Tlačna čvrstoća stabilizacijskih mješavina od zgure iz čeličana

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Received: 12.4.2011.
Corrected: 11.1.2012.
Accepted: 24.1.2012.
Online: 15.2.2012.

Compressive strength of steel slag stabilized mixes

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Preliminary note

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Compressive strenght of steel slag stabilized mixes

The compressive strength testing, conducted on stabilisation mixes with steel-furnace slag originating from the Sisak Ironworks, and on "standard" stabilisation mixes with crushed stone aggregate from "Velika" Quarry, is presented in the paper. The testing was made to check whether slag can be used as aggregate in pavement base courses, and to determine in what way compressive strength values are influenced by binder content and grading of stabilisation mixes. Compressive strength results obtained during this testing comply with stringent criteria set in technical regulations, and confirm that slag can be used in stabilized base courses of pavement structures.

Key words:
pavement structure, stabilized mixes, steel slag, compressive strength

Prethodno priopćenje

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Tlačna čvrstoća stabilizacijskih mješavina od zgure iz čeličana

U radu su opisana ispitivanja tlačnih čvrstoća stabilizacijskih mješavina sa zgurom iz željezare Sisak i "standardnih" stabilizacijskih mješavina s drobljenim kamenim agregatom iz kamenoloma "Velika". Ispitivanjem se nastojalo utvrditi pogodnost zgure kao agregata u nosivim slojevima kolničkih konstrukcija te utjecaj udjela veziva i granulometrijskog sastava stabilizacijskih mješavina na tlačne čvrstoće. Rezultati tlačnih čvrstoća dobivenih ispitivanjem zadovoljili su stroge kriterije postavljene tehničkim propisima te potvrdile mogućnost primjene zgure u stabiliziranim nosivim slojevima kolničkih konstrukcija.

Ključne riječi:
kolnička konstrukcija, stabilizacijska mješavina, čeličana zgura, tlačna čvrstoća

Vorherige Mitteilung

Ivica Androjić, Sanja Dimter

Druckfestigkeit von Stabilisierungsmischungen aus Stahlschlacke

In der Arbeit wird die Prüfung der Druckfestigkeit von Stabilisierungsmischungen aus Stahlschlacke aus der Werft Sisak und „standardmäßige" Stabilisierungsmechanismen mit gebrochenem Zuschlag aus dem Steinbruch "Velika" beschrieben. Bei der Prüfung, die zufriedenstellend ausgefallen ist, war man bestrebt, die Eignung der Schlacke als Zuschlag in den Tragschichten von Fahrbahnkonstruktionen sowie den Einfluss des Bindemittels und der granulometrischen Zusammensetzung der Stabilisierungsmischungen auf die Druckfestigkeit festzustellen.

Schlüsselwörter
Fahrbahnkonstruktion, Stabilisierungsmischung, Stahlschlacke, Druckfestigkeit

1. Introduction

Great quantities of natural materials are nowadays used in road construction. Such continuous demand for natural materials contributes to the depletion of natural resources, while in areas lacking in quality aggregates the cost of aggregate purchase and supply greatly increases the total cost of construction. Waste materials and industrial by-products can therefore be used as a good substitute to natural aggregate in road construction. These materials, requiring complex disposal and regarded as hazardous to natural environment, can prove to be economically and otherwise quite significant when used as replacement for or addition to standard materials.In the first place, the use of these materials contributes to a more rational utilization of natural aggregate reserves, and is furthermore quite favourable for curbing down environmental problems caused by disposal of waste materials. Slag is one of such materials: it occurs as by product during purification of metal, and during its melting and alloying, and has a significant potential in road construction. It has been used worldwide for many years now, and so numerous studies about its use and properties are now available. Slag is mostly used in asphalt mixes although its good properties have also made it indispensable in other layers of the pavement structure [1]. As many as 200 to 240 million tons of blast-furnace slag, and 115 to 180 million tons of steel furnace slag, are produced every year in the world, while annual production in Europe varies around 12 million tons, out of which about 65% of steel-furnace slag is used as aggregate in road construction.

Research undertaken so far in the Republic of Croatia has concentrated on the use of slag as aggregate in concrete [2, 3] and, more recently, on the use of slag as aggregate in asphalt mixes [1]. In this respect, test sections were made and slag was incorporated in unbound layers of pavement structures of approach roads, and also in bituminized base courses. Experience gained to this date on test sections and from laboratory testing results, confirm the good quality of this material and give encouragement for further testing work.

Due to heavy traffic load on our roads, pavement structures are in many cases realized with a stabilized base course. While increasing bearing capacity of pavement structures, such stabilisation layers are also a good base for pavement surfacing, and they also increase resistance of pavement structures to harmful frost action [4]. Stabilisation mixes used in construction of pavement-structure base courses are mixes composed of granular stone materials (gravel, stone, sand) that are bound by cement.

As the price of stone mix (sand, gravel or chippings) contributes significantly - sometimes with more than 70% - in the price of stabilisation mixes, the idea behind this testing was to reduce the cost of stabilisation mixes by replacing the "standard" stone mix with the crushed steel slag mix 0/31.5 coming from Sisak Ironworks, as in this way we would obtain an economically more acceptable stabilisation mix compliant with current quality requirements [6].

The steel slag originating from Sisak Ironworks is a byproduct occurring during production of steel, i.e. during separation of molten steel from impurities in steel manufacturing furnaces. These impurities are the carbon monoxide and silicon, manganese, phosphorus, and some iron in form of liquid oxide. When mixed with lime and dolomitic lime, these impurities form the steel-furnace slag or steel slag. About 150-200 kg of residues or byproducts are generated during production of one ton of steel. The slag stockpiled near the town of Sisak occupies an area of 25 hectares, and is of mixed composition: combined high furnace and electric arc furnace slag. The quantity currently deposited in this area is estimated at 1.5 million tons [5].

2. Experimental section

The objective of this analysis is to study possibilities for using slag in the stabilized base course of pavement structures, and to determine whether mechanical properties of the stabilized material can actually be realized. This particularly concerns compressive strength, as the possibilities of application are mostly dependent on this property.

2.1. Testing suitability of steel slag for use in stabilized base course

The suitability of materials for use in base courses stabilized by hydraulic binder is defined in General Technical Requirements for Road works (GTC), Volume III; Section 5-02 [6]. The material to be incorporated in stabilized base courses must meet requirements set with respect to grain size distribution and physicomechanical properties of grains. Partial laboratory tests of slag were conducted in order to establish whether this material is suitable for use in base courses stabilized by hydraulic binder. The grain size distribution of slag is presented in Figure 1, while results obtained by testing physicomechanical properties of slag are given in Table 1.

It can be seen from curve established by analyzing grain size distribution of samples that the slag mix sample (0-31.5 mm) is situated in the grain size distribution range that is considered favourable for use in base courses.In addition to the grain size distribution curve, the following requirements were also checked: uniformity coefficient is U = 32.05 (which is within the specified 15-50 range), maximum grain diameter is 31 mm (which is compliant with the specified maximum of 31.50 mm), content of voids smaller than 0.02 mm is 1.95 (which is less than the allowed 3% maximum).

The comparison of grain size distribution values obtained in this study with values specified in General Technical Requirements, Volume III, Sections 5-01.1.1 and 5-02.1.1 [6], shows that slag is suitable for use in base courses stabilized with hydraulic binder (Table 1).

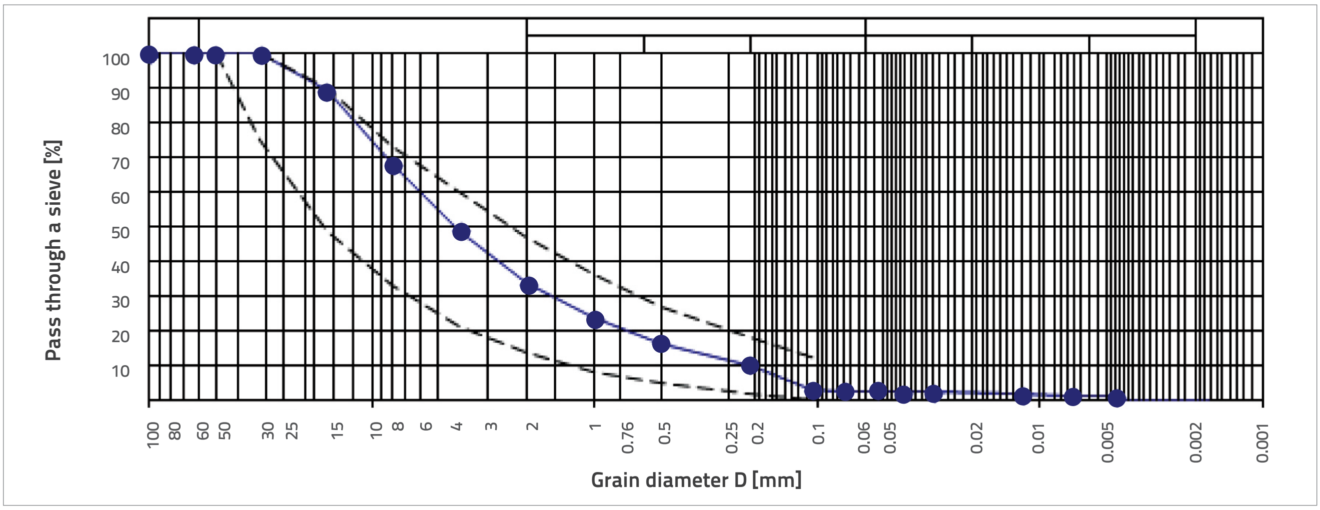

Figure 1. Grain size distribution curve for slag

Table 1. Results obtained by testing physicomechanical properties of steel slag

Property	Applicable standard	Unit	Steel slag test results	Requirements specified in GTC
Density	HRS CEN ISO/TS 17892-3	t/m³	3,13	
Content of particles smaller than 0,02 mm		mas %	1,95	< 3,0
Uniformity coefficient $U=d_{60}/d_{10}$	HRS CEN ISO/TS 17892-4 toč.5.2		32,05	15-50
Maximum grain diameter	HRS CEN ISO/TS 17892-4 toč.5.2	mm	46	< 63
Optimum moisture (Wopt)	HRN EN 13286-2 toč.6.3	%	8,30	
Dry bulk density (γ_{dmax})	HRN EN 13286-2 toč. 7.5	t/m³	2,324	
Grain shape	HRN B.B8.048	%	9,8	max. 40
Water absorption	HRN B.B8.031	%	5,8	max. 1,6
Friability	HRN B.B8.037	%	1,6	max. 7
Mineralogical & petrographical classification	HRN B.B8.003		Crushed steel slag	

The reference dry bulk density and water content were determined in accordance with HRN EN 13286-2 [7], Sections 6.3 and 7.5. The slag sample taken from stabilisation mix was subjected to the modified Proctor compaction test (energy: 2,66 MJ/m³). At that, the cement type SPECIJAL, CEM II/A-M (S-V), strength class 42.5 N, was added. The maximum dry bulk density of γ_{dmax} =2,32 t/m³ was obtained, and the optimum moisture amounted to w=8,40%.

According to results obtained during this testing, the physicomechanical properties of slag comply with requirements set for stone material, except for water absorption amounting to 5.80%, which greatly exceeds the 1.60% maximum set according to General Technical Requirements for Road Works [6].

The following tests were conducted in the Stone and aggregate laboratory (ZAG) in Ljubljana: volumetric stability of slag, disintegration of air-cooled slag due to presence of dicalcium silicate and iron, and determination of bulk density of grain and water absorption according to relevant European standards. Test results are compliant with SIST EN 1744-1/1999 and there is no danger that slag will disintegrate du to presence of dicalcium silicate and iron.

Following laboratory testing aimed at determining suitability of this material for use in base courses stabilized with hydraulic binder, it can be concluded that slug complies with required criteria as related to grain size distribution and physicomechanical properties, with the exception of water absorption where maximum water absorption is 1.6% (5.8% for slag), and that the material is therefore suitable of use in stabilisation mixes.

2.2. Properties of stabilisation mix components

2.2.1. Aggregate and binder properties

The objective of the planned testing was to compare compressive strength of stabilisation mixes containing various aggregates. In one group, the aggregate was the slag originating from Sisak Ironworks (0/31.5), while in the second group the aggregate was the standard crushed aggregate mix from Velika Quarry (0/63) which is normally used in the construction of base courses for pavement structures. The grain size distribution of the

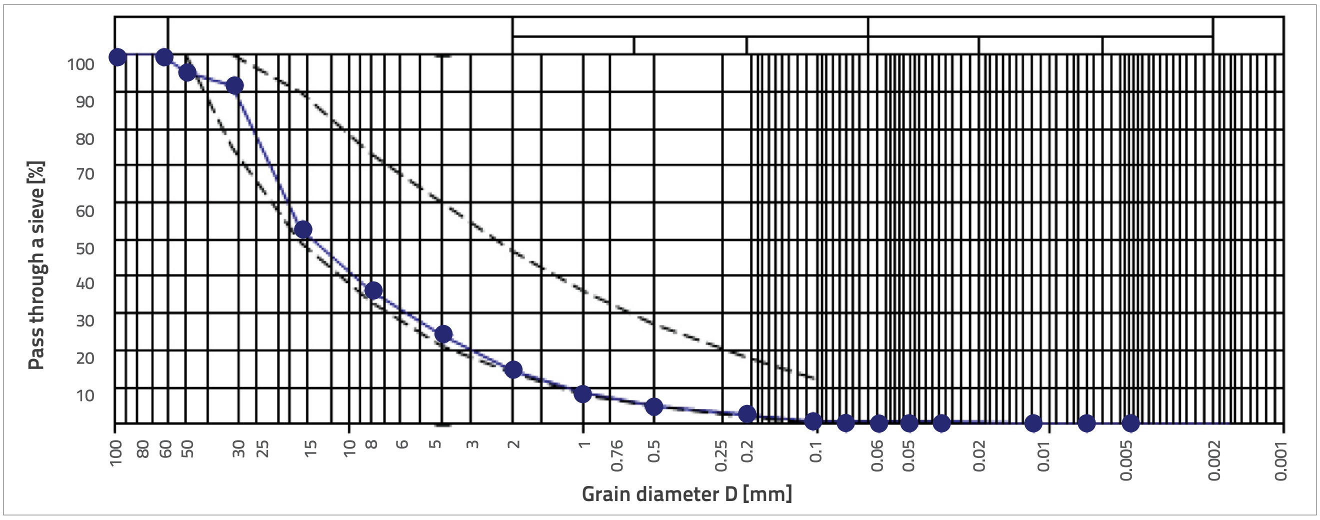

Figure 2. Grain size distribution diagram for crushed stone mix

crushed stone mix from Velika Quarry is shown in Figure 2.
The grain size distribution curve for the crushed stone mix shows that the grain size ranges from 0 to 63.0 mm. The uniformity coefficient amounts to U=17.06; the maximum measured grain is 70 mm; and the content of particles smaller than 0.02 mm is 0.53. All these results confirm that the stone material is suitable for use in base courses stabilized with hydraulic binder [6, 8].
According to the crushed stone grading, this material contains a greater quantity of coarse grains. Lesser quantity of hydraulic binder is necessary as coarser stone mixes are characterized by spot binding of aggregate.
Properties of slag used as aggregate are explained in detail in section 2.1. The grain size distribution of slag shows that the grain size is 0/31.5 mm, with considerable quantity of fine grains and with lack of coarser fraction, which is why greater quantities of cement are needed to ensure compliance with strength requirements. The steel slag is porous in structure and has greater water absorption capabilities, while its optimum moisture is by 3-5 percent greater when compared to the crushed stone mix.
The cement SPECIJAL, CEM II/A-M (S-V) 42,5N was used to stabilize both mix groups. The cement "Specijal" contains no less than 80 percent of Portland cement clinker, up to 20% of the mixture of siliceous fly ash and high furnace slag (S), and up to 5% of secondary additive (pupil) and binder regulator (natural gypsum).

2.2.2. Preparation and cure of samples

The following five stabilisation mixes were prepared for the testing:

1. steel slag with 0.5% cement (by weight),
2. steel slag with 0.7% cement (by weight),
3. steel slag with 2.0% cement (by weight),
4. crushed stone mix with 0,5% cement (by weight),
5. crushed stone mix with 0,7% cement (by weight).

Figure 3. Stabilisation mix samples (slag on the left, and crushed stone on the right)

Samples measuring 15.00 cm in diameter and 11.80 cm in height were prepared in the standard Proctor mould, with the modified Proctor compaction energy of E=2,66 MJ/m^3. After preparation, samples were pressed out of the mould by hydraulic jack, and were placed on the plastic surface at the room temperature of +20°C with 62% of ambient humidity. The samples were cured for 3, 7 and 28 days, and were then subjected to compressive strength testing.

2.2.3. Compressive strength test results

The compressive strength of stabilisation mixes depends both on material properties and on curing conditions, and is defined as an average stress in the sample exposed to uniaxial compression at the force that causes failure (HRN U.B1.030 [9]). The sample destined for compressive strength testing is placed in the jack and the pressure is increased at constant rate until sample failure. The force at failure is then registered, and the compressive strength of stabilized mixes is then calculated using the following formula:

Table 2. Compressive strength testing results

Mix No.	Mix composition	Optimum moisture [%]	Compressive strength at 3 days [MN/m²]	Compressive strength at 7 days [MN/m²]	Compressive strength at 28 days [MN/m²]
1	slag + 0,5% cem.	8,7	1,23	1,50	2,04
2	slag + 0,7% cem.	8,8	1,85	2,14	3,17
3	slag + 2% cem.	8,5	3,21	3,43	3,93
4	crushed stone mix + 0,5% cem.	5,0	2,40	2,97	3,51
5	crushed stone mix + 0,7% cem.	5,0	2,97	3,58	4,13

Table 3. Required compressive strength for stabilisation mixes

Layer/course	Compressive strength (MN/m²)	
	at 7 days	at 28 days
Base course for pavement structures of motorways and roads with heavy traffic load	2,0 do 5,5	3,0 do 6,0
Base course for pavement structures of roads with heavy & medium traffic load	1,5 do 5,5	2,5 do 6,0

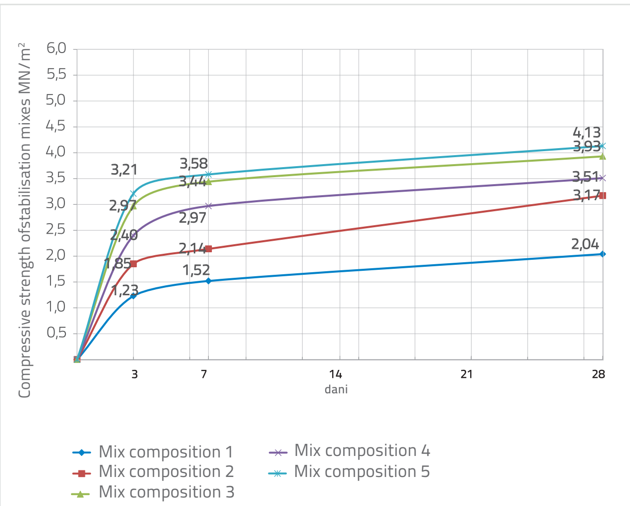

Figure 4. Compressive strength of stabilisation mixes

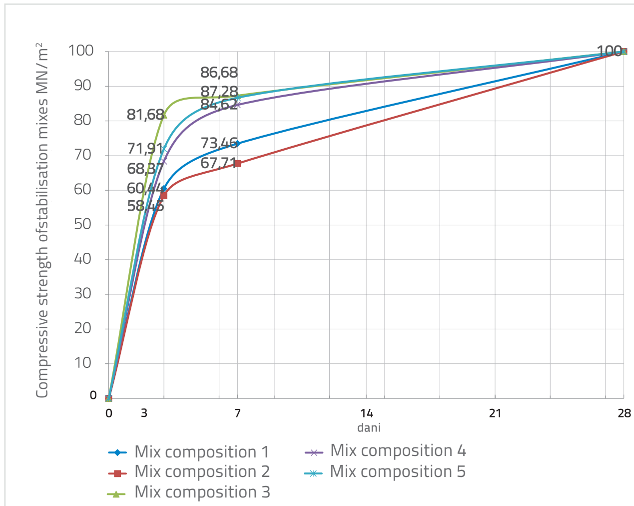

Figure 6. Compressive strength increase for stabilisation mixes under study

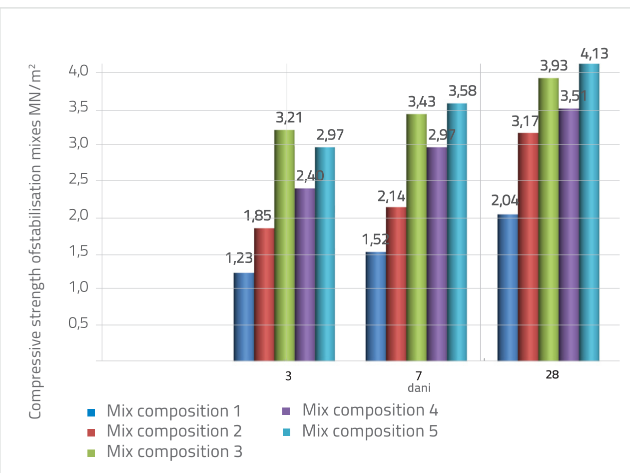

Figure 5. Histogram of compressive strengths of stabilisation mixes under study

$$f_c = \frac{P}{A} \quad (MN/m^2)$$

where:

P - compressive force at failure in MN

A - sample area in m²

Results obtained by testing compressive strength of stabilisation mixes are presented in tabular form (Table 2) and in form of a diagram (Figures 4-6).

Compressive strength values for stabilisation mixes with slag were compared at 28 days with compressive strength values specified in General Technical Requirements for Road Works [6], i.e. with HRN U.E9.024 [8]. These requirements are presented in Table 3.

3. Analysis of testing results

The comparison of compressive strength results of stabilisation mixes under study shows that the mixes with slag containing 0.7 and 2.0 percent of cement (mixes 2 and 3) meet stringent criteria for base courses of motorways and roads with very heavy traffic load. The stabilisation mix with slag containing 0.5 percent of cement (mix 1) does not meet compressive strength requirements for both groups, heavy and medium traffic load, as the compressive strength of this group amounts to 2.04 MN/m^2. The following conclusions were made after analysis of compressive strength results for steel slag mix and crushed stone mix, with equal percentage of cement and different moisture:

Although the crushed stone mix 0/63 is of coarser composition, with significantly smaller quantity of finer grains, it is still within the range permitted by General Technical Requirements for Roads. When compared to slag mix, this stabilisation mix requires less hydraulic binder to achieve the required strength.

The grading of the steel slag is 0/31.5, and it has a considerable quantity of finer fractions. This mix is also within the range permitted by General Technical Requirements for Roads [6]. As the mix contains a great quantity of fie particles, a greater percentage of cement is needed to achieve the required strength. Considering the differences between the mixes with regard to grain size distribution at similar binder content, the stabilized slag mix has lower compressive strength results (Table 4).

Table 4. Compressive strength ratio of two stabilisation mixes at 28 days

Stabilisation mixes	Compressive strength ratio at 28 days
stone mix/steel slag (with 0,5% of cement)	1,72
stone mix/steel slag (with 0,7% of cement)	1,30

It can be seen from diagrams presented in Figures 4 to 6 that compressive strengths of steel slag stabilisation mixes with 0.50 percent of cement are lower than the strength of crushed stone stabilisation mixes: 98.70% at 7 days and 72.50% at 28 days. A significant decrease in the difference between the compressive strengths can be noted at 28 days. For stabilisation mixes with 0.70% of cement, the difference in compressive strengths at 7 days is 67.29% while it falls to 30.49% at 28 days. It can be concluded from these results that the difference in compressive strength decreases with an increase in the binder quantity in stabilisation mixes, and with longer sample curing times.

After the curing time of 3 days the compressive strengths amounted to 58.45-81.68% of the total compressive strengths realized at 28 days. The lowest increase in strength at 3 and 7 days with respect to strength at 28 days is registered for the steel slag mix (mix 2) with 0.70% of cement (50.45%), while the highest increase in compressive strength is registered for steel slag mix with 2.0% of cement (mix 3). The lowest increase in strength at 7 days with respect to strength at 3 days is registered for the steel slag stabilisation mix with 2.0% of cement (5.60%), while for other mixes this increase ranges from 13.02 to 16.25% with respect to strength registered at 7 days.

When compared to crushed stone mix, the steel slag is characterized by higher water absorption rate and a more porous structure, and it requires higher quantity of binder. At that, it needs a higher quantity of water to achieve an optimum moisture and maximum dry bulk density at a given compaction energy. Due to higher water requirement (3-4%) when compared to the crushed stone mix, and at equal binder content, the compressive strength of the steel slag stabilisation mix is lower.

4. Conclusion

Results obtained by testing compressive strength of steel slag stabilisation mixes from Sisak Ironworks, and crushed stone stabilisation mixes from the Velika Quarry, are described in the paper. The testing was made to check whether slag can be used as aggregate in pavement base courses, and to determine in what way compressive strength values of steel slag stabilisation mixes are influenced by binder content and moisture.
The results are compared with a "standard" crushed stone stabilisation mix at curing times of 3, 7 and 28 days, and the following conclusions were made:

Based on laboratory testing made to determine suitability of material for use in base courses stabilised with hydraulic binder, it can be concluded that slag meets required criteria with respect to grain size distribution and physicomechanical properties, except for water absorption criterion, where the water absorption maximum is 1.6% (while 5.8% was registered for slag). However, additional testing revealed that the material is suitable for use in stabilisation mixes.

During preparation of stabilisation mixes, water content is considered to be highly responsible for increase in compressive strength. Due to difference in structure between the slag and crushed stone aggregate, the former requires greater quantity of water (3-4%) to achieve maximum density in compacted state, which is why compressive strength results for slag are lower.

During the compressive strength testing, much greater compressive strengths were registered for crushed stone stabilisation mixes when compared to steel slag stabilisation mixes, and this at similar binder content.

Steel slag stabilisation mixes with 0.7 and 2 percent of cement (mixes 2 and 3) meet stringent compressive strength requirements for traffic load categories according to [6 and 8].

Steel slag stabilisation mixes with 0.5% of cement (mix 1) do not meet these compressive strength requirements.

Taking into consideration the above test results, it can be concluded that steel slag stabilisation mixes with 0.7 and 2 percent of cement can be used in construction of stabilised base courses in pavement structures for motorways and roads with very heavy traffic load, and for roads with heavy and medium traffic load.

The use of steel slag in pavement structure courses would be acceptable from both economic and environmental standpoints: great quantities of highly affordable (waste) material would thus be used and, at the same time, the quantity of slag deposited on stockpiles would be reduced.

The results described in this paper are a contribution to the study of possibilities for using waste materials in pavement structures. Further continuation of this research, and preparation of appropriate test sections, would enable us to gain a better insight into the properties and behaviour of steel slag stabilisation mixes.

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