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AN UNCONVENTIONAL ASPHALT. SOME CHARACTERISTICS OF STEEL SLAG ASPHALT

BY

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Abstract. It has been known since ancient times that a good infrastructure is needed to develop an area. But because there are more and more areas in continuous development, raw materials are consumed with acceleration and the planet is becoming progressively occupied by waste, we are trying to find other materials than the classic ones to use in road construction. Ordinary asphalt mixtures have aggregates of different grades, filler and bitumen in their composition. If normally the aggregates used for the production of asphalt are extracted from nature, in this study we showed how we produced an asphalt with aggregates from crushed steel slag, an industrial waste, obtained after the manufacture of steel.

Inside the article you will discover the establishment of recipes for asphalt mixtures with crushed steel slag, the making of samples and their testing according to the norms in force. The results obtained are encouraging, some characteristics of this asphalt being better than the asphalt prepared with classic aggregates. The use of crushed steel slag in areas where there are dumps with this waste could generate a double benefit: the release of some storage spaces and the production of a cheaper asphalt.

Keywords: steel slag, asphalt mixture, recycle, waste.

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1. Introduction

The development of a country's infrastructure attracts investments, generating economic growth, which allows the growth of other important fields in that country. The development of the infrastructure, however, requires a significant consumption of materials, road works are large consumers of natural aggregate, these accounting for 80% ... 100% of the materials that make up the pavement layers (Răcănel and Burlacu, 2016), which is normally also a factor of pollution.

Over time, more and more solutions have been sought to find the cheapest useful materials in the infrastructure, but also whose production or exploitation should be as little polluting as possible. A very good solution that satisfies both mentioned requirements is waste. Despite protracted efforts to reduce the amount of waste produced by the mining and metallurgical industries, these types of wastes still constitute one of the world's largest waste streams (Bian *et al.*, 2012). From the use of plastics, the shredded rubber from used tires to the use of foundry sand, all have proven to be good alternatives to the materials used in road construction. Among the various by-products or waste materials, lack of natural stone and costly expense of purchasing high-quality aggregate (Chen and Wei, 2016), the utilization of steel slag as aggregate in road construction has gained the most popularity worldwide (Kumar and Varma, 2020). The use of strong and durable steel slag as an aggregate material in asphalt concrete can enhance the load-bearing capacity while at the same time conserving natural resources (Saowarot *et al.*, 2020).

Steel slag is an industrial solid waste with the largest output in the world (Liu *et al.*, 2019). This waste results from the production of steel either in Electric Arc Furnaces (EAF) by melting scrap or in Basic Oxygen Furnaces (BOF) by transforming hot liquid blast furnace metal, scrap, and fluxes.

Steel slag has many well-known applications in road construction such as asphalt mix aggregate, antiskid layer, granular base and subbase material (Kumar and Varma, 2020). Steel slag aggregates (SSA) can replace natural aggregates in asphalt and cement-based road construction, lowering the environmental impact by reducing the consumption of natural and non-renewable aggregates and the quantity of steel slag deposited on landfill sites (Louriero *et al.*, 2022). Laboratory and field experiments performed by researchers show that, inclusion of steel slag in asphalt mix may enhance the mix durability, skid resistance, stability, rutting resistance, affinity with bitumen (Kumar and Varma, 2020). The use of steel slag aggregates leads to numerous technical and economic advantages for both the user and the producer, such as: diversification of road construction materials, cost reduction by reducing transportation distances and using local materials, but most importantly, eliminating the storage piles of waste obtained from steel plants and also rehabilitating the land occupied by them (Iriciuc *et al.*, 2023).

This study aims to establish the recipes and the optimal dosage of bitumen of two asphalt mixtures, BA8 and BA16 with crushed steel slag from Liberty Galati, Romania, to determine their density and water absorption. We also want to see what are the stability and creep results on Marshall specimens from these types of asphalt mixtures.

Will the asphalt mixture with aggregates from this steel slag have results comparable to the asphalt made with classic aggregates? Do the characteristics of this asphalt fit the norms in force in Romania?

2. Materials and Methods

2.1. Establishing asphalt mixture recipes

2.1.1. Preparatory operations

a) providing the required materials for producing the asphalt mixtures:
- filer from Hoghiz, Braşov;
- bitumen from Almatard, Buzău;
- sand from Tupilaţi, Neamţ;
- steel mill slag aggregates from Liberty Galaţi (Phoenix Slag).

b) sorting of steel slag aggregates;
c) drying of all aggregates.

In order to determine the characteristics of the asphalt mixture, two recipes of asphalt mixtures with steel mill slag were established: BA8 and BA16.

The aggregates used in the preparation of asphalt mixtures are natural and artificial aggregates, according to SR EN 13043-2003/AC:2004.

The types of aggregates needed to make the recipes are:
- crushed steel mill slag aggregates 0-4 mm;
- crushed steel mill slag aggregates 4-8 mm;
- crushed steel mill slag aggregates 8-16 mm;
- natural sand 0-4 mm;
- filer.

2.1.2. Sieving of aggregates

Sieving of the aggregates in order to determine the granulometric curves was carried out with a control sieve according to SR EN 933-2:2020.

The results of the screenings can be seen in Tables 1, 2, 3, 4 and 5.

Table 1

Passing through the sieve assembly of the sort 8-16 – steel mill slag

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
22.4	-	-	-	-	-	100
16	106.40	64.00	70.70	241.10	4.02	95.98
11.2	1202.20	1405.00	1350.80	3958.00	65.94	30.04
8	644.40	505.20	556.10	1705.70	28.42	1.62
4	39.60	20.60	18.00	78.20	1.30	0.32
<4	3.40	4.20	3.80	18.90	0.32	-
	8.20	5.60	5.10			
Total	2000.80	2000.40	2000.70	6001.90	100	-

Table 2

Passing through the sieve assembly of the sort 4-8 – steel mill slag

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
11.2	-	-	-	-	-	100
8	19.80	21.10	33.00	73.90	2.46	97.54
4	947.50	944.10	948.90	2840.80	94.68	2.85
2	29.80	31.30	15.90	77.00	2.57	0.29
<2	1.90	2.00	1.20	8.60	0.29	-
	3.00	3.30	2.30			
Total	1000.10	1000.10	1000.10	3000.00	100	-

Table 3

Passing through the sieve assembly of the sort 0-4 – steel mill slag

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
8	-	-	-	-	-	100
4	5.50	12.90	9.70	28.10	1.87	98.13
2	108.80	134.20	105.00	348.00	23.20	74.93
0.125	302.90	282.10	298.40	883.40	58.90	16.03
0.063	38.80	34.90	43.60	117.30	7.82	8.21
<0.063	42.50	34.80	41.60	123.30	8.21	-
	44.10	35.90	43.30			
Total	500.10	500.00	500.00	1500.10	100	-

Table 4

Passing through the sieve assembly of the sort 0-4 – natural sand

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
8	-	-	-	-	-	100
4	6.40	8.70	10.10	25.20	1.680	98.32
2	75.80	69.10	71.30	216.20	14.413	83.91
0.125	371.70	374.20	369.90	115.80	74.387	9.52
0.063	34.60	36.10	35.00	105.70	7.047	2.47
<0.063	10.80	11.50	11.70	37.10	2.473	-
	11.50	11.90	13.70			
Total	500.00	500.00	500.00	1500.00	-	-

Table 5

Passing through the sieve assembly of the filer

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
2	-	-	-	-	-	100
0.125	12.00	14.20	13.90	40.10	13.367	86.63
0.063	11.15	12.60	13.60	37.35	12.45	74.18
<0.063	74.55	71.30	71.10	222.55	74.183	-
	76.85	73.20	72.50			
Total	100.00	100.00	100.00	300.00	-	-

Table 6

Centralizing table of the passage through the set of sieves of the aggregates used

Aggregates	**31.5**	**22.4**	**16**	**11.2**	**8**	**4**	**2**	**0.125**	**0.063**
Steel slag 8-16 mm	100	100	95.98	30.04	1.62	0.32	-	-	-
Steel slag 4-8 mm	100	100	100	100	97.54	2.85	0.29	-	-
Steel slag 0-4 mm	100	100	100	100	100	98.13	74.93	16.03	8.21
Natural sand 0-4 mm	100	100	100	100	100	98.32	83.91	9.52	2.47
Filer	100	100	100	100	100	100	100	86.63	74.18

2.1.3. Establishing aggregate dosages

Having all the necessary information, it was possible to establish the proportion of each aggregate in the recipe of the two asphalt mixtures. The recipes are presented in Tables 9 and 10, the dosages of the aggregates being also arranged graphically in Figs. 1 and 2, at the same time being able to verify their inclusion within the limits imposed by the AND 605-2016 standard.

Table 7
BA8 recipe with steel mill slag aggregates

Aggregates	%	31.5	22.4	16	11.2	8	4	2	0.125	0.063
Steel slag 4-8 mm	**37**	37	37	37	37	36.09	1.05	0.11	-	-
Steel slag 0-4 mm	**42**	42	42	42	42	42	41.21	31.47	6.73	3.45
Natural sand 0-4 mm	**14**	14	14	14	14	14	13.76	11.75	1.33	0.35
Filer	**7**	7	7	7	7	7	7	7	6.06	5.19
Average curve BA8 conformable AND 605-2016	**100**	**100**	**100**	**100**	**100**	**95**	**67**	**46.50**	**13.50**	**9**
Average curve laboratory	**100**	**100**	**100**	**100**	**100**	**99.09**	**63.02**	**50.33**	**14.12**	**8.99**

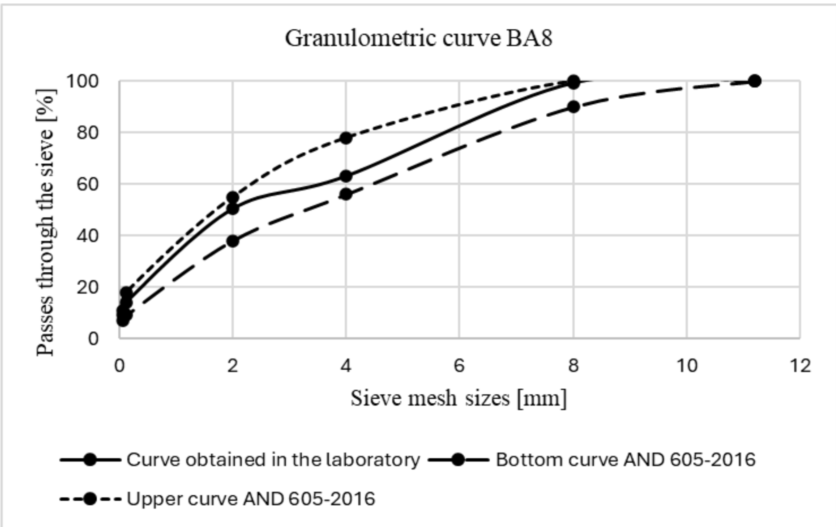

Fig. 1 − Granulometric curve BA8.

Table 8
BA16 recipe with steel mill slag aggregates

Agregate	%	31.5	22.4	16	11.2	8	4	2	0.125	0.063
Steel slag 8-16 mm	**28**	28	28	26.87	8.41	0.45	0.09	-	-	-
Steel slag 4-8 mm	**24**	24	24	24	24	23.41	0.68	0.07	-	-
Steel slag 0-4 mm	**30**	30	30	30	30	30	29.44	22.48	4.81	2.46
Natural sand 0-4 mm	**10**	10	10	10	10	10	9.83	8.39	0.95	0.28
Filer	**8**	8	8	8	8	8	8	8	6.93	5.93
Average curve BA16 conf. AND 605-2016	**100**	**100**	**100**	**95**	**-**	**71.5**	**51.5**	**37.5**	**11.5**	**9**
Average curve laboratory	**100**	**100**	**100**	**98.87**	**80.41**	**71.86**	**48.04**	**38.94**	**12.69**	**8.78**

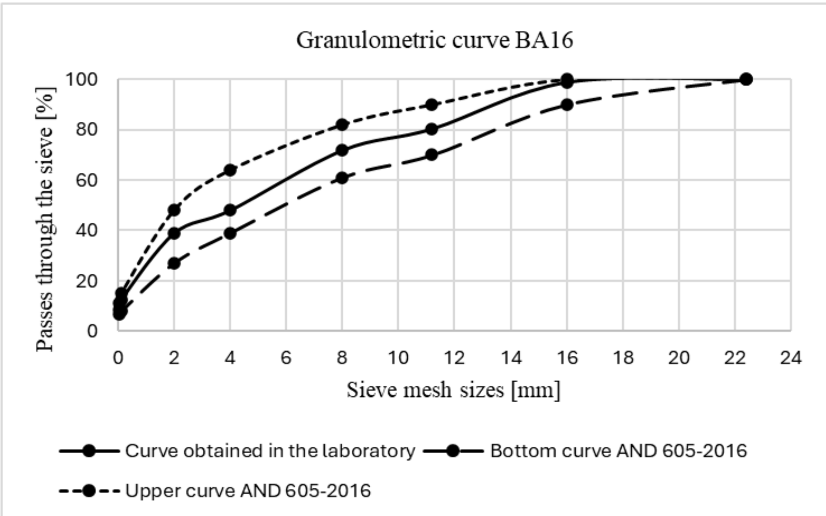

Fig. 2 − Granulometric curve BA16.

The two recipes are presented together in Table 9.

Table 9
Recipes BA8 and BA16 with crushed steel slag

Aggregates/Recipe	BA8	BA16
Steel slag 8-16 mm [%]	-	28.00
Steel slag 4-8 mm [%]	37.00	24.00
Steel slag 0-4 mm [%]	42.00	30.00
Natural sand 0-4 mm [%]	14.00	10.00
Filer [%]	7.00	8.00

2.1.4. Determination of bitumen dosages and preparation of Marshall samples

In order to be able to determine the optimal binder dosage, Marshall type samples were made with different bitumen dosages. The specimens were compacted using a Marshall compactor with 50 blows on each side.

The following determinations were made on the samples:

- Determining the density of the asphalt mixture;
- Determination of water absorption;
- Determination of creep and Marshall stability.

2.1.5. Determination the density of the asphalt mixture

The determination of the density of the asphalt mixture was carried out according to SR EN 12697-8:2019 "Asphalt mixtures. Test methods. Part 8: Determination of volumetric characteristics of bituminous samples". This is used to determine bulk density.

The apparent density values on Marshall samples as well as their graphic distribution depending on the bitumen dosage can be seen in section 3. Results, Figs. 3 and 4.

2.1.6. Determination of water absorption

Determination of water absorption is done according to AND 605-2016.

Water absorption represents the amount of water absorbed by the voids available from the outside of an asphalt mixture specimen, when kept in water under vacuum, and is measured as a percentage of the initial mass or volume of the specimen.

The water absorption values for the steel slag asphalt mixture samples as well as their graphic distribution depending on the bitumen dosage can be seen in section 3. Results, Figs. 5 and 6.

2.1.7. Determination of creep and Marshall stability

Marshall stability and creep were determined according to SR EN 12697-34:2020 - Asphalt mixtures. Test methods. Part 34: Marshall Trial.

The objective of the test is to determine the resistance to breaking of a cylindrical specimen, the force being applied to a generator.

Figures 7 and 8 in the Results section show the values recorded on the specimens for Marshall stability, creep and the ratio between them. The optimal dosage of bitumen determined from laboratory analyzes and tests on Marshall cylinders for each type of mixture is in Table 10 section Results.

3. Results

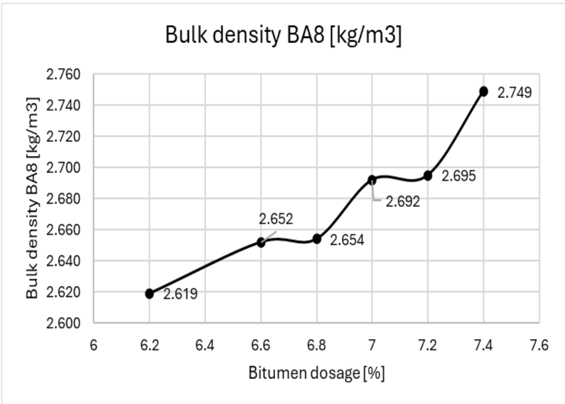

Fig. 3 − Bulk density values for BA8.

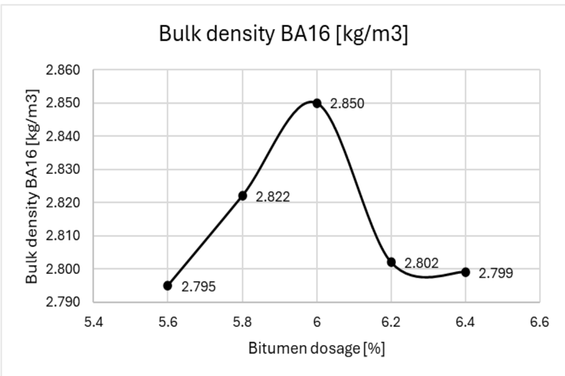

Fig. 4 − Bulk density values for BA16.

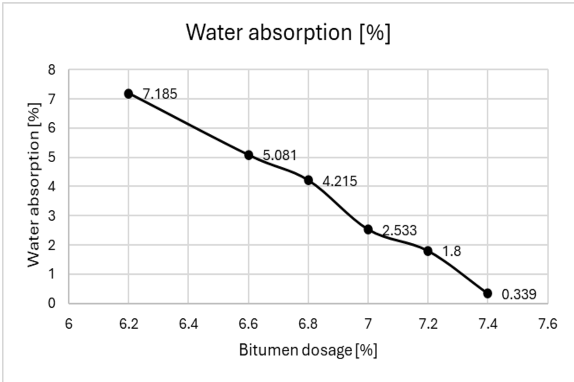

Fig. 5 − Water absorption values for BA8.

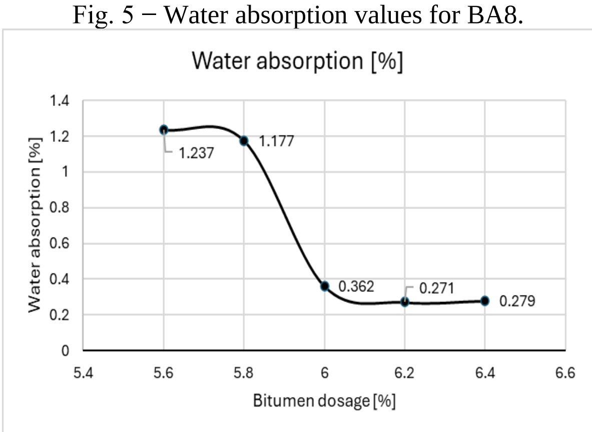

Fig. 6 − Water absorption values for BA16.

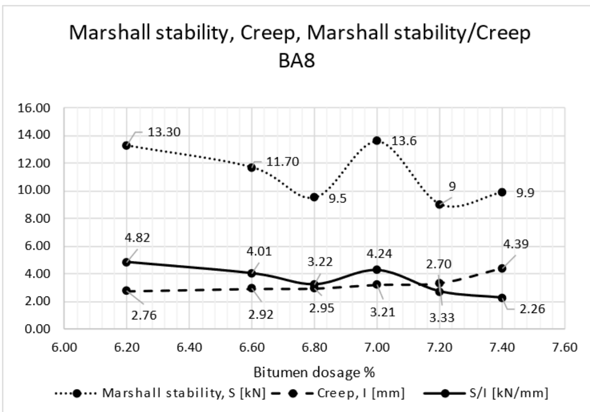

Fig. 7 − Marshall stability, Creep and S/I ratio values for BA8.

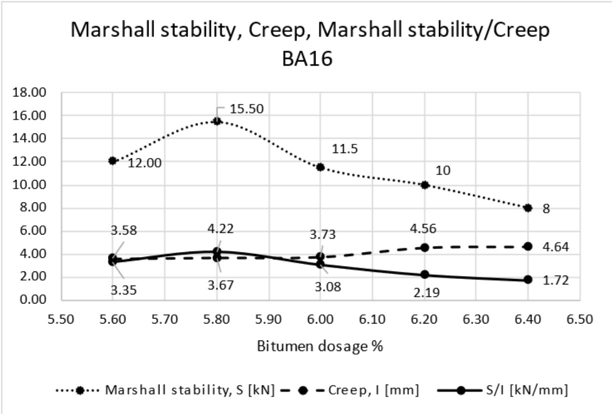

Fig. 8 − Marshall stability, Creep and S/I ratio values for BA16.

Table 10
Optimum dosage of bitumen for the tested samples

The type of mixture	Optimum dosage of bitumen, %	Minimum binder content in the mix, % AND 605-2016
BA8	7.00	6.30
BA16	5.80	5.70

The results obtained so far for the two asphalt mixtures BA8 and BA16 with steel slag aggregates from Liberty Galati are encouraging. The results are comparable with the results obtained on mixes with classic aggregates but also with other mixes with steel slag. The research shows that steel slag asphalt mixtures in general, with steel slag from Liberty Galati, Romania in particular, have results that fall within the Romanian norms in force.

5. Discussions

A centralization of the results obtained for the optimal bitumen percentage of both mixtures can be seen in Table 11.

Table 11
Results for the optimal bitumen percentage (present research)

Analyzed parameters	BA8	BA16
Optimum dosage of bitumen, %	7.00	5.8
Bulk density, kg/m^3	2.692	2.822
Water abs., %	2.533	1.177
S, kN	13.6	15.5
I, mm	3.21	3.67
S/I, kN/mm	4.24	4.22

The results of other research in the field are presented in Tables 12 and 13. Table 12 shows the results of the tests of some mixtures with steel slag from Sidex Galati from 2011 and in Table 13 the results are of a mixture with steel slag from the Buituri dump in the year 2024.

Table 12

Results for the optimal bitumen percentage (Iriciuc, 2011)

Analyzed parameters	BA8	BA16
Optimum dosage of bitumen, %	6.25	5.75
Bulk density, kg/m^3	2.641	2.696
Water abs., %	2.913	1.316
S, kN	13.1	14.1
I, mm	3.62	5.74
S/I, kN/mm	3.62	2.46

Table 13

Results for the optimal bitumen percentage (Iriciuc *et al.,* 2024)

Analyzed parameters	BA16
Optimum dosage of bitumen, %	5.75
Bulk density, kg/m^3	2.629
Water abs., %	3.642
S, kN	12.1
I, mm	3.45
S/I, kN/mm	3.51

We can see that the results are close, the mixture obtained in the present research being a little more resistant to breaking, having the best strength/deformation ratio. This can be mainly caused by a slightly different composition of the steel slag used in the three researches.

6. Conclusions

The recipes of the two mixtures fall within the norms imposed by AND 605-2016 from the point of view of the granulometric curve and the minimum dosage of bitumen. The apparent density of the asphalt mixture varies between 2.6 kg·m^{-3} and 2.9 kg·m^{-3}, being higher than the value of the apparent density of a classic mixture. The difference results from the higher density of steel slag aggregates compared to the density of natural aggregates. The S/I ratio is good, the specimens have good tear resistance as well as small deformation according to the Marshall test. They fall within the limits of AND 605-2016.

The research will be continued by subjecting the samples made from BA8 and BA16 to other tests. Asphalt mixture recipes will also be established for BAD22.4 and AB22.4 samples will be made from them and will be subjected to the same series of tests as the previous mixtures.

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*** *SR EN 12697-8:2019 - Asphalt mixtures. Test methods. Part 8: Determination of volumetric characteristics of bituminous samples.*

*** *SR EN 12697-34:2020 - Asphalt mixtures. Test methods. Part 34: Marshall Trial.*

UN ASFALT NECONVENȚIONAL. CÂTEVA CARACTERISTICI ALE ASFALTULUI CU ZGURĂ DE OȚELĂRIE

(Rezumat)

Din vremuri străvechi se știe că pentru a dezvolta o regiune este nevoie de o infrastructură bună. Însă pentru că sunt tot mai multe zone în continuă dezvoltare, materiile prime se consumă din ce în ce mai mult și planeta devine tot mai ocupată de deșeuri, încercăm să găsim și alte materiale decât cele clasice pentru a le folosi în construcția drumurilor.

Dacă în mod normal agregatele folosite pentru producerea asfaltului sunt extrase din natură, în acest studiu am arătat cum am produs un asfalt cu agregate din zgură concasată de oțelărie, un deșeu industrial, obținut în urma fabricării oțelului.

În interiorul articolului veți descoperi o serie de încercări pe materiale, stabilirea unor rețete pentru mixturi asfaltice cu zgură concasată de oțelărie, confecționarea de epruvete precum și încercarea lor conform normelor în vigoare. Rezultatele obținute sunt încurajatoare, unele caracteristici ale acestui asfalt fiind mai bune decât ale asfaltului preparat cu agregate clasice.

Folosirea zgurii concasate de oțelărie în zonele în care există halde cu aceste deșeuri ar putea genera un beneficiu dublu: eliberarea unor spații de depozitare și producerea unui asfalt mai ieftin.