THE SIGNIFICANCE OF IRON AND STEEL SLAG AS BY- PRODUCT FOR UTILIZATION IN ROAD CONSTRUCTION

ZNAČAJ TROSKI IZ PROIZVODNJE ŽELJEZA I ČELIKA KAO NUSPRODUKTA ZA UPORABU U CESTOGRADNJI

T. Sofilić[1], U. Sofilić[2], I. Brnardić[3]
[1]CMC Sisak d.o.o., Sisak, Croatia
[2]Jaruščica 9/E, Zagreb, Croatia
[3]University of Zagreb Faculty of Metallurgy, Sisak, Croatia

Subject review/Pregledni članak

ABSTRACT
Due to growing environmental awareness, as well as stricter regulations on managing industrial waste, the world is increasingly turning to researching properties of industrial waste and finding solutions on using its valuable component parts so that those might be used as secondary raw material in other industrial branches.
Although metallurgical slag is still today considered waste and is categorized in industrial waste catalogues in most countries in the world, it is most definitely not waste, neither by its physical and chemical properties not according to data on its use as valuable material for different purposes. Moreover, since the earliest times of the discovery and development of processes of iron and other metals production, slag as by-product is used for satisfying diverse human needs, from the production of medicines and agro-technical agents to production of cement and construction elements.
This paper demonstrates the possibilities of using slag as one small part of industrial waste arising from the metallurgical processes of iron and steel production. Considering the specificity of physical and chemical properties of metallurgical slags and a series of possibilities for their use in other industrial branches, this paper pays special attention to slag significant trough the history and its using in the road construction.

Key words: *metallurgical slag, construction industry, road construction*

1. INTRODUCTION

Non-reproducibility of mineral raw material reserves is especially significant from the standpoint of sustainable development, and it impresses upon us a need to preserve the mineral raw material reserves, as well as to constantly research and discover new reserves, simultaneously with utilizing the existing. Rational utilization of the existing and the aspiration for possible new mineral raw material sources is a founding determinant not only of mining and geology, but also of other specialized fields which can contribute to the accomplishment of the common goal found in the protection and management of mineral sources, especially those originating from raw materials for construction.

With this, it is of vital importance to be familiar with the technical significance of the secondary application of waste materials, but also with their possible environmental effects. Even though their application in construction reduces the quantity of landfills, which is why it can be considered as partial or total waste management, some waste materials might contain increased concentrations of substances harmful to human health or the environment, especially to the water [1 - 3].

Starting from the importance of mineral raw materials for the development of overall economy of the Republic of Croatia, with respect to producers' potentials and growing market needs, what is necessary is a systematic approach to researching alternative sources of these materials with the purpose of creating stable economic growth in the conditions of sustainable development.

At the same time, having in mind that the national environmental strategy of the Republic of Croatia [4] defines waste management as national priority with the so-called no-landfill concept, for the realization of which one should close the circle of avoiding the very creation of waste, reducing the quantity and harmfulness, recycling and reuse, some industrial waste materials have, thanks to their composition and structures, started being used as secondary raw materials in construction in Croatia as well.

2. UTILIZATION OF INDUSTRIAL WASTE IN CONSTRUCTION INDUSTRY

Because large quantities of industrial by-products and/or waste are generated from different industrial processes, waste management has become one of the major environmental concerns in the world. With the increasing of environmental awareness, devastation of land-fill area and due to its ever increasing cost, industrial by-products and/or waste utilization have become an attractive alternative to disposal. High consumption of raw materials from natural sources, high amount generating of industrial by-products and/or wastes and environmental impact require finding new solutions for a sustainable development. Recent studies [5 - 15] showed applications of nontraditional materials, also called industrial by-products and/or non-hazardous waste, have been considered in construction, especially in road construction with great interest in many industrialized and developing countries.

The road construction is one of the most material demanding industries with great economic as well as environmental impacts and for this reason significant efforts are seen in terms of recycling and reuse of industrial by-products and/or waste materials in road construction.

Application of industrial by-products and/or waste in road construction can be seen as a factor of preservation of natural non-renewable sources of mineral aggregates and simultaneous unwanted effects on the environment of all activities connected with the exploitation and transport from the origin point to the installation point. It is these factors exactly that impress upon us the need to better understand the environmental and economic aspects of using natural mineral raw materials in relation to alternative sources – industrial waste materials – which can in many ways contribute to the improvement of sustainable development in the industry of road construction.

The recycled materials of interest to road construction can be generated in industry and by demolition of civil engineering. Waste and/or byproducts obtained in such a manner would be disposed in a landfill, or used as raw material in other industry. On the basis of data from previously published works [16 - 19] recycled materials used in construction may be classified according to their source:

a) Industrial waste and/or byproducts (mining waste rock, metallurgical slags, foundry sand, coal fly ash, municipal solid waste incinerator ash, etc.);
b) Road byproducts, such as reclaimed concrete pavement materials, and reclaimed asphalt pavement materials;
c) Building demolition waste and/or byproducts (crushed concrete, tiles, and bricks).

Worldwide recycling of industrial by-products in the road sector has seriously increased during the last twenty five years, especially in the area of road-generated by-products such as reclaimed asphalt pavement, reclaimed concrete pavement, coal fly ash, blast furnace slag and steel slag. The use of waste and/or byproducts in road construction is important to divert loads that would be otherwise disposed of in landfills. A significant range of applications of different waste and/or recycled materials in road construction has been identified that has the potential to accomplish such goals, Table 1.

Table 1 - Industrial by-products and/or waste and their application in road construction [20]

MATERIALS	APPLICATIONS					
	Asphalt Concrete	Portland Cement Concrete	Stabilized Base	Flowable Fill	Granular Base	Embankment Fill
Baghouse fines	x					
Blast furnace slag	x	x			x	
Coal bottom ash/slag	x		x		x	
Coal fly ash	x	x	x	x		x
Flue gas scrubber material						
Foundry sands	x			x		
Kiln dusts	x		x	x		
Mineral processing wastes	x				x	x
Municipal combustor ash	x				x	
Non-ferrous slags	x				x	x
Quarry byproducts				x		
Reclaimed Asphalt	x				x	x
Reclaimed concrete		x			x	x
Roofing shingle scrap	x					
Scrap tires	x					x
Sewage sludge ash	x					
Steel slag	x				x	
Sulfate wastes			x			
Waste glass	x				x	

The use of recycled waste materials in road construction and the substitution for natural non-renewable mineral materials is perceived as an opportunity to save resources and avoid the impacts associated with their extraction and transportation. Industrial waste materials from different sources have been utilized in construction industry and Table 2 shows only partial list of industrial by-products and/or waste material that may be used in road construction [21]. Nehdi in one of previous reports [22] identified 43 types of secondary materials used in road construction out of which 11 are industrial waste and/or byproducts, and 7 belong to metallurgic industry.

Table 2 - Possible usage of industrial waste products in highway construction [21]

Waste product	Source	Possible usage
Fly ash	Thermal power station	Bulk fill, filler in bituminous mix, artificial aggregates
Blast furnace slag and steel slag	Iron and Steel industry	Base/Sub-base material, Binder in soil stabilization (ground slag)
Construction and demolition waste	Construction industry	Base/Sub-base material, bulk-fill, recycling
Colliery spoil	Coal mining	Bulk-fill
Spent oil shale	Petrochemical industry	Bulk-fill
Foundry sands	Foundry industry	Bulk-fill, filler for concrete, crack-relief layer
Mill tailings	Mineral processing industry	Granular base/sub-base, aggregates in bituminous mix, bulk fill
Cement kiln dust	Cement industry	Stabilization of base, binder in bituminous mix
Used engine oil	Automobile industry	Air entraining of concrete
Marble dust	Marble industry	Filler in bituminous mix
Used tyres	Automobile industry	Rubber modified bitumen, aggregate
Glass waste	Glass industry	Glass-fibre reinforcement, bulk fill
Nonferrous slags	Mineral processing industry	Bulk-fill, aggregates in bituminous mix
China clay	Bricks and tile industry	Bulk-fill, aggregates in bituminous mix

2.1 Utilization of metallurgical slags in construction industry

Slag is by-product formed in smelting, and other metallurgical and combustion processes from impurities in the metals or ores being treated. During smelting or refining slag floats on the surface of the molten metal, protecting it from oxidation or reduction by the atmosphere and keeping it clean. In iron and steel production slag phases are generated, formed mainly from the addition of mixtures of oxides and fluxes and are also composed of reaction products like those resulting from the oxidation of charge materials and the dissolution of refractory’s. Primary purpose is to refine the liquid metal by removing impurities such as S and P.

The main slags are classified in three types: ferrous slag, including iron slag generated in blast furnace process and steel slags, non-ferrous slag generated by production non-ferrous metals (Cu, Zn, Pb, Ni,..), boiler slag obtained by coal combustion plants and incineration slags generated by combustion of solid waste [20].

Generating of slag in pig iron production in blast furnace (BF), steel production in basic oxygen furnace (BOF), and in electric arc furnace (EAF) is an important step in the iron/steel making process. During this process, substances that are unwanted in the iron and steel are removed by forming complex metallic and nonmetallic oxides and silicates [23 - 27].

Steel slag is a hard, dense material somewhat similar to air-cooled iron slag. During the production of steel in BOF and/or EAF scrap metal, or metalized ore, or both, the carbon and silicon are removed as carbon dioxide, and the remaining oxidized elements are combined with added lime to form steel slag. The composition and properties of steel-making slags depend on the kind of steel-making process and/or on the type of steel. Steel slags are mostly formed in the process of remelting steel scrap in an EAF – this is the so-called black slag. Small amounts of steel slags are also produced in the processes of secondary metallurgy in a vacuum oxygen decarburization furnace – this is the so-called white slag [28]. White slag is also produced in an EAF during the production of non-rusting steels. They differ from one another in terms of chemical and especially mineral composition and consequently in their properties and their possibilities for use.

Non-ferrous slags are produced during the recovery by smelting and processing of nonferrous metal from natural ores. Also it generated in smelting often contains residual metal, which, in most cases inhibits their use without further processing. Non-ferrous slags are very often material for use us fine aggregate in the design of bituminous mixes in road construction [29 - 33].

2.2 History of use of iron and steel slag

The history of the use of iron and steel slag dates back a long way and European Slag Association noted that the earliest reports (European Slag Association, 2006) on the use of slag refer to Aristotle, who used slag as a medicament as early as 350 B.C. Application of iron slag use in road building has a long history and dates back to the time of the Roman Empire, some 2000 years ago, when slag from the iron-making forging were used in base construction [34 - 35].

Throughout history, the use of slag has ranged from the novel to the usual including: cast cannon balls in Germany (1589), wharf buildings in England (1652), slag cement in Germany (1852), slag wool in Wales (1840), reinforced concrete in Germany (1892), and slag bricks made from granulated slag and lime [36, 37] in Japan (1901). Blast furnace slag has been utilized in concrete masonry for many years. The blast furnace slag can impart many desirable properties to the masonry units such as lighter weight and increased fire resistance. Blast furnace slag products have been used successfully for agricultural applications [38 - 40].

The physical and chemical properties of mineral wool insulation, also known as slag wool [41-44] are major factors in their utility as residential and commercial insulation, pipe and process insulation, insulation for ships, mobile homes, domestic cooking appliances, and a wide variety of other applications.

In the past, the application of steel slag was not attractive because vast volumes of blast furnace slag were available. Steelmaking slag has been used commercially since at least the mid-19th century. It is currently used in all industrialized countries, wherever steel is produced. Beginning in the 20th century, many new uses for steelmaking slag were developed in a variety of industries. Steel mills and slag processors work closely together to ensure that the steelmaking slag remains a high quality product for current and future applications. 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.

Now days, due to a relatively high share 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. Through awareness of environmental considerations and more recently the concept of sustainable development, extensive research and development has removed slag from industrial waste into modern industrial product which is effectively and profitably used for many industrial purposes, especially as row material in cement production, landfill cover material, and the numerous construction and agricultural applications [45 - 53].

2.3 Utilization of iron and steel slag – current state

Slags from different metallurgical processes, including blast furnace, steel making, non-ferrous contain many useful components used for various construction purpose. Especially, mineralogical composition of metallurgical slag plays important roles in determining specific application.

Steelmaking operations, such as Basic Oxygen Furnace Process (BOF), Electric Arc Furnace (EAF) process and, nowadays rare, Open Hearth Furnace (OHR) process produce slag with different compositions. The increase in steel consumption is thus the cause of generation of slag, and consequently, growth in slag volume, had impact on developing various methods of slag utilization.

Because slag is not a mined material and production data for the world are unavailable, annual world iron and steel slag output is estimation based on typical ratios of slag to crude iron and steel output.

From this reason in recent years, some data for slags have shown discrepancies related to tonnages. Few data are available on the actual annual production of iron and steel slag because not all of the slag is tapped during a heat, and the amount of slag tapped is not routinely measured. However, both European and world production of ferrous slags can be broadly estimated, based on typical slag to metal production ratios, which in turn are related to the chemistry of the ferrous feeds to the furnaces. Nowadays, of the total amount of all types of waste produced in the EAF 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 [54].

In the period 2000-2010 level of pig iron production was 576 - 1030 million tones/y overall in the world [55, 56]. At the same period level of crude steel production was from 850 to1413 million tones/y. If we take on to assumption that there is about 250 kg of blast furnace slag (BFS) on 1000 kg of pig iron we obtained 144 – 258 million tones/y of slag in period 2000-2010, Figure 1.

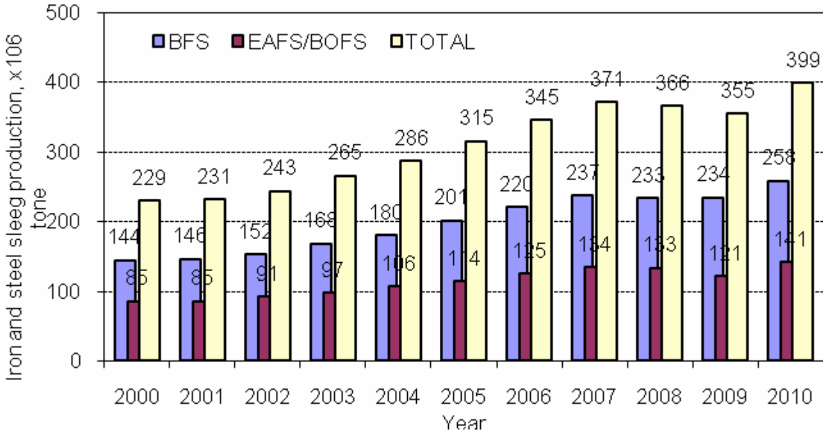

Figure 1 - Production of iron and steel slag in the World

The amount of slag which is obtained by basic oxygen process (BOF) is 8.5 – 16.5 % by weight of crude steel output, and in electric arc furnace (EAF) process is 6 – 26 % by weight of crude steel production [54] as well (Integrated Pollution Prevention and Control, 2008). For steel slag production we obtained 85 – 141 million tones/y if we calculate based on literature for statistical purpose [57] with slag generating is about 100 kg slag on 1000 kg crude steel. Analogically, the amount of generated blast furnace slag in EU 27 [55, 58] in the same period was about 18 - 29 million tones/y and amount of generated steel slag was 14 - 21 million tons/y as well, Figure 2.

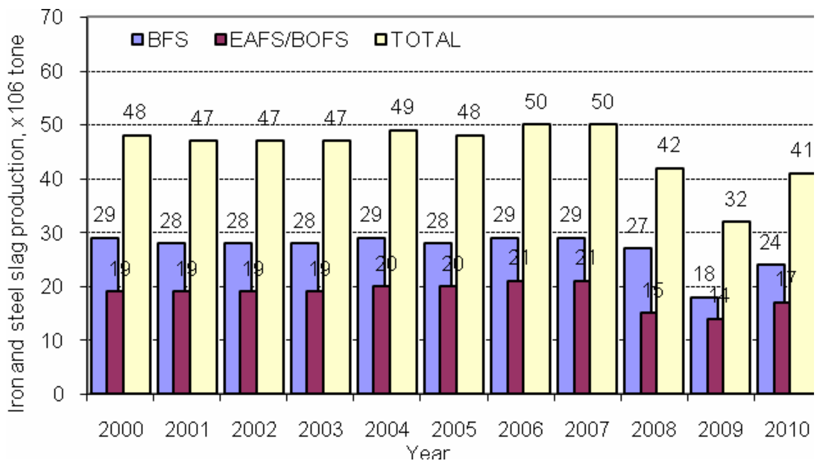

Figure 2 - Production of iron and steel slag in the EU27

According R. Bialucha et all [58] in 2008, countries of EU 27 generated more than 45 million tons of slag resulting from iron and steel making. About 22.5 million tone of slag is used for cement industry, Figure 3.

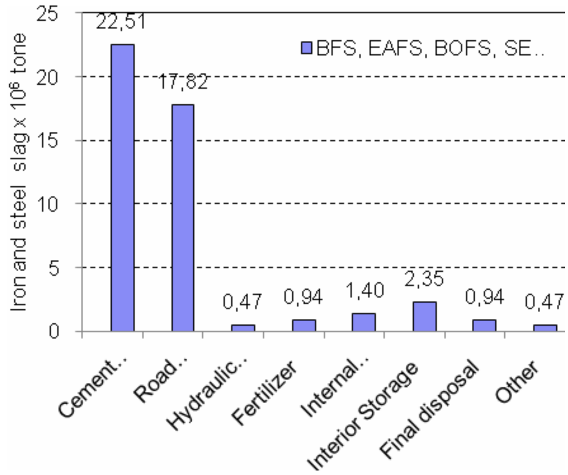

Figure 3 - Use of iron and steel slag in the Europe 2008 (total 46.9 x10^6 t)

Use of slag for road construction was 17.8 million tons (slag aggregates and slag mixtures for unbound or self-binding layers). Furthermore, almost 1 million ton of the slag was used as fertilizers in agro-technical measures and the amount of slag used in hydraulic engineering was about 0.5 million tons. For interior storage, final disposal and other were used 5.16 million tons of the slag in 2008.

3. UTILIZATION OF IRON AND STEEL SLAG IN ROAD CONSTRUCTION

The metallurgical slag has been used over the past 100 years for many industrial purposes, especially for road construction [59 - 71]. Nowadays, almost 100% of blast furnace and steelmaking slag are utilized. Due to their mechanical, physical and chemical properties, blast furnace and steelmaking slag could have numerous construction applications as showed in previously published work [47], Table 3.

Present day steelmaking slags are being successfully used in two major types of applications: (a) as a source of iron and flux materials in blast furnaces, and (b) as a high quality mineral aggregate for specific uses. It is estimated that one-half to two-thirds of the steel slags produced world-wide are used, either by recycling or in road building applications, railroad ballast, as fertilizers, etc. From this reason, slags are promoted as “sustainable” construction materials, mainly on the basis that slags substitute directly or indirectly for natural raw materials [72, 73]. Slags are commonly used in several pavement layers, mainly used as aggregates in bituminous surface course layers. Slags can also be used in the lower layers of the pavement structure as granular base, in sub base and even in embankments.

Data for generation, sale, and use of iron and steel slag in the world are rarely available or not available at all, except data for U.S.A. Data for sales, use, and transportation of iron and steel slag are developed by the U.S. Bureau of Mines from a voluntary survey of U.S.A. processors, and it is possible to find these on the website.

The obtained data about sales of iron and steel slag products generally reflect demand from the construction industry. Data showed how much of blast furnace slag was used as a ground product to replace Portland cement in concrete, as a concrete aggregate replacing common concrete aggregates and sands, as a highly skid resistant asphalt aggregate, etc.

Table 3 - Typical iron and steel slag uses [47]

Iron and steel slag uses	Environmental applications					
	Applied to land surface	Applied to land subsurface	Placed in water	Encapsulated uses	Agricultural uses	Landfill uses
Aggregate in bituminous mixes such as pavement surfaces (wearing and binder courses), bases, surface treatments, seal coats, slurry coats, and cold patch				x		
Concrete aggregate and as a cement ingredient				x		
Antiskid aggregate (snow and ice control)	x					
Surfacing stabilized shoulders, banks, and other select material	x		x	x		
Bank stabilization (erosion control aggregate)	x		x			
Gabions and riprap	x		x			
Aggregate base courses and sub-bases	x	x		x		
Unpaved driveways, surface roads, and walkways	x					
Railroad ballast	x					
Neutralization of mine drainage and industrial discharge	x	x	x			
Agricultural uses - soil remineralization and conditioning, pH supplement/liming agent, fertilizer	x				x	
Controlled, granular fills, such as those required for unpaved parking and storage areas, pipe and tank backfill, and other industrial and construction activity	x	x				
At steel mills as a fluxing agent	x	x	x	x		
Landfill daily cover material						x
Landscape aggregate	x	x				
Trench aggregate/drain fields	x	x				
Sand blast grit	x					
Roofing granules				x		
Bulk filler (e.g., paints, plastics, adhesives)				x		
Mineral wool (home and appliance insulation)				x		
Fill	x	x	x			x

This is how we came to the data on movements of the quantities of produced/marketed iron and steel slag on the U.S.A. market in certain time periods. Thus, from 1942 to 2009 the amount of produces/marketed iron and steel slag on the US market ranged from 11,300,000 t in 1944 to 33,600,000 in 1969 [74].

When talking about the application of steel slag in road construction in the period 2003-2009, it should be mentioned that the results of research of slag application conditioned a significant change in its purpose. In this period the purpose of steel slag has significantly changed, so the ratio of this slag used for road construction, was from 74.5 % to 86 % as presented in Table 4.

Table 4 - Use of steel slag in U.S.A. in period 2003-2009 [37, 74]

Use	Use of steel slag, %						
	2003	2004	2005	2006	2007	2008	2009
Asphaltic concrete	17	12.9	15.6	12.1	14.4	10.9	8.2
Road bases and surfaces	46.4	63.5	53	51	51.5	60.3	59.9
Fill	11.1	9.6	10.5	17.9	13.3	10.8	12.7
Clinker raw material	5.4	5.5	6.9	6.9	6.7	5	2.2
Miscellaneous*	2.5	2.9	2.3	0.8	2.3	0.5	0.5
Other or unspecified	17.6	5.6	11.7	11.3	12	12.7	16.5

*Railroad ballast, roofing, mineral wool, or soil conditioner

In the period from 1997 to 2009 in the U.S.A., shared of slag marketed depending on the application were as follows: for road bases and road surfaces 23 - 64 %, asphaltic concrete aggregate 8 – 27 % and Fill 10 – 28 %, Figure 4.

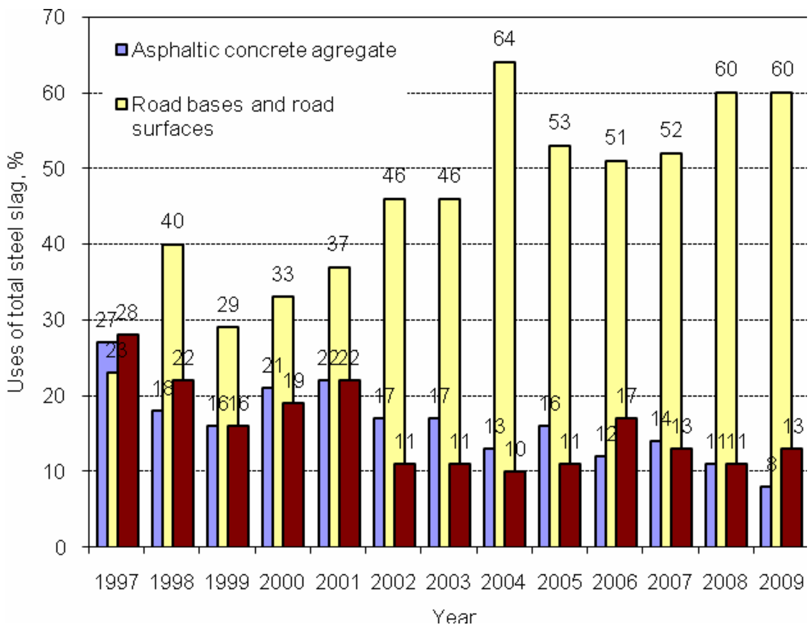

Figure 4 - The principal uses as percentages of the total steel slag in U.S.A.

This was, above all, conditioned by an increased market demand of this type of products, which is also confirmed by a significant rise in their prices. According to statistical data of U.S. Geological Survey [75], the average price of iron and steel slag ranged from 0.84 USD/t in 1942 to 22 USD/t in 2007. Here, one must emphasize that a significant difference in prices between products gotten from iron slag when compared to products gotten from steel slag is apparent. Hence, for instance, according to 2008 data, prices for products from iron slag ranged from 1.84 to 100.5 USD/t, while prices for products from steel slag were between 0.2 USD/t and 15.39 USD/t.

Although the share of steel slag products in the total amount of produced and marketed products increased from around 20 % in 1976 to around 46 % in 2008, according to Van Oss [76] the growth in prices of these products on the U.S. market took place more slowly. Because of generally low unit sales values, slag sold for aggregate generally cannot be economically transported over long distances, particularly overland. Thus, the major factors affecting the sales volumes and prices of slag are dominated by local competition from natural aggregates, the overall level of construction activity (particularly that for roads), and the existence of long-term supply contracts.

Taking into consideration the amounts of certain types of slag used in period 1998 - 2009 and their individual shares in the total of produced and marketed slags, the increase in the average price of slag went from 8.15 USD/t in 1998, 8.05 USD/t in 2001 to 22 USD/t in 2007, Figure 5. This is again the consequence of the high price of iron slag, which marks its highest recorded price in that period at 20 USD/t in 1998, reaching 100.5 USD/t in 2008 as the product of the highest quality, i.e. ground granulated blast furnace slag.

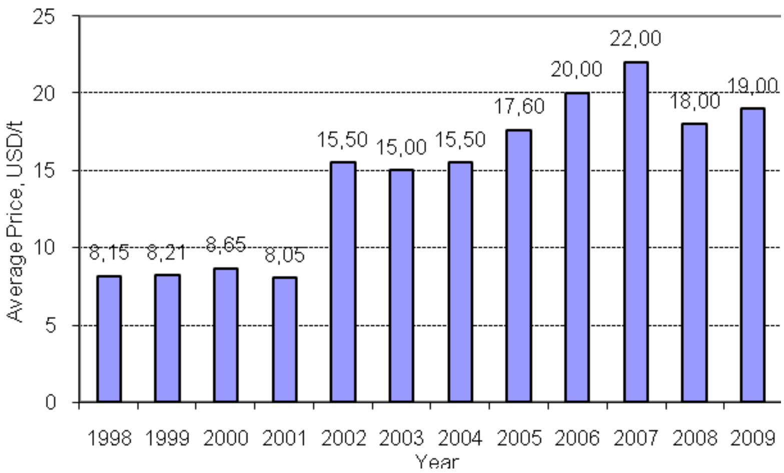

Figure 5 - Movement of average price for iron and steel slag on U.S. market

3.1 Utilization iron and steel slag in Croatia

The Croatian metallurgy, although not quite significant in European terms, has a relatively long tradition of managing its by-products, which were rarely called industrial waste, for it has started using them as raw materials in other industrial processes relatively early.

In the period from 1959 to 1976 in Ironworks Sisak (nowadays CMC Sisak), Croatia, blast furnace slag was used for the production of the so-called metallurgical cement, which was used for the production of bricks of different dimensions. To be more precise, in the unit for the production of metallurgical cement of the 52000 t/y or 10 t/h capacity, which contained up to 70 % ground granulated blast furnace slag, with the rest Portland clinker and a little gypsum [77], construction elements or blocks were produced in the following dimensions: 8 x 20 x 40 cm, 10 x 20 x 40 cm, 15 x 20 x 40 cm, 20 x 20 x 40 cm, 25 x 20 x 40 cm and 30 x 20 x 40 cm. Their annual production started with the initial 200 000 pieces in 1959, through 3 million in 1966, closing with the end of production in 1976 at 500 000 [77]. The amount of iron slag which is obtained by Croatian blast furnace is 65 % by weight of white pig iron and 70 - 75 % by weight of gray pig iron [78]. The amount of slag which is obtained by Croatian open hearth furnace (OHF) process is 15 % by weight of crude steel output, and in electric arc furnace (EAF) process is 10 % by weight of crude steel production as well. If we calculate based on literature for statistical purpose [78] with slag generating is about 650-700 kg slag on 1000 kg pig iron, we obtained for Croatian iron slag production in period 1946 – 1991 values 12,200 –156,000 tones/y.

Analogically, in the same period, the amount of generated blast furnace slag in Croatia was about 4.5 million tones and amount of generated steel slag was 1.5 million tones as well.

According to this data, in the period 1959 - 1976 almost all generated blast furnace slag was used in the production of metallurgical cement, i.e. construction elements – bricks, while a part of the slag generated before and after that period was used for filling the depressions on the surrounding territory or the repairs to roads within the factory, and the rest of the slag was disposed of at a central factory landfill. Due to economic reasons, the production of metallurgical cement and construction elements – bricks ceased in 1977, so the management of blast furnace slag was continued by selling it to Croatian cement producers up until 1991, when the production of pig iron was stopped and the blast furnaces were shut down. This is how, unfortunately, the development of application of metallurgical slags as high quality by-products ceased as well.

Large volumes of raw materials and thus significant exploitation are required for construction and maintenance of these roads. A more sustainable alternative to using traditional natural materials is to use recycled materials in road construction and maintenance. In Croatia, use of steel slag can meet the demand for a significant portion of the large volumes of construction materials needed for road building and maintenance every year.

Although Croatian iron and steel producers have long tradition and good experience with slag reusing and although the iron and steel slags have their own unique properties and are exploitable for road construction, they have never been systematically put to use on Croatian roads because of a lack of scientific studies conducted on these materials, no availability of proper design and construction standards on them, and the absence of data about the long-term behavior of these materials.

Nowadays, taking into consideration that in Croatia we expect a significant increase in steel production via procedures in electric arc furnaces, and keeping in mind the need for bulk use of these solid wastes in Croatia, it was thought expedient to explore the feasibility of utilizing steel slag as alternative aggregates in road construction i.e. in asphalt mixtures. In last two years characterization of CMC Sisak EAF slag was carried out through an examination of its properties with special emphasis on chemical and structural characteristics. Exhaustive and detailed laboratory investigations have been carried out at the Croatian Civil Engineering Institute, Zagreb, Croatia, and Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia, to develop suitable specifications for manufacturing mixtures of the tested steel slag and natural stone which can be used in road construction.

On the basis of our previously obtained results [79 - 82] of the tested chemical, physical and mechanical properties, as well as durability indicate that steel slag created during the production of EAF low carbon steel in CMC Sisak d.o.o., Croatia, fulfils the conditions required for aggregates used for bituminous mixtures and surface treatments for roads. To assess whether our steel slag is suitable for use as aggregate in asphalt mixes, it was exposed to the testing in accordance with EN 13043:2002 - Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas. The results of the examined asphalt mixtures with our EAF slag showed good results of physical and mechanical properties of asphalt mixture in comparison with asphalt mixture with natural limestone aggregate [83].

After construction of the test field using EAF slag aggregate it was found that no problems had been encountered in the designing of the mixture or in the placing of the asphalt in the test field.

In Croatia, there are almost 30 000 kilometers of roads and relatively large volumes of raw materials and thus significant exploitation are required for construction and maintenance of these roads. A more sustainable alternative to using traditional natural materials is to use recycled materials in road construction and maintenance. In Croatia, use of steel slag can meet the demand for a significant portion of the large volumes of construction materials needed for road building and maintenance every year.

4. CONCLUSION

This paper demonstrates the significance of iron and steel slag as by-product arising from the iron and steel industry, and which man could always utilize in other industrial branches, and on the basis on the said, on might conclude that it follows that:

- Today, it is estimated that worldwide 240 million tons of BFS and around 135 million tons of is generated, while in the EU member stated the total generated amount of slag from processes of steel and iron production reaches around 50 million tones, 58% of which is BFS and 42% steel slag.
- Thanks to its physical and chemical properties, BFS is today mostly used in the cement and road construction industries, although it's application in agriculture or other industries where it is used as raw material is also significant.
- In the EU member states, BFS as a by-product is mostly used in the cement and road construction industries, although, unfortunately, a small portion is still disposed of at landfills and is not being utilized. Steel slag is mostly used in road construction where the aggregate produced from this material increasingly replaces natural aggregates, especially where the origin of slag is close to the embedding point in the road considering the cost of transportation largely diminish the feasibility of application of this alternative road-construction materials.
- The knowledge of the possibilities of application of metallurgical slag in diverse industries as well as the development of technology for slag processing have caused a significant rise in the price of slag, especially if the rise of prices is perceived regarding the purpose of the slag. Thus, the average price of iron and steel slag on the U.S.A. market ranged from 0.84 USD/t (1942) to 22 USD/t (2007), and looking individually at BFS, which is much more in demand, on the U.S. market its price per ton went from 2.8 USD (1942) to 100.5 USD (2008).
- The republic of Croatia, although never quite a significant producer of iron and steel in European terms when it comes to quantities, still has a relatively long tradition of managing and using metallurgical slag. Slag generated in the process of production of pig iron in Ironworks Sisak in the period from 1959 to 1976 was

used for the production of the so-called metallurgical cement i.e. manufacture of construction blocks (bricks). Towards the end of the last century, and due to the then poor economic and political circumstances which influenced all the former countries of the south east Europe, economic development slowed down, thus also slowing down the development and improvement of slag processing from by-product to new solutions of its possible uses.

- Now days, due to a relatively high share 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. Through awareness of environmental considerations and more recently the concept of sustainable development, extensive research and development has removed slag from industrial waste into modern industrial product which is effectively and profitably used for many industrial purposes, especially as row material in road construction.
- In Croatia, there are almost 30 000 kilometers of roads and relatively large volumes of raw materials and thus significant exploitation are required for construction and maintenance of these roads. A more sustainable alternative to using traditional natural materials is to use recycled materials in road construction and maintenance. In Croatia, use of steel slag can meet the demand for a significant portion of the large volumes of construction materials needed for road building and maintenance every year.

REFERENCES

[1] Ettler, V., Piantone, P., Touray, J.C.: Mineralogical control on inorganic contaminant mobility in leachate from lead-zinc metallurgical slag: Experimental approach and long- term assessment, Mineralogical Magazine, 67(2003)6, 1269-1283.

[2] J. Loredo, L., Ordóñez, A., Álvarez, R.: Environmental impact of toxic metals and metalloids from the Muñón Cimero mercury-mining area, Journal of Hazardous Materials, 136(2006) 3, 455-467.

[3] Shams, K.M., Tichy, G., Sager, M., Peer, T., Bashar, A., Jozic, M.: Soil contamination from tannery wastes with emphasis on the fate and distribution of tri- and hexavalent chromium, Water Air Soil Pollution, 199(2009)1-4, 123-137.

[4] Waste Management Strategy of the Republic of Croatia. Official Gazette No.130/2005.

[5] Okuno, N., Ishikawa, Y, Shimizu, A., Yoshida, M.: Utilization of sludge in building material, Water Science Technology, 49(2004)10, 225-232.

[6] Akbulut, H., Gürer, C.: Use of aggregates produced from marble quarry waste in asphalt pavements, Building and Environment, 42(2007)5, 1921-1930.

[7] Almeida, N., Branco, F., Santos, J.R.: Recycling of stone slurry in industrial activities: Application to concrete mixtures, Building and Environment, 42(2007)2, 810-819.

[8] Chateau, L.: Environmental acceptability of beneficial use of waste as construction material-State of knowledge, current practices and future developments in Europe and in France, Journal of Hazardous Materials, 139(2007)3, 556-562.

[9] Huang, Y., Bird, R.N., Heidrich, O.: A review of the use of recycled solid waste materials in asphalt pavements, Resources, Conservation and Recycling, 52(2007)1, 58-73.
[10] Badur, S., Chaudhary, R.: Utilization of hazardous wastes and by-products as a green concrete material through S/S process: A review, Reviews on Advanced Materials Science, 17(2008)1-2 42-61.
[11] Garcia-Valles, M., Avila, G., Martinez, S., Terradas, R., Nogués, J.M.: Acoustic barriers obtained from industrial wastes, Chemosphere, 72(2008)7, 1098-1102.
[12] Singh, M., Garg, M.: Utilization of waste lime sludge as building materials, Journal of Scientific & Industrial Research, 67(2008)2, 161-166.
[13] Ducman, V., Mirtič, B.: The applicability of different waste materials for the production of lightweight aggregates, Waste Manage 29(2009)8, 2361-2368.
[14] Jaillon, L., Poon, C.S., Chiang, J.H.: Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong, Waste Manage, 29(2009)1, 309-320.
[15] Tam, V.W.Y.: Comparing the implementation of concrete recycling in the Australian and Japanese construction industries, Journal of Cleaner Production, 17(2009)7, 688-702.
[16] http:// www.fehrl.org/?m=32&mode=download&id_file=790
[17] Herrington, P.R., Kvatch, I., O'Halloran, K.: Assessing the environmental effects of new and recycled materials in road construction: proposed guidelines, Transfund New Zealand Research Report, 306(2006), 70.
[18] Mroueh, U.M., Eskola, P., Laine-Ylijoki, J.: Life-cycle impacts of the use of industrial by-products in road and earth construction, Waste Manage, 21(2001)3, 271-277.
[19] Carpenter, A.C., Gardner, K.H.: Use of Industrial By-Products in Urban Roadway Infrastructure Argument for Increased Industrial Ecology, Journal of Industrial Ecology, 13(2009)6, 965-977.
[20] http://www.rmrc.unh.edu/tools/uguidelines/bfsl.asp
[21] Goel, A., Animesh, D.: Emerging road materials and innovative applications, Proceedings of National Conference on Materials and their Application in Civil Engineering, Hamirpur, India, Aug. 26-27, (2004) pp 1.
[22] Nehdi, M.: Ternary and quaternary cements for sustainable development, Concrete International, 2(2001)4, 35-41.
[23] Luxan, M.P., Sotolongo, R., Dorrego, F., Herrero, E.: Characteristics of the Slags Produced in the Fusion of Scrap Steel by Electric Arc Furnace, Cement Concrete Research, 30(2000), 517-519.
[24] Cioroi, M., Nistor Cristea, L.: Recycling Possibilities of Metallurgical slag, Metallurgy and Materials Science, 1(2007) 78-82.
[25] Engström, F., Larsson, M.L., Samuelsson, C., Björkman, B.: Ageing investigation of steel slags from EAF processes, Proceedings of the 2008 Global Symposium on Recycling, Waste treatment and Clean Technology 353-358.
[26] Vlček, J., Tomkova, V., Babkova, P., Vavro, M., Alkali-Activated Composites Based on Slags from Iron and Steel Metallurgy, Metalurgija 48(2009)4, 223-227.
[27] Loncnar, M., Zupančič, M., Bukovec, P., Jaklič, A.: The Effect of Water Cooling on the Leachig Behaviour of EAF Slag from Stainless Steel Production, Materials and Technology, 43(2009)6, 315-321.

[28] Bradaškja, B., Triplat, J., Dobnikar, M., Mirtič, B.: A Mineralogical Characterization of Steel-Making Slag, Materials and Technology, 38(2004)3-4, 205-208.
[29] Vandecasteele, C., Van Den Broeck, K., Van Gerven, T., Dutre, V., Seuntjens, P., Berghmans, P., Cornelis, C., Nouwen, J.: Characterization and treatment of roads covered with zinc ashes muffle furnace fragments and lead slags from former non-ferrous metal industries in Belgium, Waste Management Research, 20(2002)4, 365-372.
[30] Gorai, B., Jana, R.K., Premchand: Characteristics and utilisation of copper slag - A review, Resources Conservation and Recycling, 39(2003)4, 299-313.
[31] Pundhir, N.K.S., Kamaraj, C., Nanada, P.K.: Use of copper slag us construction material in bituminous pavement, Journal of Science & Industrial Research, 64(2005), 997-1002.
[32] Moynihan, G.P., Fonseca, D.J., Richards, E.P.: Development of a knowledge-based system for foundry waste recycling, JSWTM, 33(2007)3, 134-141.
[33] Shi, C., Meyer, C., Behnood, A.: Utilization of copper slag in cement and concrete, Resources Conservation and Recycling, 52(2008)10, 1115-1120.
[34] http:// www.nationalslag.org/archive/nsa_publication_summary2005.pdf
[35] http:// www.nationalslag.org/.../nsa_1861_steel_slag_utilization_in_asphalt_mixes.pdf
[36] http://www.asainc.org.au/Doc/ASA_Connections_Dec_2007.pdf
[37] Mihok, L., Demeter, P., Baricova, D., Seilerova, K.: Utilization of ironmaking and steel making slags, Metalurgija 45(2006)3, 163-168.
[38] Motz, H., Geiseler, J.: Products of steel slags an opportunity to save natural resources, Waste Manage, 21(2001)3 285-293.
[39] Arkhipov, N.A., Gorokhov, V.L.: New approaches to processing slags, Metallurgist 47(2003)7-8, 303-305.
[40] Rex, M.: The use of BF, converter and ladle slags in European agriculture – benefits or risks? 4th European Slag Conference, EUROSLAG publication 1(2006), 51-62.
[41] McConnell, E., Hesterberg, T., Chevalier, J., Thevenaz, P., Kotin, P., Mast, R., Musselman, R., Kamstrup, O., Hadley, J.: Results of life-time inhalation studies of glass, mineral and slag wools and refractory ceramic fibres in rodents, Journal of occupational health and safety, Australia and New Zealand, 12(1966)3 327-332.
[42] Bynum, R.T. Jr.: Insulation handbook, McGraw Hill Profesional, NY, (2001) 143.
[43] Kurbatskij, M.N., Radionov, B.I., Kudryashov, S.Yu., Kryukov, M.Yu., Kul'pin, A.V., Samojlov, Yu.A.: Manufacturing of mineral wool products on basis of slags, Metallurgy, 1(2002), 49-54.
[44] http://www.smartwaste. co.uk/filelibrary/Mineralwool_sectorstudy.pdf
[45] Svyazhin, A.G., Shakhpazov, E.Kh., Romanovich, D.A.: Recycling the slags of iron and steel industry, Metallurgy, 4(1998), 25-27.
[46] Arora, S., Rao, P.V.T., Chakraborthy, D.S.: Use of non- conventional slags for cement making, Journal of the Institution of Engineers (India). Civil Engineering Division, 81(2000)2, 61-67.
[47] Proctor, D.M., Fehling, K.A., Shay, E.C., Wittenborn, J.L., Green, J.J., Avent, C., Bigham, R.D., Connoly, M., Lee, B., Shepker, T.O., Zak, M.A.: Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Indusrtry Slags, Environmental Science and Technology, 34(2000)8, 1576-1582.

[48] Khan, Z.A., Malkawi, R.H., Al-Ofi, K.A., Khan, N.: Review of Steel Slag Utilization in Saudi Arabia. The 6th Saudi Engineering Conference, Saudi Arabia, Dhahran, 3(2002) 369-381.
[49] Manso, J.M., Gonzalez, J.J., Polanco, J.A.: Electric Arc Furnace Slag in concrete, Journal of Materials in Civil Engineering, 16(2004)6, 639-645.
[50] Manso, J.M., Losañez ,M., Polanco, J.A., Gonzalez, J.J.: Ladle furnace slag in construction, Journal of Materials in Civil Enginnering, 17(2005)5, 513-518.
[51] Kim, E.-H., Cho, J.-K., Yim, S.: Digested sewage sludge solidification by converter slag for landfill cover; Chemosphere 59(2005)3, 387-395.
[52] Reis da Silva, J.-B., Gois de Carvalho, K.-M., Bicudo Filho, P.-S., de Abreu, L.-D. Rossi, L.-A.: Environmental risks analysis on LD steel making slag use for road pavement applications. Rev. Met. Paris, 11(2007), 540-550.
[53] Chen, S., Wang, X., He, X., Wang, W.: Laboratory study and industrial application of desulfurization using low basicity refining slag, Journal of Mining and Metallurgy, Section B: Metallurgy.
[54] Integrated Pollution Prevention and Control. BAT for the Production of Iron and Steel, EC Directorate – General JRC Joint Research Centre, European IPPC Bureau, 313(2008)382, 485.
[55] http://www.worldsteel.org/index.php?action=publicationdetail&id=97
[56] http://www.fxnonstop.com/index.php/component/content/article/101787-myart72110
[57] Skuza, Z., Kolmasiak, C., Prusak, R.: Posibilities for the Utilization of Metallurgical Slag in the Conditions of the Polish Economy, Metalurgija, 48(2009)2, 125-128.
[58] Bialucha, R., Merkel, T., Motz, H.: European environmental policy and its influence on the use of slag products, Proceedings of 2nd International Slag Valorisation Symposium, Ed.: P.T Jones et all, Leuven, Belgium, 18-20 (2011) 201-213.
[59] Geiseler, J.: Use of steelworks slag in Europe. Waste Manage, 16(1996)1-3, 59-63.
[60] Murthy, A.V.S.R., Mathur, S., Kumar, P.: Use of Steel Plant Slags in Road Construction, Journal of the Institution of Engineers (India). Civil Engineering Division 78(1997)2, 76-79.
[61] Kumar, P., Kumar, A.: Steel industry waste utilisation in road sector of India, Journal of the Institution of Engineers (India). Civil Engineering Division, 80(2000)4, 182-185.
[62] Shao-Peng, W., Wen-Feng, Y., Yong-Jie, X., Zhen-Hua, L.: Design and Preparation of Steel Slag SMA. Journal of Wuhan University of Technology – Materials Science Edition, 18(2003)3, 86-88.
[63] Frias Rojas, M., Sanchez de Rojas, M.I.: Chemical Assessment of the Electric Arc Furnace Slag as Construction Material: Expansive Compounds, Cement and Concrete Research, 34(2004), 1881-1888.
[64] Aiban, S.A.: Utilization of steel slag aggregate for road bases, Journal of Testing and Evaluation, 34(2006)1, 65-75.
[65] Asi, I.M., Qasrawi, H.Y., Shalabi, F.I.: Use of steel slag aggregate in asphalt concrete mixes, Canadian Journal of Civil Enginnering, 34(2007), 902-911.
[66] Asmatulaev, B.A., Asmatulaev, R.B., Abdrasulova, A.S., Levintov, B.L., Vitushchenko, M.F., Stolyarskiiv, O.A.: Using blast-furnace slag in road construction, Steel Translations, 37(2007)8, 722-725.

[67] Chaurand, P., Rose, J., Briois, V., Olivi, L., Hazemann, J.-L., Proux, O., Domas, J., Bottero, J.-Y.: Environmental Impacts of Steel Slag Reused in road Construction: A Crystallographic and Molecular Approach, Journal of Hazardous Materials, 139(2007), 537-542.
[68] Wu, S., Xue, Y., Ye, Q., Chen, Y.: Utilization of Steel Slag as Aggregates for Stone Mastic Asphalt (SMA) Mixtures, Building Environment, 42(2007), 2580-2585.
[69] Kök, B.V., Kuloglu, N.: Effects of Steel Slag Usage as Aggregate on Indirect Tensile and Creep Modulus of Hot Mix Asphalt. G.U., Journal of Science, 21(2008)3, 97-103.
[70] Yunxia, L., Mingkai, Z., Xiao, C., Fang, X.: Methods for Improving Volume Stability of Steel Slag as Fine Aggregate, Journal of Wuhan University of Technology-Materials Science Edition, 23(2008)5, 737-742.
[71] Ahmedzade, P., Sengoz, B.: Evaluation of steel slag coarse aggregate in hot mix asphalt concrete, Journal of Hazardous Materials, 165(2009)1-3, 300-305.
[72] Dippenaar, R., Industrial uses of slag (the use and re use of iron and steelmaking slags). Ironmak, Steelmark 32(2005)1, 35-46.
[73] Dziarmagowski, M.: Possibilities of converter slag utilization, Archives of Metallurgy and Materials, 50(2005)3, 769-782.
[74] http: //minerals.usgs.gov/ds/2005/140/ironsteelslag-use.xls
[75] http://minerals.er.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/myb1-2008-fesla.pdf
[75] http://minerals.er.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/myb1-2008-fesla.pdf.
[76] Čepo, Ž.: Željezara Sisak 1938-1973, Ed.: SOUR MK-ŽS, Sisak, 1974, Croatia, 183.
[77] Čepo, Ž.: Željezara Sisak 1938-1978, Ed.: SOUR MK ŽS, Sisak, 1978, Croatia, 284.
[78] Sofilić, T., Merle, V., Rastovčan-Mioč, A., Ćosić, M., Sofilić, U.: Steel Slag Instead Natural Aggregate in Asphalt Mixture, Archives of Metallurgy and Materials, 55(2010)3 657-668.
[79] Sofilić, T., Mladenovič, A., Sofilić, U.: Characterization of EAF Steel Slag as Aggregate for Use in Road Construction, Chemical Engineering Transactions, 19(2010), 117-123.
[80] Sofilić, T., Barišić, D., Rastovčan Mioč, A., Sofilić, U.: Radionuclides in steel slag intended for road construction, Journal of Radioanalytical and Nuclear Chemistry, 284(2010)1, 73-77.
[81] Sofilić, T., Ćosić, M., Mladenovič, A., Sofilić, U.: Utilization of EAF Steel Slag as Alternative Aggregate in Road Construction, Proceedings Book of „Utilization of steelmaking slags with by-product recovery“, Krakow, Poland, 2010, 105-120.
[82] Sofilić, T., Rastovčan-Mioč, A., Ćosić, M., Merle, V., Mioč, B., Sofilić, U.: Steel Slag Application in Croatian Asphalt Mixture Production, Proceedings of International Scientific Conference, Management of Technology Step to Sustainable Production MOTSP 2010, Ed.: P. Ćosić, S. Dolinšek, G. Đukić, G. Barić, Rovinj, Croatia, 2010.
[83] http://www.epa.gov/osw//nonhaz/define/pdfs/steel-final.pdf