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POSSIBILITIES OF APPLICATION OF SLAG IN ROAD CONSTRUCTION

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Subject review

Road construction is an activity in which natural resources are utilized the most in comparison with other branches of civil engineering. Large quantities of natural materials, gravel, rocks and sand are built into kilometres of newly-built roads or in reconstruction of decrepit roads. At the same time, the sustainable development concept requires a more efficient management of waste materials and preservation of environment. The paper presents the basic characteristics of slag, describes some of foreign research studies carried our so far, and analyses domestic experience and the possibilities of the application of slag in road building in the Republic of Croatia.

Key words: *properties, road building, steel slag, waste materials*

Mogućnosti primjene zgure u cestogradnji

Pregledni članak

Cestogradnja je djelatnost koja u usporedbi s ostalim granama graditeljstva najviše troši prirodne resurse. Velike količine prirodnih materijala, šljunka, kamena i pijeska ugrađuju se u kilometre novoizgrađenih cesta ili pri rekonstrukciji dotrajalih cesta. Istovremeno, koncept održivog razvoja traži učinkovitije zbrinjavanje otpadnih materijala i očuvanje okoliša. U radu su prikazane osnovne karakteristike zgure, opisana su neka od dosadašnjih inozemnih istraživanja, analizirana domaća iskustva te mogućnost primjene zgure u izgradnji cesta u Republici Hrvatskoj.

Ključne riječi: *cestogradnja, čeličanska zgura, otpadni materijali, svojstva*

1 Introduction
Uvod

Large quantities of natural materials are traditionally used in road construction. Uncontrolled depletion of natural, non-renewable resources leads to environmental destruction and distortion of natural balance. Concurrently the world faces the problem of management of an increasing quantity of waste, so that linking the two problems leads to a simple solution: a growing and more diverse application of waste materials in road building and other areas of civil engineering alike.

Waste materials whose application is possible in road construction are divided into three basic groups: re-usable construction materials, industry by-products and natural construction materials of a lower usability value [1]. The first group includes the materials that were used one or more times, such as materials from unbound base courses (gravel, sand, and rock) and materials from bitumen and hydraulically bound layers. Slag and fly ash belong to the group of industry by-products, whereas the group of natural construction materials with lower usability value is primarily represented by excavation materials and quarry waste.

2 About slag
O zguri

2.1 Slag production method
Metod proizvodnje zgure

Slag is a waste material generated in purifying metals, their casting and alloying. In the course of this process, slag is generated in two phases. In the first phase the ore is exposed to high temperatures (melting) in order to separate impurities. Separated impurities are collected and removed, and this "waste" material is called slag. During further processing of metal (casting, alloying) various substances are added to purified metal which melt it and enrich it, and in those processes slag is generated again as a by-product.

The type of generated slag depends on the method of cooling of the melted mass (Fig. 1) and on the type of processed metal (non-ferrous and ferrous slag).

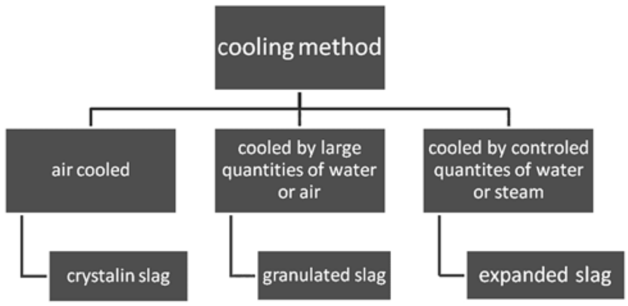

Figure 1 *Division of slag in terms of cooling method*
Slika 1. *Podjela zgure u uvjetima metode hlađenja*

Crystalline slag has cellulose or porous structure (the result of gas bubbles generated in the melted mass) and is usually considered to be in the group of aggregates with normal weight.

In the production of granulated slag sand-sized grains are created. Due to its composition, this material has excellent hydraulic properties, and in the presence of an appropriate activator (such as calcium hydroxide) will behave in a manner similar to Portland cement.

Expanded or foamy slag is more porous and has a smaller volume than air cooled slag.

Given the type of metal being processed, slag is divided into two basic groups: non-ferrous slag (from the production of aluminium, ferrochrome, and ferromanganese) and ferrous slag (from the production and casting of iron and steel).

The current quantity of ferrous slag from ironworks in Sisak and Split, on Croatian landfills, is estimated at approximately 1,8 million tons. A large quantity of this material on landfills and its potential as a substitute for traditional materials has instigated Croatian researchers to carry out research into the possibilities of various applications of slag in construction [2, 3], primarily as an aggregate in concrete mixtures.

2.2
Basic properties of steel slag
Osnovna svojstva čeličanske zgure

Steel slag is generated as a by-product in the production of a specific type of steel from melted iron. This procedure of steel production is carried out according to one of the three procedures known so far: the one in basic oxygen furnace, procedure of processing in electric arc furnace and nowadays mainly abandoned procedure in open-hearth furnace. In each of the three procedures the furnace is filled with hot and/or cold metal and additives to obtain steel with desired characteristics [4]. Then the melted steel and impurities are separated from the furnace, with the impurities consisting mainly of carbon monoxide and silicon, manganese, phosphorus, and some iron in the form of liquid oxides. Combined with lime and dolomite lime, those impurities create steel slag mostly cooled naturally – air cooled – or cooling can be accelerated by sprinkling water. The names of slag originate from the procedure in which the slag was generated (Fig. 2), but very frequently all types of slag are simply called steel slag [4].

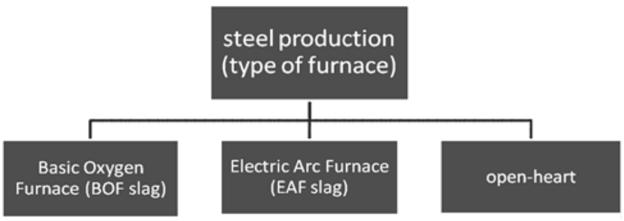

***Figure 2** Names of steel slag based on production procedure*
***Slika 2.** Nazivi čeličanske zgure temeljeni na proizvodnom postupku*

Like the name, the composition of this material depends on the procedure in which it was generated, composition of steel additives and the very type of steel being produced and the cooling speed.

In the composition of steel slag there is a significant share of free calcium and magnesium oxides [5], which are considered responsible for the biggest lack of this material and its limited usage in road building. Namely, steel slag is very expansive, and due to this reason the volume can change by as much as 10 % (free oxides of calcium and magnesium under the influence of humidity hydrate, causing large changes of volume) [5, 6]. Slag weathering in atmospheric conditions is considered to be one of the most appropriate methods of eliminating this adverse property. The weathering period varies depending on the application method and the type of slag itself, i.e., the quantity of free calcium and magnesium oxides. Therefore, it sometimes takes only several months of weathering in atmospheric conditions or occasional sprinkling with water [5]. According to Belgian and Dutch regulations [5], for the use of slag in unbound base courses one year of weathering is sufficient, whereas there are known data on the need for weathering for as much as 18 months before using the slag as aggregate. Those big changes of volume limit the use of steel slag in rigid pavement [7], however, they can be controlled (in asphalt mixtures), or even used as improvement of the properties of built-in material in shoulders or non-asphalt parking areas.

The presence of free calcium oxide, accounting for more than 1 %, causes another adverse property of steel slag, namely, the appearance of white powder in the form of sediment. Free CaO from leachate is bound with water, creating calcium hydroxide, $Ca(OH)_2$, which, when exposed to atmospheric conditions, reacts with carbon dioxide, CO_2, creating calcium carbonate ($CaCO_3$) [5]. It settles down in the form of white powder and may cause obstructions in the drainage systems and water retention. Those obstructions are particularly dangerous in the case of freezing, which renders large damage to pavement structures. This, however, unlike expansions, cannot be prevented by slag weathering.

Among other characteristics two should be stressed – a big bulk density of steel slag and unit weight of 1600-1920 kg/m^3. The grains of this material are pointed, with rough surface, and this is particularly suitable in case of use in asphalt mixtures for reason of an increase in adhesiveness between the pavement and the wheels. The big angle of internal friction (40°-45°) contributes to big stability of materials and CBR value of up to 300 % [5].

Steel slag belongs to medium alkaline materials, with pH values of 8-10.

2.3
Historic overview of the application of slag in road building
Povijesni pregled primjene zgure u cestogradnji

The first appearance of slag was recorded as early as the year 700 B.C. [8]. At that time in the area of the British islands iron processing was recorded, and thereby the appearance of slag. It can be concluded from this data that the history of slag is as old as the melting process in which it is generated.

Slag was used for the first time in road construction as early as Roman era, when slag rubble from processing of crude iron was utilized in building the road bed. The first modern roads in the building of which slag was utilized were built in England, in 1813 [8], and after that the use of slag spread fast to the American continent as well. The use of slag in road building was recorded there for the first time in 1830. As early as 15 years later, after good experiences with the application of this material in road building were confirmed, slag started to be used in railway construction as well [4].

More massive application of slag in various activities began in mid-19th century with the discovery of latent hydraulic properties of granulated blast-furnace slag. Since then, blocks obtained by casting of slag have been massively applied in Europe and America for road pavements.

In the course of World War I the production of steel increased, and this also implied an increase in the production of slag [8]. Given the increase in production, the need for management of waste materials also emerged. Intensive building of military roads in whose building slag was used again contributed to resolving the newly-arisen problem.

According to 1978 data [4] illustrated in Tab. 1, application of slag is possible in different road layers. The same source specifies the presence of slag in base courses: the use of slag is the biggest in *unbound base courses*, somewhat lower in cement-stabilized layers and in asphalt mixtures. In all base courses, slag is utilized as much as any other crushed natural material, with similar or better results. The cost of construction in these circumstances is lower or similar to the price of construction with natural materials [4].

Table 1 *Overview of applications of ferrous slag* [4]
Tablica 1. *Pregled aplikacija na bazi željezne zgure* [4]

Application	1978	1992
	iron slag, %/steel slag, %	
Base courses	35/57	46/35
Aggregate in asphalt concrete	16/7	16/13
Embankment	11/21	10/16
Pavement surfacing	10/6	1/3

2.4 Overview of foreign research in application of slag
Pregled inozemnih istraživanja primjene zgure

The first experiences in the application of slag as an aggregate in asphalt mixtures date from 1969, when a trial road section was built in Toronto, on which steel slag was utilized as an aggregate in base courses and road asphalt surfaces [6, 9]. The studied asphalt mixtures have demonstrated very good properties in terms of bearing capacity, resistance to external impacts, and durability.

In 1974, in Ontario (Ontario Ministry of Transportation and Communications) 17 trial road sections were built on which slag was applied in asphalt concrete that was carried out as a measure of rehabilitation of concrete pavement with a view to increasing surface friction [6, 9, 10]. The obtained results have demonstrated good resistance of road surfaces to friction and good properties of adhesiveness of road surfaces. It was established that the number of traffic accidents on wet pavement was approximately the same as the number of accidents that occurred on dry pavement.

Emery [5, 9] states that in the first uses of slag in asphalt there were occurrences of fractures and heaves of pavement, which later on was linked to the lack of stability of slag because of free oxides of calcium and magnesium. The reasons were an insufficiently careful selection of materials and improper embedding method. Hydration of free oxides due to which expansion occurred was usually prevented, i.e., controlled by a sufficient time period of slag weathering before its use in pavement base courses. However, the same author [6, 9] specifies that weathering is not the critical criterion in the utilization of slag in asphalt layers if smaller slag fractions are used, with grain size of 13-13.2 mm. In the process of production of asphalt mixture the aggregate undergoes the washing and screening phases, as well as drying, with ensuing instantaneous hydration and expansion of slag. The second condition that enables application without preliminary weathering is pre-coating the aggregate grain with a bitumen film that limits potential expansion [6]. For aggregates with larger grain size, in particular those larger than 19 mm, the necessary weathering period of a minimum of 30 days is specified. An additional measure of prevention of pavement deformation due to expansion which is specified is the recommendation that slag used in asphalts should contain up to 3 % of ingredients other than slag [5], whereas Emery [9] and Wu et al. [11] limit the share of free CaO to a maximum of 6 %. In his doctoral thesis Mäkikyrö [12] specifies a significantly stricter criterion of the share of free CaO, if non-weathered slag is utilized, and states that this percentage is only 4 % for slag applied in bitumen layers and 7 % in unbound base course. Canadian regulations, as an additional measure against the possibility of occurrence of deformations in the course of the use of the pavement [5], limit the expansion to 1 %.

Although up to this point mostly negative properties arising from the presence of free calcium oxide have been highlighted, it has also had a positive impact in the application of slag in asphalt mixtures. Namely, Shen et al. [13] state that the presence of free CaO increases the resistance to stripping, adhesion between aggregate grains and binder, thus contributing to higher durability of road surface. The increase in adhesion is facilitated by the very nature of slag as a by-product of the steel production process, i.e., it does not contain clay [14].

Physical properties of slag should be highlighted among other advantages of slag in its utilization in asphalt mixtures. Sharp edges, a proper grain shape, and rough surface texture also contribute to better adhesiveness of aggregate binder and grain, and increase the coefficient of internal friction of bituminous overlay more than any other natural aggregate. Those physical properties, in addition to the proper granulometric composition, increase shear tightness of mixtures and resistance to appearance of rut [14]. It is for this reason that those mixtures are most frequently used in places where great wear resistance and good adhesiveness of pavement is required, such as roads in industrial installations, parking spaces exposed to heavy freight vehicles and junctions.

Among physical properties of steel slag Emery and Ali et al. [5, 6, 10] highlight a great specific weight and density of steel slag, which also increases specific weight and density of asphalt mixtures in comparison with those with natural aggregate. This big specific weight leads to the advantage of those mixtures in winter-time road maintenance. Emery and Shen et al. [5, 6, 13] also state that a strong stability of mixtures containing steel slag as aggregate (as much as 1,5-3 times greater than that in standard mixtures) and increased maintenance of temperature and dryness aggregate, besides reducing the energy consumption in winter rehabilitation of pavement, contributes to the duration of rehabilitation and easier disposition. In embedding those mixtures have demonstrated high workability, long-term maintenance of temperature, and very good compaction properties [5, 6, 10, 14].

The confirmation of the convenience of utilization of this waste material in asphalt mixtures was provided by research carried out at McMaster University [6, 9], which has demonstrated that elasticity modules of asphalt mixtures with steel slag are higher by 20-80 % than mixtures with standard aggregate at temperature of 29 °C. Emery [9] states that the values of Poisson coefficients of those mixtures are lower than the standard ones, which additionally points to a higher stability during utilization and resistance to the occurrence of plastic deformations. With regard to those data and the state of pavement structure stress, he indicates the possibility of designing of pavement structures with reduced thickness of asphalt concrete compounds up to as much as 37 mm [6]. This could make up for one of the disadvantages of these mixtures, a bulk density higher by 15-25 %, which increases costs of transportation of fresh asphalt mixtures. Among the disadvantages is also the increased need for binder due to granular sharp edges and rough surface.

Steel slag can be applied as an aggregate both in hot and cold asphalt mixtures. The only limitation specified as regards this use is the quantity of aggregate made up of slag. More precisely, mixtures with 100 %-share of steel slag as aggregate have proven to be sustainable to appearance of fractures at large distances and big bulking of mixtures due to sharp edges and regular grain shape [5]. Ahmedzade and Sengoz [15] indicate that in such mixtures there may appear an increased need for binder in the course of the production and stripping of bitumen binder in pavement utilization. For this reason it is recommended that slag is used only as a replacement for smaller or larger aggregate grain size in the applications in wear-exposed asphalt layers. According to Ahmedzade and Sengoz [15], the research carried out by Asi has shown that asphalt concrete mixtures are more friction-resistant if they contain 30 % of slag and that 75 % substitution of limestone aggregate by slag has rendered significant improvements of mechanical properties of asphalt concrete. Among those properties particularly important is the Marshall stability, for which the research conducted by Kara [15] has demonstrated a better stability than the mixtures with the limestone aggregate. This is the reason for the higher resistance to permanent deformations of such overlays, as well as higher stiffness. The research indicated above also included testing of electric conductibility, which also confirmed that slag was an aggregate with better performance. Electric conductibility may be useful in the use of special techniques of winter maintenance (e.g. in the maintenance of runways).

Authors Shen et al. [13] showed in their research that porous asphalt with BOF slag has a number of advantages: lower susceptibility to abrasion, better absorption due to big porousness and excellent drainage of water from pavement surface (higher traffic safety) and better properties in terms of traffic noise, i.e., they belong to the "silent" overlays group.

Xue et al. [16] in their research included rehabilitation of stiff pavement by a new layer of stone mastic asphalt (SMA) in which the slag is utilized as aggregate and concluded: expansion of embedded layer is very slow (7 days – only 1 %), adhesion connectivity between aggregate grains and binder is exceptionally good, which results in increased resistance of pavement to wear and tear, better resistance to permanent deformations at high temperatures, and better resistance to the appearance of fractures at low temperatures [11].

Application of slag in unbound base courses has been described by authors Motz et al. [17]. A number of trial road sections with slag in unbound base courses were constructed, while the research carried out a comparison of layers containing steel slag as an aggregate and layers with crushed stone. A comparison of the results has shown that the layers with slag have demonstrated higher bearing capacity immediately after material compaction. Further increase in the strength was explained by carbonate hardening due to free oxides of calcium. According to the source [14], attaining of greater bearing capacity may also be accounted for by the shape of slag grain which is convenient for compaction, creating a very hard, compact and durable surface that may sustain heavy traffic loads.

Authors De Bock et al. [18] described the application of slag from the production of stainless steel as aggregate in cement-bound base courses in the building of a warehouse plateau in Belgium. Volume changes of embedded material and compressive strength were observed, and the obtained results of volume change of 2,3 % after 7 days and compressive strength of 7 MPa indicated that the material was of satisfactory quality. The same authors presented another example of the utilization of slag from production of stainless steel in rigid pavement structures for pavement of rolled concrete constructed on a side suburban road. In that case the measured value of CBR was no less than 250 %, but this value declined quickly to 80 % with the increase in the humidity of the material. Problems have been observed with the appearance of fractures and swelling of pavement due to the reaction of free calcium oxides and water.

The problem of hydration of free oxides may be resolved by a proper selection of grain size distribution of slag, as discussed by Mäkikyrö in his dissertation [12]. Research results have indicated that small grain slag (0/4 mm) has bigger expansion properties than larger-grain slag. This fact represents an advantage provided that slag is applied as a binder, in particular if the share of binder in comparison with the aggregate is low – in that case expansiveness of slag is lost in the total mixture mass.

Numerous authors, Mäkikyrö [12], Shena et al. [19], Luckman and Satish [20], and Mahieux et al. [21], have pointed to weak cementitious and pozzolanic behavior of steel slag. However, despite poor pozzolanic behavior, research still continues and new methods of utilization of slag as binder or binder addition are being sought.

In their research Luckman et al. [20] have found and described the method of processing EAF (Fig. 2) slag with a view to improving cementitious behavior. EAF slag was melted and cooled under water-jet, with the resulting significant changes in the slag composition and structure. The results of laboratory tests have shown that this procedure increased 4 times the pozzolan hardness.

Authors Mahieux et al. [21] have proven poor activation of BOF (Fig. 2) slag in cement mixtures, given that a lack of pozzolana reaction after 28 and 90 days of hardening was observed. Research has shown that this slag cannot be applied as the main constituent of hydraulic binders in road building, but that its free oxides may be used for activation with other materials, e.g., blast furnace slag from iron production. Research by the same authors [21] has shown that mixtures of blast furnace and BOF slag with the addition of activators accounting to 5 % did not demonstrate any problems in terms of expansion, and it has also been observed that higher values of compressive strengths are attained with smaller grain size of BOF slag.

In his doctoral dissertation Mäkikyrö [12] studied mixtures of steel slag, cement, and granulated blast furnace slag. The resultants have shown that, although to attain equal properties of bearing capacity of mixtures with blast-furnace slag as the mixtures with cement, bigger thicknesses of the layer and a greater quantity of binder were required, the slag-based binders develop good strengths in stabilized mixes and are convenient for utilization in road building.

2.5 Croatian experiences in application of slag

Hrvatska iskustva u primjeni zgure

Currently there are two landfills of such slag in the Republic of Croatia, one close to Sisak and the other one on the site of the Split Ironworks. Slag from the Sisak

Ironworks is a combination of blast-furnace and electric arc furnace steel slag used in road building as a stabilization layer and in agriculture, where smaller grain size is used as soil improver. So far electric arc furnace steel from the Split Ironworks has not been used, and is deposited on the site. The estimated quantities of slag on landfills are approximately 1,8 mil. tons.

Research carried out to date in the Republic of Croatia in the area of application of slag as aggregate in concrete is the one by the authors Netinger et al. [2] and [3]. There is an ongoing research on the application of slag as aggregate in asphalt mixtures.

Authors Netinger et al. [3] have studied the possibilities of the application of slag as aggregate in concrete mixtures. Large grain size of slag from the Split and Sisak Ironworks to standard HRN EN 12620/AC:2600 *Aggregates for concrete* were tested, and the obtained results were compared with properties of the usual dolomite aggregate. Both slag types fulfilled the requirements set in the Technical Regulation for Concrete Structures and may be considered an acceptable substitute for the standard aggregate.

The research studies described above have confirmed good properties of slag as an alternative material and can definitely be considered an "encouragement" in initiating new research on the possibilities of the application of slag in construction.

3 Conclusion
Zaključak

Application of slag as an alternative to standard materials in the world has been known for a number of years, and accordingly numerous research studies have been carried out in that area. Slag is used the most in asphalt mixtures, although its good properties are also used for application in other layers of pavement structure, primarily unbound base courses and embankment.

An area of application that has not been studied extensively so far is the application of slag in stabilized mixtures for construction of base courses, which could be of great interest for domestic road construction. Namely, in the last ten years road building in the Republic of Croatia was based on motorway building, and in this process, given the very heavy traffic load, cement-bound base courses were designed to increase the bearing capacity. Domestic slag has a significant quantity of calcium oxide, CaO (25-30 %, whilst free CaO accounts for 0,22-0,28 %), which is the basic indicator of pozzolanic behaviour of the material. The quantity of CaO indicates primarily the existence of the possibility of utilization of slag as binder or a portion of binder, but also as aggregate in stabilized base courses, which creates a possibility of new research in this area.

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