RESEARCH ON THE USE OF BOF STEEL SLAG AGGREGATES WITH DOLOMITE SAND WASTE TO DEVELOP HIGH PERFORMANCE ASPHALT CONCRETE

Viktors Haritonovs, Martins Zaumanis, Guntis Brencis, Juris Smirnovs
Institute of Transport Infrastructure Engineering, Faculty of Civil Engineering, Riga Technical University, Riga, Latvia

ABSTRACT

The dolomite and sandstone that can be found in Latvia, lack the mechanical strength and for most of the large motorways the aggregates are imported from other countries causing the increase of the costs and growth of emissions from transportation. On the other hand, large amounts of BOF steel slag aggregates with good qualities are being produced in Latvia and put to waste. During the recent decades, the dolomite sand waste has been accumulating and its quantity has reached a million of tons and is rapidly increasing. This huge quantity of technological waste needs to be recycled with maximum efficiency.

The lack of experience on the use of steel slag and dolomite sand waste requires an accelerated evaluation of the asphalt performance-based characteristics. This paper presents the testing results of dense graded asphalt concrete AC 11 mixtures made of four types of aggregate: steel slag, dolomite sand waste, conventional imported dolomite aggregates and conventional local crushed quartz sand that were proportioned to develop a mixture that would satisfy the requirements of permanent deformation and stiffness. Analysis of the results showed that mixes with steel slag and dolomite waste sand or unconventional aggregate combination with dolomite in coarse portion, crushed quartz sand in sand portion and dolomite waste sand in sand and filler portions had high resistance to plastic deformations. These mixes can fully satisfy and in some cases significantly overcome the requirements of local asphalt specifications for highly loaded motorways.

Keywords: Steel slag, dolomite waste sand, dense graded asphalt concrete, permanent deformations, wheel tracking test

1. INTRODUCTION

The industries of steel manufacturing and production of the crashed dolomites struggle to realize the co-products of the production. During the recent years, huge quantities of technological waste, such as steel slag and very fine crushed sand that need to be recycled with maximum efficiency have accumulated in Latvia (Fig 1 and Fig 2). At the same time the road building industry in Latvia strives to utilize the local aggregates because the physically-mechanical characteristics for most of the materials do not meet the normative requirements.

In the EU and North America steel slag is used in: bitumen bound materiāls, pipe bedding, hydraulically bound mixtures for subbase and base, unbound mixtures for subbase, capping, embankments and fill construction, clinker manufacture and fertilizer and soil improvement agent. However, in Latvia for commercial road construction purposes it has been used only for unbound mixtures.

During the recent decades, the dolomite sand waste has been accumulating in Latvia and its quantity has reached more than a million of tons. The produced waste mostly remains unused on quarries occupying the place and increasing the overall technological costs. However, the research on the perspective use of dolomite waste sand in production of asphalt has received relatively little attention. For example, this material could be used to fully or partially replace the fine and filler portions. Such situation requires an integrated approach to recycling of the produced co-products [1-5].

Figure 1: Unfractionated BOF slag aggregate

Figure 2: Unused dolomite waste sand

The purpose of this research is to develop an asphalt mixture that would be resistant to heavy transport load by using composite materials as steel slag and dolomite waste sand. To achieve this aim following asphalt compositions were proportioned and mixed:

– reference mixture from traditional dolomite aggregate and quartz sand;

– mixture, consisting exclusively of by-products;

– combined mixture using different by-product and traditional mineral aggregate combinations.

Bitumen BND 60/90 and Polymer Modified Bitumen (PMB) 50/70-53 which was modified with Styren-Butadien-Styren (SBS) was used for mixing. All the combinations were tested for physical and mechanical (wheel tracking test) characteristics.

2. MATERIALS

Following materials were used in the study: Basic Oxygen Furnace (BOF) slag, dolomite waste sand, conventional aggregate (crushed dolomite and quartz sand) and bitumen.

2.1 Aggregate tests

Tables 1 and 2 summarize the chemical composition and major metal content of the BOF slag.

Table 1: Chemical composition of BOF slag

Oxide content, %						
CaO	MgO	SiO_2	MnO	Al_2O_3	TiO_2	FeO
30,6	18,9	19,9	6,3	5,0	0,52	16,3

Table 2: Major metal content of BOF slag

Metal content, %								
Fe	Al	Ca	Mg	Cr	Mn	Cu	Ni	Si
70,3	0,07	0,08	0,05	0,06	0,7	0,13	0,05	0,29

The physical and mechanical properties steel slag, dolomite waste sand, crushed dolomite aggregate and quartz sand are summarized in table 3. Physical and mechanical properties were determined according to standard EN test methods. The properties of BOF steel slag correspond to the highest category of LVE EN 13043 standard. The test results of steel slag main properties show very low flakiness index – 2, excellent mechanical strength with average LA value of 19, high frost resistance with average MS value of 3,0 low fines content – 0,5% and slag expansion tests, show that the expected swelling should be negligible. However, according to Latvian Road Specifications 2010, not more than 20 persent of BOF steel slag is allowed for wearing courses[6]. This restriction is due to the high abrasivity of the material.

Table 3: Physical and mechanical characteristics of the aggregate

Physical and mechanical properties	Standard	BOF steel slag	Dolomite waste sand	Crushed dolomite aggregate	Crushed quartz sand
Loa Angeles coefficient (LA), %	LVS EN 1097-2	19	-	22	-
Resistance to wear. Nordic test (A_N), %	LVS EN 1097-9	14,4	-	15,7	-
Sand equivalent test, %	LVS EN 933-8	80*	60	-	91
Flakiness Index (FI), %	LVS EN 933-3	2	-	12	-
Flow coefficient (E_{CS})	LVS EN 933-6	43*	33	-	35
Water absorption, %	LVS EN 1097-6	2,4	-	2,7	5,4
Grain density, Mg/m^3	LVS EN 1097-6	3,25	2,80	2,80	2,70
Fine content, %	LVS EN 933-1	0,5	18,6	0,9	0,9
Freeze/ thawing (MS), %	LVS EN 1367-2	3	-	9	-
Expansion, %	LVS EN 1744-1 p.19.3	2	-	-	-
Methylene blue test (MB), g/kg	LVS EN 933-9	-	0,5	-	-
Carbonate content, %	LVS EN 196-21	-	> 90	-	-
Rigden air voids, %	LVS EN 1097-4	-	28-30	-	-
Delta ring and ball test, °C	LVS EN 13179-1	-	11	-	-

Dolomite waste sand test results present excellent angularity with average flow coefficient of 33. The fines content in dolomite waste sand is more than 10% therefore the Latvian Road Specifications 2010 require this material to satisfy also the requirements attributed to mineral filler. Test results show that the fines quality is high – the material has low methylene blue (MB) value – 0,5, high carbonate content – more than 90%, excellent Rigden air voids and Delta ring and ball tests – 28 and 11 respectively (Table 3).

2.2 Aggregate gradation

In total nine aggregate gradations were used for producing the AC 11 mixtures – five unconventional co-product aggregate and four conventional crushed dolomite and quartz sand aggregates (Tables 4 and 5). Dolomite waste sand can be categorized as G_F85, steel slag 0/5 as G_A90 and steel slag 4/8 as $G_C90/20$ according to LVS EN 13043. Steel slag which is categorised as 8/11 does not confirm with any of the standard categories, because only 81,8 present particles are passing D sieve (11,2mm) while the standard requires at least 85 present. The 2/5 steel slag also does not correspond to the standard category, because of the high percentage of particles passing 1,0 mm (d/2) sieve (the standard requires <5).

Table 4: Co-product aggregate gradation

Sieve, mm	**Passing, %**				
	BOF Steel slag				**Dolomite waste sand**
	0/5	2/5	4/8	8/11	0/2
11,2	100	100	100	81,8	100
8,0	99,9	100	94,6	17,9	100
5,6	99,2	99,2	47,6	4,7	100
4,0	95,6	62,4	16,3	2,0	99,5
2,0	66,4	22,4	4,4	1,3	90,1
1,0	39,3	14,1	3,6	1,2	67,1
0,5	21,6	10,1	3,4	1,2	52,9
0,250	11,4	7,5	2,8	1,0	44,4
0,125	6,0	5,1	2,0	0,8	34,6
0,063	3,5	3,6	1,4	0,8	18,6
Category	GA90	N/A	GC90/20	N/A	GF85

2.3 Bitumen tests

Base bitumen BND 60/90 (category defined in accordance to Russian specifications) and SBS polymer modified bitumen PMB 50/70-53 was used for the testing. Base bitumen is characterized by a pen of 65 dmm at 25°C, softening point is reached at 50,4 °C and Fraas temperature is -25°C. The SBS modified bitumen has a pen of 59 dmm, softening point of 67,7°C and Fraas temperature -16°C. All the test results of the bitumen BND 60/90 and PMB 50/70-53 are shown in Table 6.

Table 5: Conventional aggregate gradation

Sieve, mm	Passing, %			
	Crushed dolomite			Crushed quartz sand
	2/5	5/8	8/11	0/5
11,2	100	100	90,7	100
8,0	100	88,4	16,1	100
5,6	93,0	11,7	4,1	98,4
4,0	57,6	3,1	1,7	89,6
2,0	9,1	1,8	1,3	71,9
1,0	2,7	1,5	1,3	55,0
0,5	2,0	1,3	1,1	34,9
0,250	1,8	1,2	1,0	10,5
0,125	1,7	1,0	0,9	1,4
0,063	1,4	0,9	0,7	0,7
Category	GC90/15	GC85/15	GC90/20	GA90

Table 6: Typical characteristics of the bitumen BND 60/90 and PMB 50/70-53

Parameter	Standard	Bitumen	
		BND60/90	PMB 50/70-53
Penetration at 25°C, dmm	LVS EN 1426	65,0	59,0
Softening point, °C	LVS EN 1427	50,4	67,7
Fraas temperature, °C	LVS EN 12593	- 25,0	- 16,0
Kinematic viscosity, mm^2/s	LVS EN 12595	607	-
Dynamic viscosity, Pa·s	LVS EN 12596	340	-
Elastic recovery, %	LVS EN 13398	-	88
Ageing characteristics of bitumen under the influence of heat and air (RTFOT method)			
Loss in mass, %	LVS EN 12607-1	-0,1	0
Retained penetration, %	LVS EN 1426	70,8	40,0
Increase of a softening point, °C	LVS EN 1427	6,4	1,9
Fraas breaking point after aging, °C	LVS EN 12593	-20,0	-
Retained elastic recovery,%	LVS EN 13398	-	84

3. MIX DESIGN

Dense graded AC mixtures have been designed by using conventional and unconventional raw materials. Aggregate gradation fulfilled the basic requirements defined in LVS EN 13108-1 and the complementary Latvian criteria specified in [6]. The Marshall mix design procedure was used for the determination of the optimal bitumen content for the reference mixture, considering the mixture test results for Marshall stability and flow, as well as the volumetric values: air voids (V), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB). Test specimens for Marshall Test had the shape of cylinder with diameter of 101mm and height range from 62,5to 64,5mm. All of them were prepared in the laboratory by impact compactor according to LVS EN 12697-30 with 2×50 blows of hammer 50°C temperature.

In total three different groups of mixtures were analysed:

- Two reference mixtures without co-products (with conventional and SBS bitumen), which were used as a control;
- Mixtures containing only BOF slag and dolomite waste sand;
- Combination of conventional and unconventional materials.

In order to determine the potential of using unconvential aggregates in the mixtures, the second and third group of mixtures were prepared by using only conventional bitumen. Each group of mixtures are characterized by different bitumen contents in the range 5,4 – 7,0% on the weight of the aggregate. The optimal bitumen content was determined by optimisation of the volumetric characteristics and considering resistance to deformation with wheel tracking test. This variation of bitumen content even with having similar grading curves is connected with high hygroscopicity of dolomite waste material and differences in aggregate bulk density and surface texture for steel slag.

4. PERFORMANCE EVALUATION

4.1 Resistance against permanent deformations

Resistance against permanent deformation was determined according to standard LVS EN 12697-22 method B (wheel tracking test with small size device in air). This test method is designed to repeat the stress conditions observed in the field therefore can be categorised as simulative. The asphalt mixture resistance to permanent deformation is assessed by the depth of the track and its increments caused by repetitive cycles (26,5 cycles per minute) under constant temperature (60°C) (Fig. 4.). The rut depths are monitored by means of two linear variable displacement transducers (LVDTs), which measure the vertical displacements of each of the two wheel axles independently as rutting progresses.

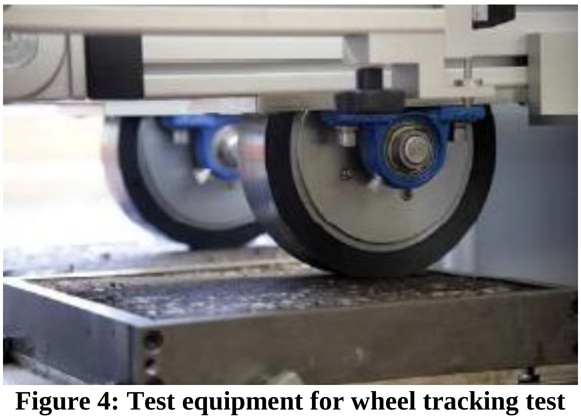

Figure 4: Test equipment for wheel tracking test

Rectangular shape specimens with the base area of 305×305mm have been prepared for the test by using roller compactor according to LVS EN 12697-33 (Fig. 5). Thickness of the tested specimens conforms to that of the traditional pavement surface layer – 40mm. The test assesses three parameters:

– Wheel Tracking slope (WTS_{AIR}), which is defined as increase of the depth of the wheel track per 1000 test cycles;
– Rut depth (RD_{AIR}), which is the accumulated permanent deformation after 10000 cycles;
– Proportional rut depth (PRD_{AIR}), which is the relative depth of wheel track after 10000 test cycles in proportion to the test specimen thickness.

Figure 5: Roller compactor

Figure 6 reports the evolution of the loading cycles – rut depth curves during the test conducted. The wheel tracking slope has been calculated by using the equation

$$WTS_{AIR} = \frac{(d_{10000} - d_{5000})}{5} \quad (1)$$

where WTS_{AIR} is the wheel tracking slope in mm per 10^3 load cycles; d_{5000} and d_{10000} is the rut depth after 5000 and 10000 load cycles. The experimentally obtained curves illustrate asphalt as typical visco–elasto–plastic material – the first phase has a decreasing wheel tracking slope (creep rate), whereas the second has a constant wheel tracking slope.

Wheel tracking slope in Latvia has been regulated by requirements in Road Specifications 2010. All of the mixtures fulfilled the requirement on the category of $WTS_{AIR\ 0,3}$ for a road with intensive traffic. The results are presented in Table 7. The largest plastic strain of 5,78 mm and the highest wheel tracking slope of 0,29 mm in 1000 cycles appear for the reference mixture with base bitumen. The results for reference mixture with SBS modified bitumen are only slightly better (5,05 mm and 0,2 8mm/1000 cycles). The asphalt concrete mixture which was produced entirely from co-products shows surprisingly good resistance to permanent deformations, having an average rut depth value of 1,54 mm and wheel tracking slope of 0,12 mm/1000 cycles. The mixture with combination of co-product and conventional aggregate had somewhat worse test results: the rut depth value of 3,94 mm and the wheel tracking slope of 0,19 mm/1000 cycles. The steel slag fractions of 0/5 and 2/5 in this mixture were replaced with dolomite filler and crushed quartz sand, because of the strength and angularity the fine steel slag fractions which can cause excessive wear of the asphalt production and paving equipment. It is also important that the combination of aggregates allowed reducing the bitumen content by significant 1% (from 7% to 6%).

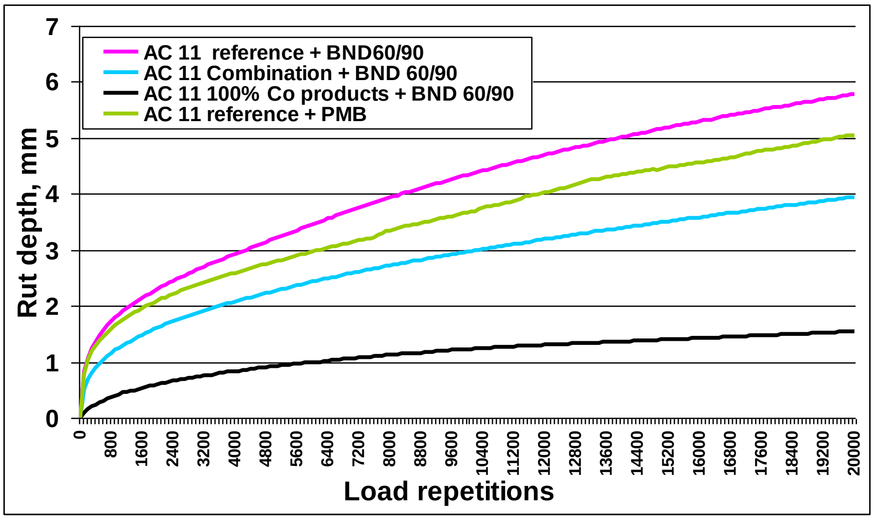

Figure 6: Wheel tracking test curves

Table 7: Characteristics of wheel tracking test

Asphalt mix		**WTS_{AIR}, mm/1000cycles**	**RD_{AIR}, mm**	**PRD_{AIR}, %**
Reference	BND 60/90	0,29	5,78	14,45
	PMB	0,28	5,05	12,63
Co-products		0,12	1,54	3,85
Combination		0,19	3,94	9,85

CONCLUSIONS

BOF Steel slag aggregates meet the Road Specifications 2010 requirements in Latvia as a road construction aggregate. Physical and mechanical properties of steel slag aggregates are comparable with the characteristics of conventional natural aggregate usually used in transportation infrastructure. Steel slag aggregates have high resistance to fragmentation with average LA value of 19, excellent shape (FI_2) and texture characteristics. The values of these parameters are higher than for conventional dolomite and granite aggregates that are used in Latvia. The main disadvantages of the material are high density which rises the transportation costs and large porosity that forces to use more bitumen than for conventional asphalt materials.

Dolomite sand waste fulfils the highest standard LVS EN 13043 category in terms of angularity, having an average value of flow coefficient of 33 which also fulfils the Latvian Road Specifications 2010 requirements for sand. The dolomite waste sand has a high filler content – 18,6% and therefore has to be tested for the properties of filler. The research showed high quality of this material because of low methylene blue value (MB_F 0,5), high carbonate content (CC_{90}), excellent Rigden air voids ($V_{28/38}$) and Delta ring and ball ($\Delta_{R\&B}$ 8/25) test results.

Mixture from 100% steel slag and dolomite waste sand that was prepared using base bitumen BND 60/90 shows high resistance to permanent deformation WTS_{AIR}0,12. However, this combination has high optimum binder content – 7%. Mixture form steel slag and dolomite aggregate in coarse portion and dolomite waste sand and crushed quartz sand in the sand and filler portion had a little lower resistance to permanent deformation ($WTS_{AIR\ 0,19}$) than the mixture made only from steel slag.

However the value was significantly higher than for both reference mixtures with dolomite aggregates, crushed quartz sand and limestone filler with both conventional and SBS modified bitumen - $WTS_{AIR\ 0,29}$ and $WTS_{AIR\ 0,28}$ respectively. This mixture with combination of conventional aggregate and co-products has also significantly lower bitumen content which lowers the production costs compared to mixture made entirely from co-products.

Further analysis of the effect of using waste products should involve research on the resistance to deformations in low and moderate temperatures. It must also include further optimisation of co-product and conventional aggregate in order to reduce the bitumen content while still maintaining high resistance to permanent deformation, fatigue and thermal cracking.

REFERENCES

[1]. The European Slag Association: „EUROSLAG", Legal status of slags. Position paper, Available: http://www.euroslag.com [Accessed: Aug 10, 2011].

[2]. D. Xirouchakis, V. Manolakou. *Properties of EAF Slag Produced in Greese: A Constructional Material for Sustainable Growth: .5th Internationa Conference Bituminous Mixtures and Pavements,* pp. 287– 297, June 1-3, 2011, Thessaloniki, Greece.

[3]. U. Bagampadde, H. I. Al-Abdul Wahhab, S.A. Aiban. "Optimization of Steel Slag Aggregates for Bituminous Mixes in Saudi Arabia." Journal of Materials in Civil Engineering., , vol 11., issue 1, pp.30-35. ISSN: 0899-1561Feb. 1999.

[4]. M. Pasetto, N. Baldo. Mix Design and Performance Characterization of Bituminous Mixtures with Electric Arc Furnace Steel Slags: *5th Internationa Conference Bituminous Mixtures and Pavements,*, pp. 748 – 757, 287– 297,June 1-3, 2011, Thessaloniki, Greece.

[5]. A. Korjakins, S. Gaidukova, G. Šahmenko, D. Bajāre, D. Pizele. "Investigation of Alternative Dolomite Properties and Their Application in Concrete Production". Scientific Proceedings of Riga Technical university. Construction Science Vol 2. Issue 9, pp. 64-71. ISSN 1407-7329, 2008.

[6]. "Road Specifications 2010" approved by Order No 01.01-03/173 of the Ministry of Traffic on 7. Sept. 2009. 239pp., Available: http://www.lvceli.lv/lv/Files/Publications/629/CELU_SPECIFIKACIJAS_2010_GALA_REDAKCIJA_arTK_23jul09_labojumiem_grafikiem.pdf [Accessed: Aug 10, 2011].