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STEEL SLAG ASPHALT – AN ECOLOGICAL ASPHALT. LABORATORY STUDIES

Andreea Monoranu, Ph.D. Student Eng., Faculty of Civil Engineering and Building Services, 700050, Technical University "Gh. Asachi" from Iasi, Romania, andreeamonoranu03@gmail.com

Abstract

We hear talking more and more often around us about waste and recycling. Developed and developing countries pay special attention to the careful collection of waste, their storage and above all, where possible, their reintroduction into the economic circuit. This is caused by the fact that the population of the planet is increasing, the needs are increasing and implicitly the production of waste is also increasing. The sector that produces one of the largest amounts of waste is the metallurgical industry. This paper studies some properties of an asphalt produced with a metallurgical waste, more precisely steel slag. This work presents the establishment of two asphalt mixture recipes with steel slag, the determination of apparent density, water absorption as well as the testing of the specimens to find out the stability and creep. The tests will be carried out in the Laboratories of the Faculty of Construction and Installations of Iași. The results will be presented in the form of tables and graphs and will be compared with the limits imposed by the regulations in force but also with other research in the field. The purpose of this work is to determine if the results obtained in the tests mentioned above for these types of ecological mixtures, BAD22.4 and AB22.4 with steel slag from Liberty Galati from the year 2022, fall within the limits imposed by the regulations in force but also how they compare to the results of older research. The conclusions will show whether these mixtures are compliant or not, and comments will also be made on the performance of these ecological mixtures.

In the context in which different types of mixtures with steel slag from different metallurgical plants, from Romania and abroad, were studied, this study completes the information from the scientific world showing the properties of the asphalt mixtures with steel slag from Liberty Galați in present. The study can have an important economic impact, especially for the areas near the metallurgical plant where the slag is located, thus significant savings can be made in terms of road paving if the decision is made to use asphalt mixtures with steel slag.

Keywords: asphalt mixture, waste, recycling, sustainability, eco-asphalt

1. INTRODUCTION

Two of the most important characteristics that people wish to have in the country they live in are: a strong economy and a low degree of pollution. A strong economy cannot be based only on the exploitation of resources, which are finite, in order not to collapse. For this reason, developed countries as well as developing countries have begun to apply the principles of the circular economy more and more in recent years. A sustainable circular economy is defined as a transition where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized [1]. The broad objective of a circular economy model is to reduce the linear flow of materials through recycling and re-use in order to rejuvenate the life cycle of a material [2]. Recyclability refers to the amenability of waste materials to be captured and converted into a new material and/or re-used in the same capacity [2]. Regarding waste, the largest producer of it is industry. The metallurgical industry is a branch of it that deals with obtaining metals from ores, bringing its "contribution" to the generation of 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 [3]. One of the main processes in the metallurgical industry is the production of steel. Steel slag is the main waste product in the steelmaking process [4]. Steel slag is the oxidized material that is generated when lime, dolomite, and other auxiliary materials are added, and oxygen is blown onto the pig iron produced by a blast furnace to remove carbon (C), phosphorus (P), sulfur (S), and other components to produce crude steel in a basic oxygen furnace (BOF) [4]. This waste is a mixture of metal oxides and silicon dioxide and may contain metal sulfide along with metal in the elemental form [5]. Because of its chemical composition and technical properties, it can be reused as raw material in steel plants and can serve as a substitute for aggregates in civil engineering [4].

Asphalt began to be used on a large scale in Europe starting with the 19th century. Since then, taking into account the increase in demand for this material, increasing amounts of aggregates have been exploited. Asphalt mixture is a superior pavement material used in road construction, which consists of filler, bitumen and aggregate [6]. The quality of the road structure is determined by the quality of each road layer, which requires the quality for the composing materials [7].

Road works are large consumers of natural aggregate, these accounting for 80% ... 100% of the materials that make up the pavement layers [8]. Constructing a single kilometer of new road requires the consumption of 30,000 tons of aggregates [9]. Lack of natural stone and costly expense of purchasing high-quality aggregate promote the utilization of steel slag [10]. Replacing natural aggregates by wastes and by-products is one of the most widespread techniques used to achieve sustainable roads since it provides a double benefit. On the one hand, the extraction and production of raw materials decreases, reducing the consumption of water, electricity, diesel and also the production of noise and dust. Moreover, the deposit of waste in landfill is avoided, extending landfill lifetime and reducing emissions [9]. Generally, the higher mechanical properties of steel slag suggest that its inclusion in asphalt mixtures can provide high-performance pavement layers [11]. 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 [12]. In their works Kumar and Varma and Loureiro with his team say that steel slag asphalt mix can be designed to satisfy both volumetric and mechanical properties [13] respectively, incorporating steel slag aggregate or recycled concrete aggregate in asphalt mixtures for road pavements has functional, mechanical, and environmental advantages [14]. Also, the Romanian C. Iriciuc with his team state that the utilization of steel slag aggregates in asphalt mixtures represents a sustainable solution with significant economic and environmental benefits [15].

In this paper, we presented the establishment of two asphalt mixture recipes: BAD22.4 and AB22.4 with crushed steel slag from Liberty Galați, testing them later to find out more physicochemical properties.

Do the two types of mixture studied have results that fall within the limits imposed by the current regulations? Is it feasible to continue researching asphalt mixes with steel slag?

2. EXPERIMENTAL PROGRAM

2.1. Characteristics of the mixture

The characteristics of the steel slag that will be introduced in the asphalt mixture recipes are presented in Table 1.

Table 1. The characteristics of the steel slag

Characteristic	**U.M.**	**Values obtained**	
		0-4 (mm)	*4-31.5 (mm)*
The density of the oven-dried granules (ρ_{rd})	(Mg/m^3)	3.163	3.259
Density of saturated granules with dry surface (ρ_{ssd})	(Mg/m^3)	3.227	3.319
Apparent density of the granules (ρ_a)	(Mg/m^3)	3.379	3.466
Water absorption of granules (WA_{24})	(%)	2.014	1.828
Crushing resistance LA method	(%)	*10-14 (mm)*	
		16.9	
Crushing resistance SZ impact method	(%)	*10-14 (mm)*	
		15.5	
Wear resistance (micro-Deval) (M_{DE})	(%)	*10-14 (mm)*	
		14.3	

2.2. Determining asphalt mixture recipes

2.2.1. Sieving of aggregates

To observe the characteristics of this type of asphalt mixture, two asphalt mixture recipes with steel slag were established: BAD22.4 and AB22.4.

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

The aggregates used to make the recipes are:

- steel slag aggregate 0-4 mm;
- steel slag aggregate 4-8 mm;
- steel slag aggregate 8-16 mm;
- steel slag aggregate 16-22.4 mm;
- natural sand 0-4 mm;
- filer.

The screening results can be seen in the Tables 2, 3, 4, 5, 6 and 7.

Table 2. Passage of sort 16-22.4 steel slag through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
31.5	-	-	-	-	-	100.00
22.40	55.300	69.400	16.500	141.200	0.941	99.060
16.00	3927.40	3636.400	3508.800	11072.600	73.801	25.260
11.20	963.500	1245.200	1371.100	3979.800	23.860	1.400
8.00	45.400	39.200	101.000	185.600	1.237	0.160
<8.00	3.300	7.200	5.500	24.200	0.161	-
	8.800	10.600	4.800			
Total	5000.400	5000.800	5002.200	15003.400	100.000	-

Table 3. Passage of sort 8-16 steel slag through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
22.40	-	-	-	-	-	100.00
16.00	106.400	64.000	70.700	241.100	4.020	95.980
11.20	1202.200	1405.000	1350.800	3958.000	65.940	30.040
8.00	644.400	505.200	556.100	1705.700	28.420	1.620
4.00	39.600	20.600	18.000	78.200	1.300	0.320
<4.00	3.400	4.200	3.800	18.900	0.320	-
	8.200	5.600	5.100			
Total	2000.800	2000.400	2000.700	6001.900	100.000	-

Table 4. Passage of sort 4-8 steel slag through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
11.20	-	-	-	-	-	100.000
8.00	19.800	21.100	33.000	73.900	2.460	97.540
4.00	947.500	944.100	948.900	2840.800	94.680	2.850
2.00	29.800	31.300	15.900	77.000	2.570	0.290
<2.00	1.900	2.000	1.200	8.600	0.290	-
	3.000	3.300	2.300			
Total	1000.100	1000.100	1000.100	3000.000	100.000	-

Table 5. Passage of sort 0-4 steel slag through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
8.00	-	-	-	-	-	100.000
4.00	5.500	12.900	9.700	28.100	1.870	98.130
2.00	108.800	134.200	105.000	348.000	23.200	74.930
0.125	302.900	282.100	298.400	883.400	58.900	16.030
0.063	38.800	34.900	43.600	117.300	7.820	8.210
<0.063	42.500	34.800	41.600	123.300	8.210	-
	44.100	35.900	43.300			
Total	500.100	500.000	500.000	1500.100	100.000	-

Table 6. Passage of sort 0-4 natural sand through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
8.00	-	-	-	-	-	100.000
4.00	6.400	8.700	10.100	25.200	1.680	98.320
2.00	75.800	69.100	71.300	216.200	14.413	83.910
0.125	371.700	374.200	369.900	115.800	74.387	9.520
0.063	34.600	36.100	35.000	105.700	7.047	2.470
<0.063	10.800	11.500	11.700	37.100	2.473	-
	11.500	11.900	13.700			
Total	500.000	500.000	500.000	1500.000	-	-

Table 7. Passage of filer through the assembly of sieves

D, mm	Remained			Remained Σ g	Remained %	Passed %
	I	II	III			
2.00	-	-	-	-	-	100.000
0.125	12.000	14.200	13.900	40.100	13.367	86.630
0.063	11.150	12.600	13.600	37.350	12.450	74.180
<0.063	74.550	71.300	71.100	222.550	74.183	-
	76.850	73.200	72.500			
Total	100.000	100.000	100.000	300.000	-	-

Table 8. Table centralizing the passage through the set of sieves of the aggregates used

Aggregates	31.50	22.40	16.0	11.20	8.0	4.0	2.0	0.125	0.063
Steel slag 16.0-22.4 mm	100.00	99.060	25.260	1.400	0.160	-	-	-	-
Steel slag 8.0-16.0 mm	100.00	100.00	95.98	30.04	1.62	0.32	-	-	-
Steel slag 4.0-8.0 mm	100.00	100.00	100.00	100.00	97.54	2.85	0.29	-	-
Steel slag 0.0-4.0 mm	100.00	100.00	100.00	100.00	100.00	98.13	74.93	16.03	8.21
Natural sand 0.0-4.0 mm	100.00	100.00	100.00	100.00	100.00	98.32	83.91	9.52	2.47
Filer	100.00	100.00	100.00	100.00	100.00	100.00	100.00	86.63	74.18

In tables 9 and 10 we find the limits of the percentages of fillers and natural aggregates, respectively the granulometric zone of the asphalt mixtures according to normative 605/2016.

Table 9. The limits of the percentages of fillers and natural aggregates

Natural aggregates – fractions from the total mixture	Wearing course			Binder course	Base course	
	BA 8 BAPC 8	**BA 11.2 BAPC 11.2**	**BA 16 BAPC 16**	**BAD 22.4 BADPC 22.4 BADPS 22.4**	**AB 22.4 ABPC 22.4**	**AB 31.5 ABPC 31.5 ABPS 31.5**
Filler and sand fractions<0.125mm,%	9.0…18.0	8.0…16.0	8.0…15.0	5.0…10.0	3.0…8.0	3.0…12.0
Filler and fraction (0.125---4 mm), %	The difference until 100					
Natural aggregates > 4 mm,%	22.0…44.0	34.0…48.0	36.0…61.0	55.0…72.0	57.0…73.0	40.0…63.0

Table 10. The granulometric area of bituminous concrete and bituminous coating

The mesh size of the sieve conforming to SR EN 933-2, [mm]	BA 8 BAPC 8	BA 11.2 BAPC 11.2	BA 16 BAPC 16	BAD 22.4 BADPC 22.4 BADPS 22.4	AB 22.4 ABPC 22.4	AB 31.5 ABPC 31.5 ABPS 31.5
45.0	-	-	-	-	-	100.0
31.50	-	-	-	100.0	100.0	90.0… 100.0
22.40	-	-	100.0	90.0… 100.0	90.0… 100.0	82.0… 94.0
16.0	-	100.0	90.0… 100.0	73.0… 90.0	70.0… 86.0	72.0… 88.0
11.20	100.0	90.0… 100.0	-	-	-	-
8.0	90.0… 100.0	75.0… 85.0	61.0… 82.0	42.0… 61.0	38.0… 58.0	54.0… 74.0
4.0	56.0… 78.0	52.0… 66.0	39.0… 64.0	28.0… 45.0	27.0… 43.0	37.0… 60.0
2.0	38.0… 55.0	35.0… 50.0	27.0… 48.0	20.0… 35.0	19.0… 34.0	22.0… 47.0
0.125	9.0… 18.0	8.0… 16.0	8.0… 15.0	5.0… 10.0	3.0… 8.0	3.0… 12.0
0.063	7.0… 11.0	5.0… 10.0.	7.0… 11.0	3.0… 7.0	2.0… 5.0	2.0… 7.0

2.2.2. Determination of aggregate percentages

Gathering all the information, we can create the recipes for the two asphalt mixtures. The percentages of the aggregates related to each mixture are presented in tables 11 and 12.

Table 11. BAD22.4 recipe with steel slag aggregates

Aggregates	%	31.5	22.4	16	11.2	8	4	2	0.125	0.063
Steel slag 16-22.4 mm	**25**	26.00	24.77	6.32	0.35	0.04	-	-	-	-
Steel slag 8-16 mm	**22**	22.00	22.00	21.12	6.61	0.36	0.07	-	-	-
Steel slag 4-8 mm	**20**	20.00	20.00	20.00	20.00	19.51	0.57	0.06	-	-
Steel slag 0-4 mm	**14**	14.00	14.00	14.00	14.00	14.00	13.74	10.49	2.24	1.15
Natural sand 0-4 mm	**14**	14.00	14.00	14.00	14.00	14.00	13.76	11.75	1.33	0.35
Filer	**5**	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.33	3.71
Average curve BAD22.4 conformable AND 605-2016	**100**	**100**	**90…100**	**73…90**	-	**42…61**	**28…45**	**20…35**	**5…10**	**3…7**
Average curve laboratory	**100**	**100.00**	**98.77**	**80.44**	**59.96**	**52.91**	**33.14**	**27.30**	**7.90**	**5.21**

Table 12. AB22.4 recipe with steel slag aggregates

Aggregates	%	31.5	22.4	16	11.2	8	4	2	0.125	0.063
Steel slag 16-22.4 mm	**30**	30.00	29.72	7.58	0.42	0.05	-	-	-	-
Steel slag 8-16 mm	**20**	20.00	20.00	19.20	6.01	0.32	0.06	-	-	-
Steel slag 4-8 mm	**17**	17.00	17.00	17.00	17.00	16.58	0.48	0.05	-	-
Steel slag 0-4 mm	**15**	15.00	15.00	15.00	15.00	15.00	14.71	11.24	2.40	1.23
Natural sand 0-4 mm	**15**	15.00	15.00	15.00	15.00	15.00	14.75	12.59	1.43	0.37
Filer	**3**	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.60	2.23

The recipes of BAD22.4 and AB22.4 are presented together in Table 13.

Table 13. Recipes BAD22.4 and AB22.4 with steel slag

Aggregates/Recipe	BAD22.4	AB22.4
Steel slag 16-22.4 mm [%]	25.00	30.00
Steel slag 8-16 mm [%]	22.00	20.00
Steel slag 4-8 mm [%]	20.00	17.00
Steel slag 0-4 mm [%]	14.00	15.00
Natural sand 0-4 mm [%]	14.00	15.00
Filer [%]	5.00	3.00

2.2.3. Identification of optimum bitumen percentages and preparation of Marshall samples

In Table 14, you can see (according to AND 605/2016) the optimal percent of bitumen.

Table 14. Binder content (optimum)

<table>
<tr><th>Layer type</th><th>Asphalt mixture (type)</th><th>Binder content in the mixture (minimum) %</th></tr>
<tr><td rowspan="7">wear (running)</td><td>MAS11.2</td><td>6.00</td></tr>
<tr><td>MAS16</td><td>5.90</td></tr>
<tr><td>BA8
BAPC 8</td><td>6.30</td></tr>
<tr><td>BA 11.2
BAPC 11.2</td><td>6.00</td></tr>
<tr><td>BA16</td><td>5.70</td></tr>
<tr><td>BAPC16</td><td>5.70</td></tr>
<tr><td>MAP16</td><td>4.00</td></tr>
<tr><td>binder</td><td>BAD 22.4
BADPC 22.4
BADPS 22.4</td><td>4.20</td></tr>
<tr><td>base</td><td>AB 22.4
ABPC 22.4
AB 31.5
ABPC 31.5
ABPS 31.5</td><td>4.00</td></tr>
</table>

Marshall cylinders were manufactured from mixtures with different bitumen percents, compacted with 50 beats on each side. In order to find out the optimal percent of bitumen for each of the two types of asphalt, determinations were made to find out: density, water absorption, creep and Marshal stability.

2.2.4. Density of the asphalt mixture

To determine the density of the asphalt mixture (bulk density) the SR EN 12697-8:2019 standard was followed.

The steps taken in the laboratory were as follows:

1. Keeping the samples in a water bath at a temperature of 20°C for 60 minutes after which they are removed and wiped with a damp cloth to remove surface water
2. Determination of the mass of the test sample in a dry state by weighing in air (m_1)
3. Immersion of the sample in water
4. After stabilizing the water, determine the mass of the sample in water (m_2)
5. Determine the apparent density of the sample from the asphalt mixtures with the formula:

$$\rho_{bdry} = \frac{m_1}{m_1 - m_2} \rho_w \qquad (1)$$

where,

ρ_{bdry} – dry apparent density of the specimen [kg/m^3]; m_1– mass of the dry sample [g]; m_2 – mass of the sample in water [g]; ρ_w – density of water at test temperature [kg/m^3], considered 997.1 [16].

The results of this determination can be seen in Chapter 3, Figures 1 and 2.

2.2.5. Water absorption

To determine water absorption, standard AND 605-2016 was followed. 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.

Working method [17]:

After completing the steps for finding the apparent density proceed as follows:

1. The samples are inserted into the absorption vessel (vacuum extinguisher), a vessel in which there is water at a temperature of 20°C, it

is closed and put into operation for three hours so as to achieve a low pressure of 15. . .20 mm Hg after about 30 minutes

2. After the three hours, the vacuum extinguisher is turned off, keeping the samples in water for another two hours at atmospheric pressure
3. After the two hours, take them out of the water and wipe them with a damp cloth. They are weighed in air (m_3) and then in water (m_4)
4. Calculate the initial volume (V) and the final volume of the sample (V_1) with the formulas:

$$V = (m_1 - m_2)\frac{1}{\rho_w} \tag{2}$$

$$V_1 = (m_3 - m_4)\frac{1}{\rho_w} \tag{3}$$

5. Calculate the water absorption

The absorption can relate either to the volume of the sample (A_v) or to its mass (A_m), the formula being different also in case V>V1 or V< V1. Thus we have the following formulas:

A. When $V>V_1$:

$$A_m = \frac{m_3 - m_u}{m_u}100 \tag{4}$$

$$A_v = \frac{(m_3 - m_u) - \rho_w}{(m_1 - m_2) - \rho_w}100 \tag{5}$$

B. When $V<V_1$:

$$A_m = \frac{(m_3 - m_u) - [(m_3 - m_4) - (m_1 - m_2)]}{m_u}100 \tag{6}$$

$$A_v = \frac{\{(m_3 - m_u) - [(m_3 - m_4) - (m_1 - m_2)]\}/\rho_w}{(m_1 - m_2) - \rho_w}100 \tag{7}$$

The results of this determination can be seen in Chapter 3, Figures 3 and 4.

The limits for water absorption determined by tests on Marshall cylinders according to AND 605-2016 are presented in Table 15.

Table 15. Value limits for water absorption according to AND 605-2016

Type of mixture	**Water absorption % vol.**
Open graded asphalt concrete	1.5...6.0
Bituminous coating	1.5...6.0

2.2.6. Creep and Marshall stability

To determine creep and Marshall stability, it was followed standard SR EN 12697-34:2020. The purpose of the test is to find out the resistance to breaking of a cylindrical specimen when the force is being applied to a generator.

Working method:

a) The specimens not used for the absorption test are placed in water at a temperature of 60°C and kept for 30 minutes.

b) After the 30 minutes, remove the specimens from the water bath and insert it into the apparatus for the Marshall test

c) Start the test - load the test specimen at a speed of 50 mm/min. The moment we notice that the attempt no longer increases, but on the contrary decreases, the attempt stops.

d) The Marshall stability represents the load, expressed in kN, that has been reached at the moment when the specimen breaks. The flow index (creep) is the deformation reached by the vertical diameter of the specimen at the moment when the break occurred and is expressed in mm [18].

The results of this determination can be seen in Chapter 3, Figures 5, 6, 7, 8, 9 and 10.

The limits for the physical-mechanical characteristics determined by tests on Marshall cylinders according to AND 605-2016 are presented in Table 16.

Table 16. Value limits for Marshall stability, Creep and S/I ratio according to AND 605-2016

Type of mixture	**S - stability at 60°C, [kN]**	**I - flow rate, [mm]**	**S/I [kN/mm]**
Open graded asphalt concrete	5.0...13	1.5...4.0	≥ 1.2
Bituminous coating	6.5...13	1.5...4.0	≥ 1.6

3. RESULTS

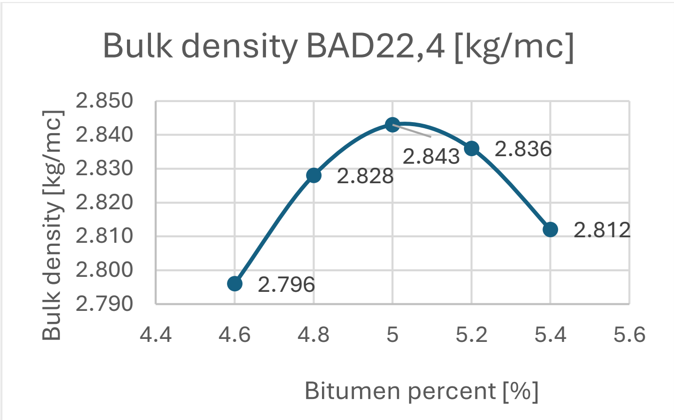

Figure 1. Bulk density values for BAD22.4

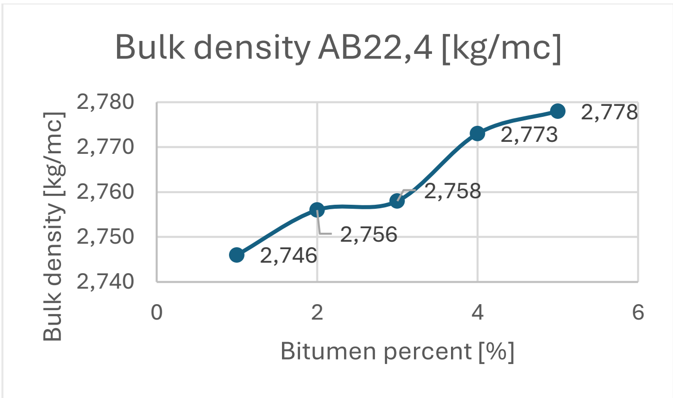

Figure 2. Bulk density values for AB22.4

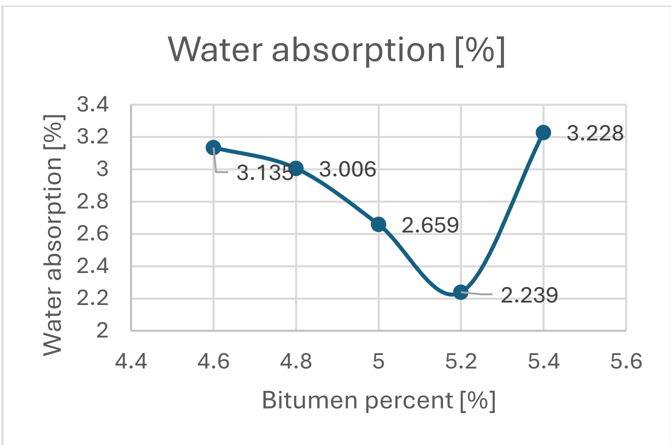

Figure 3. Water absorption values for BAD22.4

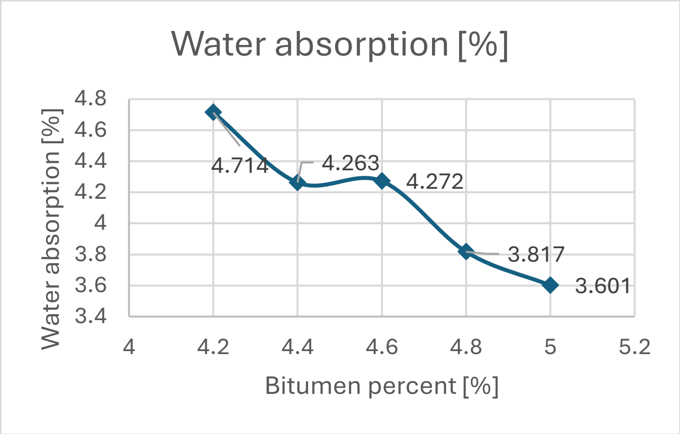

Figure 4. Water absorption values for AB22.4

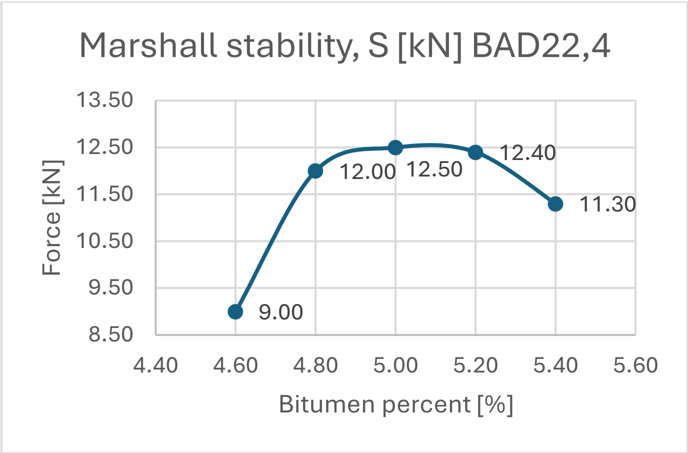

Figure 5. Marshall stability values for BAD22.4

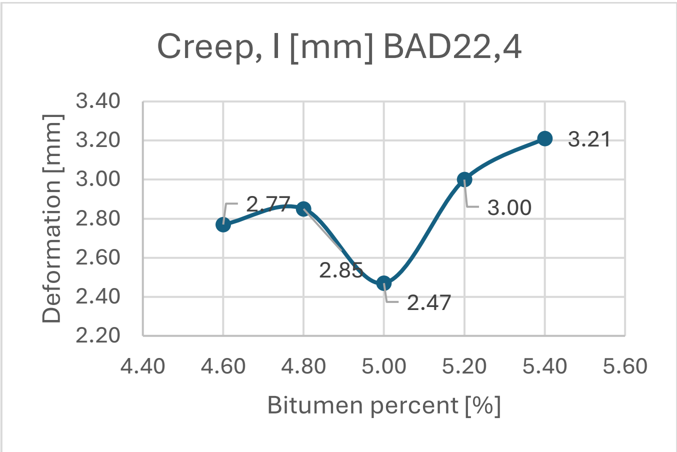

Figure 6. Creep values for BAD22.4

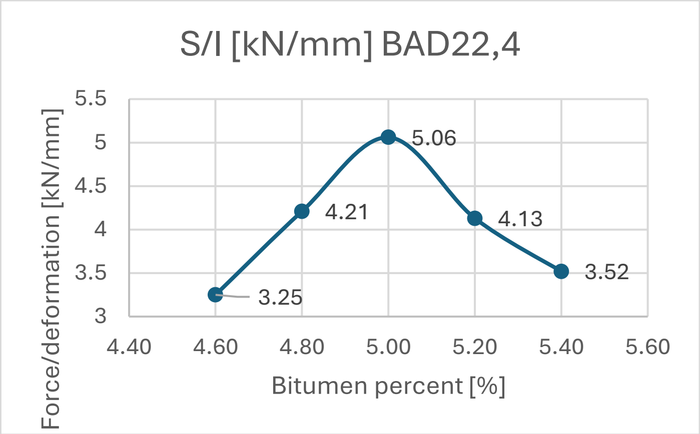

Figure 7. S/I ratio values for BAD22.4

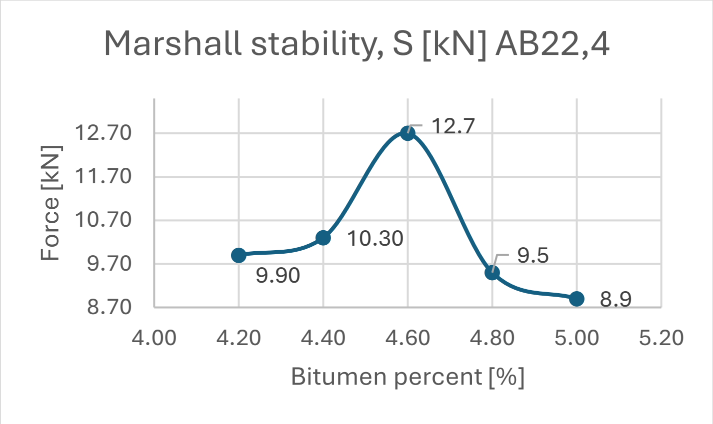

Figure 8. Marshall stability values for AB22.4

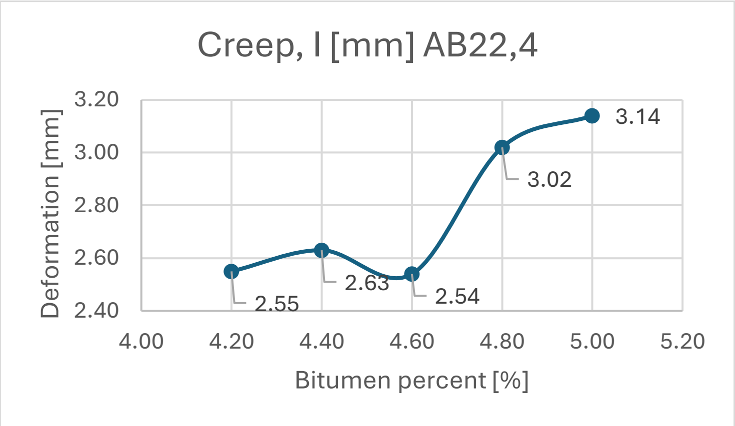

Figure 9. Creep values for AB22.4

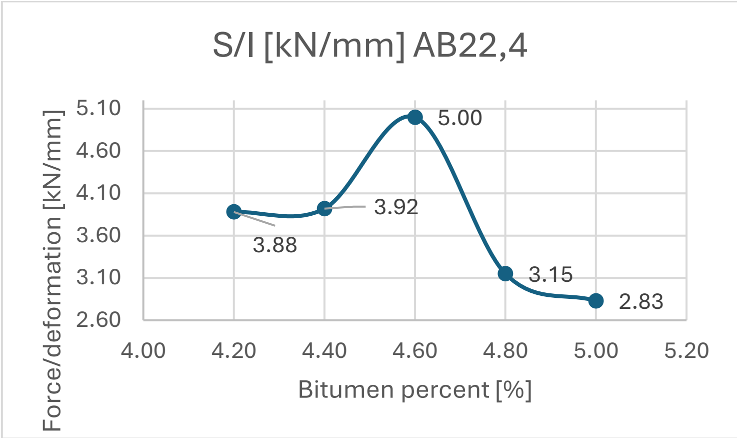

Figure 10. S/I ratio values for AB22.4

The choice of the optimal percentage of bitumen for the two mixture recipes was made by correlating all the results obtained. It is obvious that the best mixture is the one that has the best stability, the lowest creep but also the other characteristics: apparent density and water absorption are satisfactory. The optimal bitumen percentage chosen for each individual mixture can be seen in Table 17.

Table 17. Bitumen - optimum percent

Mixture	Optimum percent of bitumen, %	Minimum bitumen content in the mix, % AND 605-2016
BAD22.4	5.00	4.20
AB22.4	4.60	4.00

4. DISCUSSION

The results obtained on the samples from the asphalt mixture with steel slag can be compared with other researches in the field. For example, the results obtained on samples from the asphalt mixture BAD25 with steel slag from Galati by C. Iriciuc from 2011 and the results obtained for AB25 with steel slag from Galati in the work of the authors C. Lixandru, M. Dicu, C. Răcănel and A. Burlacu from 2015. The results obtained by them are presented in Table 18 and the results of the current study are presented in Table 19.

Table 18. Apparent density, water absorption, stability, creep BAD25 and AB25 [19], [7]

Mixture	Optimum percent of bitumen, %	Apparent density, kg/mc	Water absorption, % vol.	Stability, kN	Creep, mm
BAD25	5.00	2.639	3.785	15.1	4.15
AB25	4.50	2.2	8	12.8	4.62

Table 19. Apparent density, water absorption, stability, creep BAD22.4 and AB22.4

Mixture	Optimum percent of bitumen, %	Apparent density, kg/mc	Water absorption, % vol.	Stability, kN	Creep, mm
BAD22.4	5.00	2.843	2.659	12.5	2.47
AB22.4	4.60	2.758	4.272	12.7	2.54

By comparing these results we can observe a higher apparent density in the current samples, a much lower water absorption, a slightly lower stability but also a creep almost halved. All these differences are caused both by the fact that in the first two examples of the mixture we have slightly larger grain sizes, but especially by the fact that the composition of steel slag has changed in the last 10 years due to changes in the production circuit. Taking into account the comparison with the results previously obtained on the steel slag mixture from Galati, we can say that overall the current results are slightly better than the previous results, the current steel slag mixture from Liberty Galati is slightly better performing than the produced with slag from 10 years ago.

As stated by other studies on the same topic 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 [20]. The same studies concludes that the use of crushed steel slag in the preparation of asphalt concrete for the binder layer can be asserted with certainty to fully meet the required quality conditions [20].

For the scientific world, the research results only confirm, once more, the good properties of asphalt with steel slag. The results of the tests carried out so far encourage the continuation of research in this field.

5. CONCLUSIONS

If we compare the results obtained for water absorption, stability and creep for the two mixtures studied, figures 3,4,5,6,7,8,9,10, with the limits imposed by AND605/2016 that we presented in the tables 15 and 16, we find that they are compliant.

Taking into account the comparison of the results for mixtures with slag from the past, where we noticed that the mixtures with current slag are at least as efficient as those, but also the fact that the amount of slag in the dumps is increasing, steel production being higher, it can be states that the use of steel slag in asphalt mixtures is a good solution both from a qualitative and ecological point of view.

Considering the good results obtained, the study will be continued with the submission of the two asphalt mixture recipes with steel slag to other static tests and some dynamic tests.

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