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PARTIAL REPLACEMENT OF NATURAL AGGREGATES BY INCORPORATING STEEL SLAG FOR THE MANUFACTURE OF ASPHALT MIXTURE

BY

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Abstract. Creating high-durable asphalt mixtures by implementing steel slag in the mix aggregate as a partial substitute constituted the main objective of the work. The addition of slag is beneficial for increasing the asphalt strength, but simultaneously, high content of this by-product tends to reduce the Marshall stability. The experiment tested asphalt mixture making up to 76% slag content, but the best results were obtained for the specimen with 57% slag, i.e. compression strength after 24 hours of 4.8 MPa and after 28 days of 3.6 MPa. In addition, less expensive materials (4-8 mm-slag granulometric class and electro filter dust) were adopted, without negatively influencing the usual product characteristics.

Keywords: asphalt mixture, bitumen, natural aggregate, steel slag, filler.

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1. Introduction

The pavement structure represents the most important road layer, which directly supports the requirements of the traffic as well as the action of external climatic and hydrological factors. The most frequently used pavement structure is bituminous, whose binder is bitumen and the most utilized type is the permanent pavement (with a lifespan of at least 12 years) (Llopis-Castelló *et al*., 2020). Asphalt mixtures are constituted of specific material mixtures of bituminous pavement structure (natural aggregate, filler, and bitumen). The most frequently used aggregates are chippings, natural and crushed sands, ballasts, uncrushed and crushed gravels (Pavement materials, 2010). The most widely used filler is made by grinding the limestone. Electro filter dust, slaked lime powder, cement, etc. are also suitable as fillers. The optimal size of the filler is below 90 µm (in proportion of at least 80 %). Harder bitumen (D 50/70 type) is preferred recently, offering higher stability to asphalt mixtures (Bitumen 50/70, 2023).

Steel slag is a by-product of the steelmaking process, constituted “in-situ” for technological purposes, because through it the required level of steel components is ensured, practically controlling the balance of each element between the liquid metal bath and the viscous slag (Dondi *et al.,* 2021). In the slag composition there are chemical elements such as calcium, silicon, iron, manganese, aluminum, magnesium, sulfur, phosphorus, etc.) in an oxide state. Sulfur and phosphorus are undesirable elements in the steel composition, being significantly reduced through their technologically passing into slag, but there is a major interest for metals inherently trapped in the slag mass. Unlike the blast furnace slag, which is available in much higher quantities and is captured into special ladles in a molten state for its granulation in a short time, the steel slag is captured in a solidified state and is stored in dumps. The recovery process by separating the metals from the slag mass is carried out later, after which the rest of the slag can be used for road construction. In general, in the perimeter of steelmaking plants there are large spaces occupied with the storage of this by-product. The interest for the effective use of these wastes, but especially for their elimination (after the recovery of metals) due to the environmental (mainly the soil) pollution, has intensified in the last 4-5 decades.

The problem analysed in this paper aims to create high durable asphalt mixtures by using steel slag as an industrial by-product provided by the steelmaking industry in large quantities. The wear resistance and the high level of affinity with bitumen exhibited by the slag are the main attributes of its use in making asphalt mixtures, partially replacing the natural granite aggregate as the raw material of conventional mixtures (Moura *et al.*, 2022). The experimental tests used proportions of 50-100% steel slag aggregates and the results led to the limitation of this range to no more than 75% to avoid an asphalt mixture structure with excessive air voids. Also, it was found that asphalt mixtures with 75% steel slag present workability problems due to the porous surface of the slag.

According to (Circular economy, 2015), the circular economy is a making and consumption economic template that contains the repair, recycling and reusing existing materials, their life-cycle being extended. Practically, the circular economy implies the advanced reduction of waste. This recent document of the European Parliament constitutes the essence of the concern of researchers and manufacturers in the field of road pavement for the use of industrial by-products and waste in order to make more economical materials with superior properties (Plati, 2019). On the other hand, the replacement of conventional aggregates and fillers with industrial by-products contributes to the cleaner manufacture of asphalt mixtures, leading to the reduction of the carbon footprint of preparing processes (Woszuk *et al.*, 2019).

According to (Masoudi *et al.*, 2017), the electric-arc furnace (EAF) slag is the most frequently used coarse aggregate in road pavement as a partial substitute for the conventional natural aggregate. The oxide composition of EAF slag can widely vary. According to the data presented in the literature by (Yildirim and Prezzi, 2011) typically, its composition includes 10-40% FeO, 22-60% CaO, 6-34% SiO_2, 3-14% Al_2O_3, and 3-13% MgO. The objective of the work (Masoudi *et al.*, 2017) was determining the long-term performances of the hot asphalt mixture containing the slag from the EAF furnace. The new asphalt mixture was tested regarding the Marshall stability test, modulus of elasticity at 25 and 40°C, indirect tensile strength, and moisture behaviour. The test conclusions were improving the Marshall stability, increasing the rigidity, the modulus of elasticity, and the tensile strength. It was also observed that the asphalt mixtures with implemented slag have a reduced aging compared to the traditional mixtures.

Recently, several experiments have been conducted to investigate the treatment of the porous surface of steel slag. Ma *et al.*, 2020 used a silane coupling agent for the treatment of the slag surface and improved the adhesion properties of the slag to the asphalt, but the treatment effect at this stage proved modest. Alnadish *et al.*, 2021 used a modifier composed of polyvinyl alcohol, acrylic, and polyester for the treatment of the slag surface and the results led to an increase in rutting and cracking resistances.

Steel slag has been used in the last decades in several asphalt mixture types (hot mix asphalt, dense-graded asphalt concrete, hydraulic road binder as main component, etc.). The results demonstrated that the slag addition into asphalt mixtures led to obtain high resistance to deformation and to damage caused by moisture and fatigue. The rough texture of particles included in the slag could ensure better mechanical properties (Dondi *et al.*, 2021; Arabani and Azarhoosh, 2012; Aquib *et al.*, 2023).

A work carried out by some authors of the current paper (Paunescu *et al.*, 2016) aimed to capitalize the 4-8 mm granulometric class of steel slag (obtained through the double crushing process) by replacing the natural aggregate in weight proportions between 30-70%. The reference specimen was a hot asphalt mixture made with BA 25 type natural aggregate. The experimental results of the physical-mechanical characterization of mixture variants (three versions of asphalt mixture using steel slag of 30, 50, and 70% as well as the reference specimen) showed the improvement of their features for all three new experimental versions compared to those of the reference specimen excluding the Marshall stability test. It recorded decreases in its values below the admissible limits when using steel slag of over 50% (6.9-7.1 kN), so that the experiment adopted the using option of 30% slag as the highest limit. The used steel slag was supplied by ArcelorMittal Galati (Romania), coming from the LD steelmaking process. In metallurgical terms, the most modern and efficient steelmaking process based on oxygen blowing is that made in the oxygen converter (LD steelmaking process). The steel slag of this process (in its final phase) contains 12-17% SiO_2, 40-52% CaO, 8-24% FeO, 1-6% Fe_2O_3, 8-14% MnO, 1-4% Al_2O_3, 2-8% MgO, around 1% Cr_2O_3, 0.2% S, and preferably at most 1.8% P_2O_5 (Rău and Tripșa, 1973).

Steel slag with grain size over 8 mm is capitalized in the last decades in Romanian road construction (Zăman *et al.*, 2006). Recent research has been focused on testing the use of the granulometric range of 4-8 mm, with a lower request on the market. The much higher density (3.2-3.6 $g \cdot cm^{-3}$) of steel slag (Thomas *et al.*, 2019) compared to that of the natural aggregate (1.9-2.7 $g \cdot cm^{-3}$) used in the manufacture of the traditional asphalt mixture would allow improving the hardness, mechanical strength, and the wear resistance of the mixture. Also, the steel slag structure is suitable for good adhesion to bitumen. However, it was experimentally found that a high proportion of slag generates large volume of voids, negatively influencing the quality of the asphalt mixture. Determining the optimal limit of the slag proportion is the main objective of the current work.

2. Materials and Methods

The materials adopted in this experiment were selected for preparing BA 25 type-asphalt mixture (Salah and El-Haggar, 2007) using steel slag as a partial substitute for natural mineral aggregates in successive proportions of 34.8, 57, and 76%. Double-crushed converter steel slag allowed the selection of the 4-8 mm-granulometric class in weight proportion of about 14% of the total slag mass thus processed. As a part of the batch of converter slag provided by ArcelorMittal Galati and partially used in the experiment presented in the paper (Paunescu *et al.*, 2016), this waste of the steelmaking industry was also chosen in the experiment described below to replace the natural aggregate of BA 25 type-asphalt mixture.

The aggregate was composed of river sand with predominant grain size below 90 µm and the highest size of 3 mm as well as granite chippings with grain size in the range of 3-25 mm, the sand/chippings ratio being within the limits of 0.43-0.62. The bulk density of river sand was 1.52 $g \cdot cm^{-3}$, while the average bulk density of chippings was 2.70 $g \cdot cm^{-3}$.

The binder of the asphalt mixture prepared in this experiment was the bitumen in a harder version (D 50/70 type). Bitumen Penetration Grade 50/70 is a standard material used as a paving grade bitumen adequate for road construction and producing asphalt pavements with high properties. The physical state of Bitumen 50/70 type commercially available is solid, being packed in barrels, in which it solidifies by cooling.

As a filler of the production process of asphalt mixture, electro filter dust with very fine grain size under 100 µm also procured from the steelmaking industry (ArcelorMittal Galati) was chosen. The adopted amount of the filler (bulk density of 1.95 $g \cdot cm^{-3}$) was kept constant (at 159.2 $kg \cdot m^{-3}$) in all tested versions.

The composition of experimental versions of asphalt mixture adopted in this work is shown in Table 1.

Table 1

Composition of experimental version of asphalt mixture

Composition	Version 1 (34.8% slag)		Version 2 (57% slag)		Version 3 (76% slag)	
	$kg \cdot m^{-3}$	%	$kg \cdot m^{-3}$	%	$kg \cdot m^{-3}$	%
D 50/70 type bitumen	151.1	5.6	151.0	5.2	151.2	4.8
Aggregate						
- river sand (below 3 mm)	437.1	16.2	286.0	9.8	169.2	5.4
- chippings (3-25 mm)	1011.7	37.5	655.1	22.5	271.6	8.7
- steel slag (4-8 mm)	938.9	34.8	1658.7	57.0	2378.8	76.0
Total aggregate	2387.7	88.5	2599.8	89.3	2819.6	90.1
Electro filter dust as a filler (below 3 mm)	159.2	5.9	159.2	5.5	159.2	5.1
Total dried asphalt mixture	2698	100	2910	100	3130	100

According to the data in Table 1, three experimental versions of asphalt mixture specimens were prepared by mixing the ingredients in the mentioned proportions. Converter steel slag with a grain size between 4-8 mm obtained through double crushing was introduced into the aggregate mass, successively replacing 34.8% (version 1), 57.0% (version 2), and 76.0% (version 3) of the usual aggregate. It was considered that the bulk density of the steel slag is significantly higher (3.2-3.6 $g \cdot cm^{-3}$) compared to that of the aggregate components (river sand and chippings).

The usual methods of preparing the asphalt mixture are hot and cold. In this experiment, the cold method was adopted. A mechanical mixing plant was used, being composed of a metal vessel with hemispherical bottom, in which metal paddles perform mechanical stirring of the mixture at 600-800 rpm.

In order to carry out the tests for determining features of asphalt mixture specimens, cubic shaped specimens (with the side of 100 mm) were made for measuring the apparent density, compressive strength, thermal stability, void volume, and swelling the materials. Cylindrical specimens (diameter of 100 mm and height of 63.5 mm) were achieved to measure the Marshall stability.

The apparent density of the samples was determined by the hydrostatic method (EN 12697-5:2009). The compressive strength testing was performed after 24 hours at 22 and 50℃ and after 28 days with 100 kN-axial press plant in the Metallurgical Research Institute Bucharest (Romania). The thermostability coefficient was determined calculating the ratio between the compressive strength value at 22℃ and that of the strength measured at 50℃. The air voids content in a compacted asphalt mixture was determined by comparing the density of a compacted specimen with the highest theoretical density of the mixture, considering this difference as air voids (Martinez and Bayomy, 1991). The water-absorbing amount of the specimen while keeping it under water at ambient temperature for 28 days was determined to indicate the swelling degree of the sample. The usual method of identifying the water-absorbing amount consists in weighing the specimen mass with an electronic balance before and after the material has been under water for 28 days SR EN 1097-6:2013). The test to determine the stability of the asphalt mixture (Marshall test) was performed with cylindrical specimens. The method is based on the application of a certain force on the sample generator following its breakage (SR EN 12697-34:2020). The load value that causes the specimen to break represents the Marshall stability value, measured with SUN-BT-001 model, originating in India.

3. Results and Discussion

The test results of the three experimental versions of asphalt mixture specimens mentioned above are presented in Table 2.

Considering the much higher value of the steel slag density compared to those of the other components of the aggregate, the asphalt mixture density increased from 2.79 to 3.20 $g \cdot cm^{-3}$ with the increase in the slag proportion as a substitute for the aggregate from 34.8 to 76%.

The compressive strength reached more than satisfactory values at the early age (after 24 hours) of 4.6-4.8 MPa at 22℃ and, respectively, 2.0-2.4 MPa at 50℃, while after 28 days of storage in ambient temperature water the strength kept the relatively high level of its values (between 3.3-3.7 MPa).

The thermostability coefficient of asphalt mixture specimens (i.e. the ratio of the compressive strength after 24 hours measured at 22 and 50℃, respectively) was at a normal level, reaching the highest value (2.3) in version 1 (with the least replacement of aggregate with slag) and decreasing to 2.0 in version 3 (with the highest degree of replacement with slag).

Table 2
Characteristics of asphalt mixture specimens

Characteristic	Version 1 (34.8% slag)	Version 2 (57% slag)	Version 3 (76% slag)
Density ($g\cdot cm^{-3}$)	2.79	2.98	3.20
Compressive strength after 24 hours (MPa)			
- at 22°C	4.6	4.8	4.8
- at 50°C	2.0	2.3	2.4
Compressive strength after 28 days (MPa)	3.3	3.6	3.7
Coefficient of thermostability	2.3	2.1	2.0
Air voids volume (%)	3.9	4.8	6.8
Water-absorbing after 28 days in ambient temperature water (%)	2.7	2.6	2.9
Marshall stability (kN)	8.2	7.1	5.7

The content of air voids volumetrically increased from 3.9% (version 1) to 6.8% (version 3). It was also found by other authors (Moura *et al.*, 2022) that the asphalt mixture structure containing large volume of air voids does not favor the mixture workability. The porous surface of the slag used as a substitute in high proportions (over 60-70%) of the aggregate contributes to the formation of an asphalt mixture with porous structure.

The Marshall stability test applied to experimental specimens showed a sharp decrease of the stability value of asphalt mixture with the increase of the slag proportion in the mixture aggregate mass. Thus, version 3 characterized by the presence of slag in the highest proportion (76%) reached the stability level of 5.7 kN, slightly below that acceptable (5.89 kN) for this type of material (Ogundipe, 2016).

Testing water-absorbing of asphalt mixture specimens indicated normal values of this physical characteristic (between 2.6-2.9%). In general, the water absorption into the aggregate mass should not exceed 3%, because the exposure of the material to freeze-thaw cycles lead to destruction in the asphalt mixture structure.

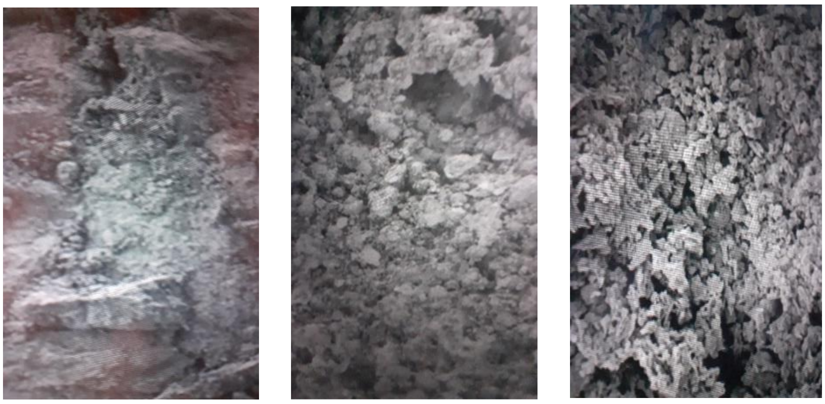
Images of the surface appearance of steel slag pavement specimens are shown in Fig. 1.

Image (c) representing the surface of the specimen with the highest proportion of steel slag partially replacing the aggregate of the mixture is edifying for the porous structure due to the addition of slag. In the other images (a and b) the pores are not very visible and normally the filler used (electro filter dust) has the ability to fill them.

a b c

Fig. 1 − Surface appearance of steel slag pavement specimens
a – 34.8% steel slag; b – 57% steel slag; c – 76% steel slag.

The porous structure of the specimen made in version (c) is much more visible in Fig. 2 representing the microstructural appearance of the steel slag pavement specimens.



a b c **|----| 100 µm**

Fig. 2 − Microstructural appearance of steel slag pavement specimens
a – 34.8 % steel slag; b – 57 % steel slag; c – 76 % steel slag.

According to picture (c), the size of pores (not filled with the filler) from the specimen surface is within the limits of 10-40 µm. Pictures (a and b) do not suggest the existence of porous surfaces.

Considering the results of this experiment as well as the fact that the specimen (c) made by applying version 3 (with the highest amount of aggregate released by the introduction of steel slag) showed a major decrease of stability measured by the Marshall test, the specimen (b) corresponding to version (b) was chosen as the optimal version.

Compared to other works published in the literature, the composition of the asphalt mixture included some original elements. Thus, the granulometric class of steel slag chosen by the authors (4-8 mm) was rarely used both in the world and in Romania. Unlike the majority of preferences expressed in the literature regarding the material type used as filler (ground limestone), the authors' team opted for electro filter dust, a much less expensive by-product resulting from EAF metallurgical processes.

In the optimal version, produced by using the addition of 57% steel slag as a substitute for natural aggregates (sand and granite gravel), the compression strength after 24 hours reached 4.8 MPa (at 22°C) and respectively, 2.3 MPa (at 50°C), while the strength after 28 days decreased to 4.6 MPa. The thermostability coefficient calculated as a ratio between the two values of compression resistance after 24 hours had an acceptable value of 2.1. The void volume was at a mid-level value of 4.8%, influencing the acceptable level of Marshall stability (7.1 kN). Among the three experimental versions, the optimal version had the lowest water absorption value (2.6%) determined after 28 days of storage.

4. Conclusions

The objective of the work was to test the manufacture of an asphalt mixture based on the advanced partial replacement of the usual natural aggregate with steel slag under the conditions of using a granulometric class (4-8 mm) rarely applied in this field as well as the adoption of a less expensive filler (electro filter dust) compared to limestone. The results were appreciable despite the use of some raw materials rarely applied in this type of manufacturing process. The optimal degree of replacement of natural aggregates with steel slag (57%) without negatively influencing the main mechanical and physical characteristics of the final product is considered high-performance by comparison with the results of other authors.

In the future, investigating the possibilities of increasing the replacement degree of natural aggregates with steel slag without affecting the material stability will be among our research priorities in this field.

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ÎNLOCUIREA PARȚIALĂ A AGREGATELOR NATURALE PRIN ÎNCORPORAREA ZGURII DE OȚEL PENTRU FABRICAREA MIXTURII ASFALTICE

(Rezumat)

Crearea amestecurilor asfaltice cu înaltă durabilitate prin implementarea zgurii de oțel în agregatul amestecului ca o substituire parțială a constituit principalul obiectiv al lucrării. Adaosul zgurii este benefic pentru creșterea rezistenței asfaltului, dar în același timp, un conținut înalt al acestui produs secundar are tendința de a reduce stabilitatea Marshall. Experimentul a testat producerea amestecului asfaltic până la 76% conținut de zgură, dar rezultatele optime au fost obținute în cazul probei cu 57% zgură, adică rezistența la compresiune după 24 ore de 4,8 MPa și după 28 zile de 3,6 MPa. În plus, materiale mai puțin scumpe (clasa granulometrică a zgurii între 4-8 mm și praful de electrofiltru) au fost adoptate, fără a influența negativ caracteristicile uzuale ale produsului.