaCO_3 + H_2O \tag{2}$$

The free CaO present in the slag, and when exposed to humidity, ties the humidity by creating hydroxide, and in combination with carbon (IV) oxide present in the atmosphere turns into a carbonate which has a larger volume. The consequence of all this is the swelling of the slag. Consistent with this, reactions of transformation of the free MgO into $MgCO_3$ occur as follows:

$$MgO + H_2O \Leftrightarrow Mg(OH)_2 \tag{3}$$

$$Mg(OH)_2 + CO_2 \Leftrightarrow MgCO_3 + H_2O \tag{4}$$

Elimination of the possible volume instability caused by the presence of free CaO and/or MgO is most commonly conducted by slag weathering methods, i.e. by weatering (exposure to atmospheric conditions of the solid slag for a certain period of time at free atmosphere to transform the free Ca/Mg-oxide into Ca/Mg-hidroxide) or 'quenching' by water. Slag processing conducted in order to transform the possibly present free CaO and free MgO into a hydroxide form has been done using the method of 'quenching' by water for the needs of this testing.

To defining of EAF steel slag application possibilities in asphalt mixture production it was necessary to prove its volume stability (according to EN 1744-1; point 19.3). The volume stability tests results, Table 3, have shown that both steel slag aggregates are applicable for use in asphalt mixture production.

The procedure of testing volume stability of the observed slag specimens has determined that the water-cooled slag has the expansion of up to 2.9%, thus placing it into the highest class (3.5% is allowed) according to EN 13043. The air-cooled slag expands up to 5.3%, thus entering the class of up to 6.5 according to EN 13043.

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 were.

The measured values of densities and water absorption are given in Table 4. The obtained results of slag resistance to wear in the wet state meets the requirements of the highest class, Table 5. Resistance of slag to fragmentation via the 'Los Angeles' method are given in Table 6. The obtained results of shape index and flakiness index are showed in Table 7 and 8. The obtained polishing value are given in Table 9. The measured values of durability via testing by magnesium sulphate and by freezing and thawing method are presented in Table 10 and 11.

TABLE 3

The volume stability tests results

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 %)
Water cooled slag								
WCS1	1572	2.78	25.31	1.19	2.62	2.9	−0.53	0.39
WCS2	1579	2.77	25.60	1.44	3.16			
Air cooled slag								
ACS1	1607	2.72	24.59	2.38	5.13	5.3	−0.43	0.31
ACS2	1613	2.71	24.87	2.59	5.56			

TABLE 4

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 $\boldsymbol{WA}_{24}$, (%)
			ρ_{ssd}	ρ_{rd}	ρ_a	
Water cooled slag						
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
Air cooled slag						
0/4	100	1039.2	3.36	3.30	3.52	1.9
4/8	100	1105.5	3.53	3.47	3.69	1.7
8/16	100	2024.9	3.54	3.49	3.67	1.4
16/32	100	5034.8	3.54	3.48	3.68	1.6

TABLE 5

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 $\bar{M}_{DE}$	Class (EN 13043) M_{DE}
Water cooled slag				
8/16 mm wet	10/11.2 (30-40%) 11.2/14 (70-30%)	7.8	8	$M_{DE}10$
		7.3		
Air cooled slag				
8/16 mm wet	10/11.2 mm (30-40%) 11.2/14 mm (70-30%)	7.2	7	$M_{DE}10$
		7.4		

TABLE 6

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 (EN13043) LA
Water cooled slag			
10/11.2	30	13	LA_{15}
11.2/14	70		
Air cooled slag			
10/11.2	30	16	LA_{20}
11.2/14	70		

TABLE 7

Flakiness index according to EN 933-3

Mass of the test part of the specimen, M_0 (g)	Fraction size (mm)	Total flakiness index FI	Class (EN13043) FI
Water cooled slag			
645.1	4/8	4	FI_{10}
3530.9	8/16	2	FI_{10}
10024.8	16/32	4	FI_{10}
Air cooled slag			
800.4	4/8	6	FI_{10}
2918.5	8/16	5	FI_{10}
10563.8	16/32	6	FI_{10}

TABLE 8

Shape index according to EN 933-4 (item 6.2; $D \leqslant 2d$)

Mass of the test part of the specimen, M_0 (g)	Aggregate fraction size di/Di where $Di \leqslant 2d_i$ (mm)	Shape index SI	Class (EN 13043) SI
Water cooled slag			
350.6	4/8	1	SI_{15}
3537.3	8/16	3	SI_{15}
6123.4	16/32	4	SI_{15}
Air cooled slag			
511.1	4/8	3	SI_{15}
2918.5	8/16	10	SI_{15}
6272.1	16/32	5	SI_{15}

TABLE 9

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
Water cooled slag					
72.0	71.6	54.7	54.5	70	PSV_{68}
73.0		54.3			
71.0		55.0			
70.3		54.0			
Air cooled slag					
72.0	71.8	54.7	54.5	70	PSV_{68}
71.0		54.3			
72.0		55.0			
72.0		54.0			

TABLE 10

Testing by magnesium sulphate according to EN 1367-2

Petrography description (EN 932-3)	Tested fraction size (mm)	Fraction of lab sample used for getting the test part of the specimen (mass %)	Value of magnesium sulphate for every test specimen *MS*	Median value of the magnesium sulphate $\bar{MS}$	Class (EN 13043) *MS*
Water cooled slag					
Steel slag	8/16	100	1.00	1	MS_{18}
			0.90		
Air cooled slag					
Steel slag	8/16	100	0.8	2	MS_{18}
			2.4		

TABLE 11

Determining resistance to freezing and thawing according to EN 1367-1

Fraction size d/D.(mm)	Number of laboratory samples	Test result (Loss of mass %)	Class (EN 13043) ***F***
Water cooled slag			
8/16	3	0.4	*F1*
Air cooled slag			
8/16	3	0.8	*F1*

TABLE 12

Comparison of physical properties of aggregates

Characteristic	CMC Sisak slag		Diabaz Croatia	Bazalt Austria	Filit Slovenia
	WCS	ACS			
Resistance to fragmentation (LA)	13	16	15	15	20
Resistance to abrasion (micro-Deval)	8	7	8	8	10
Frost resistance (Mg_2SO_4,% by weight)	1.0	2	0.0	0.0	0.0
Frost resistance, freezing and thawing (% by weight)	0.4	0.8	0.0	0.0	0.0
Fines (% by weight)	0.5	0.5	0.5	0.5	0.7
Water absorption (% by weight)	1.6	1.8	0.4	0.6	0.5
Bulk density (Mg/m^3)	3.4	3.3	2.8	2.8	2.9
Volume stability (% V/V)	2.9	5.3	Not Relevant	Not Relevant	Not Relevant

The results of those tests, Table 3-11, indicate that the tested slag, regardless of the way of cooling, satisfy the characteristics necessary for their use in asphalt mixtures. The results of those tests have been compared to natural aggregates commonly used in the manufacture of asphalt mixtures. The mechanical characteristics oh both aggregates, the steel slag aggregates and the natural aggregate, are given in Table 12.

4. Conclusion

The obtained examination results show that the EAF slag generated in the steel mill of CMC Sisak d.o.o. does not differ from the slag formed in other steel mills which use the EAF process.

X-Ray diffraction phase analysis of the tested slag (air and water-cooled) identified wustite (FeO), srebrodolskite i.e. dicalcium ferrite ($2CaO{\cdot}Fe_2O_3$, $Ca_2Fe_2O_5$), larnite and alite i.e. dicalcium and tricalcium silicates ($2CaO{\cdot}SiO_2$ and $3CaO{\cdot}SiO_2$), brownmillerite ($Ca_2(Al, Fe)_2O_5$) and mayenite ($12CaO{\cdot}7Al_2O_3$).

The analysed steel slag does not contain the glass phase, therefore 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 analyses have determined that CaO ranges in water cooled slag and air cooled slag are 33.22 and 38.48%, Fe_2O_3 29.64 and 24.20%, SiO_2 10.86 and 11.01%, MgO 13.09 and 10.22%, Al_2O_3 1.66 and 8.67%, MnO 6.18 and 5.47%, Na_2O 0.02 and 0.07%, K_2O 0.06 and 0.04%.

The obtained results of eco-toxicity showed that the slag does not contain constituents which might in any way affect the environment harmfully, thus that it can be disposed of at non-hazardous waste disposal sites.

Even though the procedure of testing volume stability of the examined slag specimens determined the better volume stability on the WCS specimen (2.9%) when compared to ACS specimen (5.3%), the conclusion arises that in relation to natural volcanic aggregates used in asphalt mixtures on highways and other top-class traffic load roads the examined slag has equally good properties, and can be used in the production of asphalt mixtures.

The determined densities of both specimens are high, which was expected considering aggregate origin. Geometric properties of slag samples both in terms of shape index and flakiness index satisfy the highest criteria ($\boldsymbol{FI}_{10}$; $\boldsymbol{SI}_{15}$).

Resistance of both specimens to wear in the wet state satisfies the highest class ($\boldsymbol{M_{DE}10}$). Resistance of both specimens to fragmentation via the Los Angeles method the sample satisfies the highest class ($\boldsymbol{LA}_{15}$ and $\boldsymbol{LA}_{20}$). Water absorption on the examined fractions of both specimens is bigger than 1%, and the tested durability via magnesium sulfate method, as well as freezing and thawing method, and the final results ($\boldsymbol{MS}_{18}$ and $\boldsymbol{F}_1$) satisfy the required criteria. The polishing value is very good in both specimens, satisfying the highest class ($\boldsymbol{PSV}_{68}$).

According to the above said values and comparison with values of natural aggregates used in asphalt mixtures on top-class traffic load roads, the examined slag has demonstrated equally good properties, thus confirming that, considering the measured values, regardless of the way of cooling, the slag can be used in the manufacture of asphalt mixtures.

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