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Characterization Of The Eaf Steel Slag As Aggregate For Use In Road Construction

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The use of industrial by-products requires knowledge of the characteristics of the materials. This paper presents characterization data on slag generated in the melting of steel scrap by electric arc furnace (EAF). Characterization of electric arc furnace slag (EAFS), as one of the most significant types of non-hazardous metallurgical waste, was carried out through an examination of its physical and chemical properties with special emphasis on chemical and structural characteristics and potential use in road construction.

Croatian EAF black steel slag, generated from carbon steel production process in CMC Sisak d.o.o., is the most interesting from the asphalt technology point of view, but in order to assess the suitability and reusing potential of EAFS in asphalt mixture production, it is necessary to know its chemical, radiochemical, physical, morphological, mineralogical, and textural characteristics, as well as how it interacts with individual segments of the environmental system.

For this purpose, the study was carried out using several different analytical methods and this paper aims to explore the feasibility of utilizing steel slag as aggregates in asphalt mixtures. Optical Microscopy (OM), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS) were employed to study the texture, morphology and composition of steel slag.

Tests on the soundness of the slag for use as aggregate in road construction were carried out in accordance with European standards.

Keywords: Metallurgical by-products; steel slag; characterization; road construction
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1. Introduction

Metallurgical waste generated in Croatia is mostly collected by the waste producers themselves and partly by the companies doing separate collecting of waste as their primary activity. The generated metallurgical waste is partly recovered and returned to the production process (reuse) and part of the waste is sometimes used by other industries as secondary raw material (recycling), whereas the largest part still ends on often non-regulated landfills for industrial waste within the factory grounds.

There are many such landfills on the Croatian territory and the landfills for disposal of metallurgical and metal-processing waste are particularly hazardous for the environment. Most frequently, metallurgical waste disposed of in this manner involves large volumes of various types of slag, dust, sludge, and similar materials, some of which can be hazardous pollution sources.

Electric arc furnace steel slag (EAFS) is a by-product from the steel making process, the majority of which ends up in deposits and thus gradually becomes an environmental problem, so the availability of ways to handle slag is getting more important. On the other hand, most industrialized countries; there is great demand for aggregate mainly in civil engineering industry, especially in the field of road construction. The last statement holds us responsible to save natural resources of aggregate by using industrial waste and/or by-products and to increase their utilization rate. Exploitation of natural mineral aggregate such as carbonate and volcanic rocks either brings about environmental problems or make costs of projects increase sharply because of lack of such aggregates.

In order to assess the suitability and reusing potential of EAFS in asphalt mixture production, it is necessary to know its chemical, radiochemical, physical, morphological, mineralogical, and textural characteristics, as well as how it interacts with individual segments of the environmental system. For this purpose, several different analytical methods were applied. This paper aims to explore the feasibility of utilizing steel slag as aggregates in asphalt mixtures. Optical Microscopy (OM), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS) 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 EAFS 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 examined EAFS, when compared to steel slag properties of other Slovenian steel producers 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.

2. Exsperimental

EAFS is derived during low carbon steel production in Steel Mill of CMC Sisak, Croatia. After tapping, the molten slag was cooled with 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 basic mineralogical and chemical characteristics of the EAFS, a mineral analysis was conducted by Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-Ray Diffraction Analysis (X-RDA). Total chemical analysis of EAFS was performed by Atomic Absorption Spectroscopy (AAS) in combination with X-Ray Fluorescence (X-RFA).

Considering that in Croatia EAFS 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.

The examination of the granulometric composition, the shape of the particle, the flakiness index, the shape index, resistance to fragmentation, density and water absorption, polished stone value, resistance to freezing and thawing, magnesium sulfate test, volume stability as well as the determination of resistance to thermal shock was done according to the European Standards (EN 196, EN 933-1, EN 933-4, EN 1097-2, EN 1097-6, EN 1097-8, EN 1367-1, EN 1367-2, EN 1744-1 and EN 1367-5).

3. Results And Discussion

3.1 Mineralogical analysis of steel slag

Analysis of EAFS (average sample) identified wustite (FeO), dicalcium and tricalcium silicates ($2CaO.SiO_2$, C_2S amd $3CaO.SiO_2$, 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. The EAFS is well crystallised, and has a comparatively homogenous structure.

3.2 X-Ray diffraction analysis of steel slag

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).

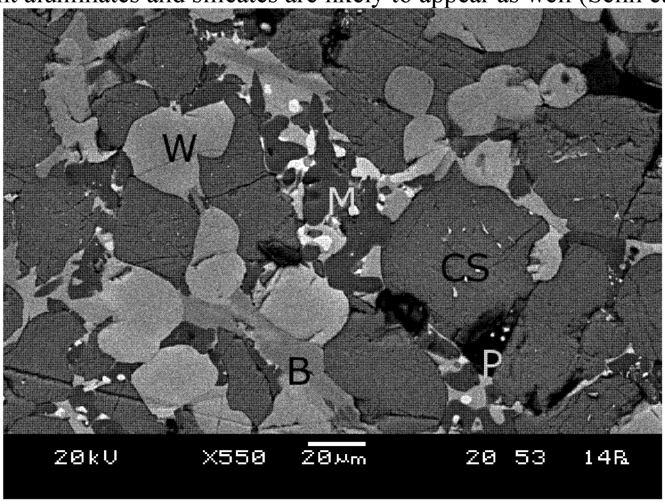

Fig.1. Scanning electron micrograph (SEM) – characteristic slag microtexture: wustite (W), calcium silicate (CS), brownmillerite (B), mayenite (M), pores (P) and inclusions of iron (white)

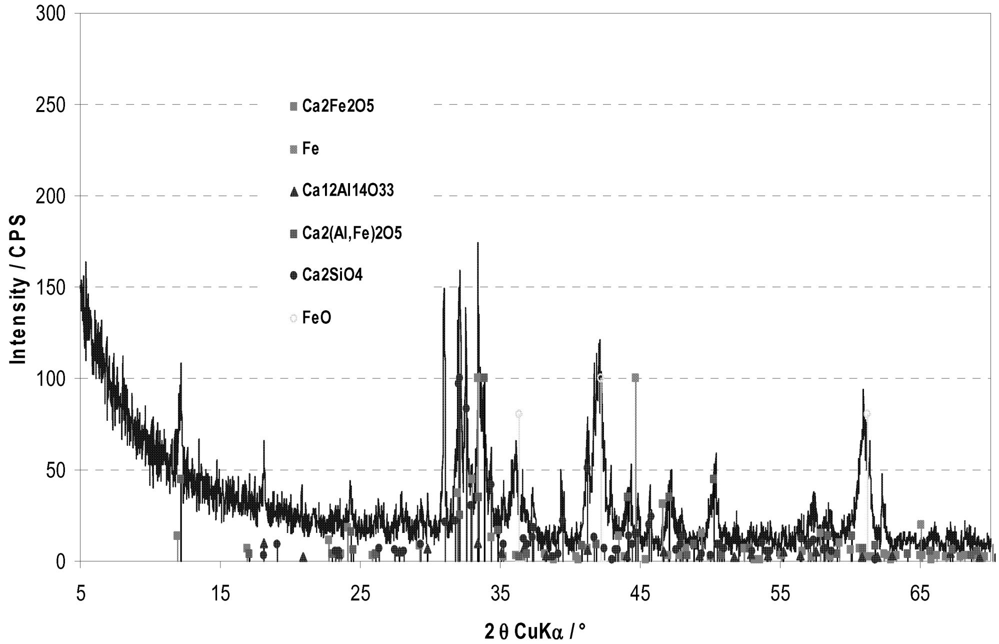

Fig.2.XRD patterns of investigated slag

Identification of the present mineral phases has been conducted on the basis of recorded diffractogram, as showed in Fig. 2, obtained by recording a rotating slag specimen on the diffractrometer device Philips, PW 1830 in the angle area of 5 to $70^o/2\Theta$ with applying CuKα-radiation, the voltage of the X-ray tube was 40 kV and anode electricity totalled 40 mA. 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 and environmental impact

Chemical analysis of the examined EAFS (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 for aggregates analysis. Chemical analyses of investigated EAFS 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 %,

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%.

EAFS specimens were tested in acreditated laboratory, and with the purpose of determining physical and chemical characteristics of slag waste for permanent disposal, according to valid regulations (Ordinance on the methods and conditions for the landfill of waste, categories and Operational requirements for waste landfills, 2007). The results of determining physical and chemical characteristics of the eluate showed that steel slag satisfied 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. To define EAFS application possibilities in asphalt mixture production, it was necessary to prove its volume stability (according to EN 1744-1; item 19.3). The volume stability test results, on average 2.9%, have shown that steel slag aggregates are applicable for use in asphalt mixture production.

3. 6 Determination the mechanical characteristics of EAFS

For the purpose of determining suitability of EAFS 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 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 0/4mm 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 composition satisfy the highest criterion ***G_C 90/10***, while fraction 16/32mm has been classified as (***G_C 90/15)***; small particles ratio in 0.063mm on 8/16 and 16/32mm 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**). 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. The obtained polishing value is very high, satisfying the highest criteria (***PSV_{68}***). The determined densities are high, which was to be expected considering aggregate origin. The water absorption on tested fractions is more than l%, so 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%).

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 1 as well.

Table 1: Comparison of physical properties of EAFS and natural aggregates

Properties	EAFS	Natural aggregates	
		Diabaz Croatia	Carbonate Croatia
Resistance to fragmentation (LA)	13	15	29
Resistance to abrasion (micro-Deval)	8	8	11
Frost resistance (Mg_2SO_4, % by weight)	1.0	0.0	1.7
Frost resistance, freezing and thawing (% by weight)	0.4	0.0	0.3
Polished stone value, PSV	70	NA	32
Fines (% by weight)	0.5	0.5	NA
Water absorption (% by weight)	>1	<1	<1
Bulk density (Mg/m^3)	3.4	2.8	NA
Volume stability (% V/V)	2.9	NR	NR

NR – Not relevant; NA – Not available

4. Conclusion

The results of testing mechanical, physical and chemical properties of EAFS generated during the production of low carbon steel in the steel mill of CMC Sisak, Croatia, and with the purpose of determining its suitability for asphalt mixtures production, 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;
- Chemical analyses 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 % i K_2O 0,06% and the analysed EAFS 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;
- The results of eco-toxicity determination intended for permanent disposal showed that the EAFS 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;
- Al results of the tested geometric, physical and mechanical properties, as well as durability indicate that EAFS 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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