



PERFORMANCE OF ASPHALT CONCRETE WITH DOLOMITE SAND WASTE AND BOF STEEL SLAG AGGREGATE

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Abstract. The rapid growth of traffic loads in Latvia increases the demands for asphalt carrying capacity on large motorways. The dolomite and sandstone that can be found in Latvia lacks the mechanical strength and for most of the large motorways the aggregates are imported from other countries causing increase of costs and growth of emissions from transportation. On the other hand, large amounts of Basic Oxygen Furnace (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 also been accumulated and its quantity has reached a million of tons and is rapidly increasing. This huge quantity of technological waste needs to be recycled with max efficiency. The lack of experience in 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 the mixes with steel slag and dolomite waste sand or unconventional aggregate combination with dolomite in coarse portion, crushed quartz sand in sand portion plus dolomite waste sand in sand and filler portions had high resistance to plastic deformations and fatigue failure. These mixes can fully satisfy and in some cases significantly overcome the requirements of local asphalt specifications for highly loaded motorways.

Keywords: Basic Oxygen Furnace (BOF) steel slag, dolomite sand waste, asphalt mixture, permanent deformation, wheel tracking test, fatigue.

1. Introduction

During the recent years, huge quantities of technological waste, such as steel slag and very fine crushed dolomite sand that need to be recycled with max efficiency have accumulated in Latvia (Figs 1, 2). The produced waste mostly remains unused in quarries occupying space and increasing the overall technological costs. At the same time the road building industry in the Baltic States strives to utilize the local aggregates because the physical-mechanical characteristics of most of the materials do not meet the normative requirements (Bulevičius *et al.* 2011).

The coproducts (slag) of iron and steel production have been used commercially since 19th century. In the European Union and North America steel slag is used in: bituminous bound materials, 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 (Xirouchakis, Manolakou 2011). However, in Lat-

via, for commercial road construction purposes, it has been used only for unbound mixtures.

The research has showed that production of asphalt mixtures with high performance characteristics is possible by using steel slag aggregate (Pasetto, Baldo 2011). However, the studies have also indicated that, because of the high angularity and texture of the particles, the asphalt often has poor workability. Therefore, the application of slag may have more potential in combination with conventional aggregates (Bagampadde *et al.* 1999).

The second most widespread coproduct in Latvia is the dolomite waste sand. It has been accumulating in quarries for many years and currently its quantity has reached several million tones. Previously, it was used in agriculture as the lime substitute for soil treatment and in the building industry as the quartz sand equivalent. Currently, researchers in Latvia also offer to utilize the dolomite sand waste in the concrete production (Korjakins *et al.* 2008). However, the research on the perspective use of dolomite waste sand in production of asphalt has received relatively little attention. For example, this materi-

al could be used to fully or partially replace the fine and filler portions.

The goal of this study is to examine the performance properties of asphalt mixtures that contain different dosages of dolomite waste and Basic Oxygen Furnace (BOF) steel slag and to compare the results with reference asphalt mixture produced with conventional aggregates. The testing includes determination of plastic deformations and fatigue life.

2. Materials

The following materials were used in the study: BOF slag, dolomite waste sand, conventional aggregate (crushed dolomite and quartz sand) and bitumen.

2.1. Aggregate tests

The Latvian law classifies BOF slag and dolomite sand waste as non-hazardous solid materials according to the Council Directive 91/689/EEC on Hazardous Waste. The



Fig. 1. Unfractionated BOF slag aggregate



Fig. 2. Unused dolomite waste sand

Table 1. Chemical composition of by-products

Oxide content, %			
BOF steel slag		Dolomite waste sand	
Oxide	Content, %	Oxide	Content, %
CaO	30.6	CaO	31.0
MgO	18.9	MgO	17.0
SiO ₂	19.9	SiO ₂	2.5
MnO	6.3	Na ₂ O	0.82
Al ₂ O ₃	5.0	Al ₂ O ₃	0.64
TiO ₂	0.52	K ₂ O	0.76
FeO	16.3	Fe ₂ O ₃	0.34

chemical analysis (Table 1) shows that both co-products contain a prevalence of CaO and MgO but the BOF steel slag also contains a large amount of SiO₂ and FeO.

The physical and mechanical properties of steel slag, dolomite waste sand, crushed dolomite aggregate and quartz sand are summarized in Table 2. The tests were carried out according to the European standard (EN) test methods. The properties of BOF steel slag correspond to the highest category of standard LVE EN 13043 Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and other Trafficked Areas. However, because of high abrasivity of this material, the proportion of it for wearing courses according to Latvian Road Specifications 2010 has been restricted to 20%. The test results of steel slag main properties show a very low flakiness index – 2, excellent mechanical strength with average Los Angeles coefficient (LA) value of 19, high frost resistance with average Magnesium Sulfate (MS) test value of 3, low fines content – 0.5% and slag expansion tests showed that the expected swelling should be negligible (Table 2).

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.

2.2. Aggregate gradation

In total, 9 aggregate gradations were used for producing the AC 11 mixtures – 5 unconventional co-product aggregate and 4 conventional crushed dolomite and quartz sand aggregates (Table 3).

Dolomite waste sand is categorized as G_F85, steel slag 0/5 as G_A90 and steel slag 4/8 as G_C90/20 according to the LVS EN 13043. Steel slag which is categorised as 8/11 does not confirm to any of the standard categories, because only 81.8% particles pass D sieve (11.2 mm) while the standard requires at least 85%. The 2/5 steel slag also does not correspond to the standard category because of high percentage of particles passing 1.0 mm (d/2) sieve (the standard requires < 5).

2.3. Bitumen tests

Unmodified bitumen BND 60/90 (category is defined in accordance to Russian specifications) and SBS polymer modified bitumen PMB 45/80-55 was used for the testing. Unmodified bitumen is characterized by a pen of 65 dmm at 25 °C, softening point is reached at 50.4 °C and the Fraas temperature is –25 °C. The SBS modified bitumen has a pen of 59 dmm, softening point of 67.7 °C and the Fraas temperature –16 °C. All the test results of the bitumen BND 60/90 and PMB 50/70-53 are shown in Table 4.

Table 2. Physical and mechanical characteristics of the aggregate

Physical and mechanical properties	Standard	BOF steel slag	Dolomite waste sand	Crushed dolomite aggregate	Crushed quartz sand
Los Angeles coefficient (<i>LA</i>), %	<i>LVS EN 1097-2</i>	19	–	22	–
Resistance to wear. Nordic test (<i>A_N</i>), %	<i>LVS EN 1097-9</i>	14.4	–	15.7	–
Sand equivalent test, %	<i>LVS EN 933-8</i>	80*	60	–	91
Flakiness Index (<i>FI</i>), %	<i>LVS EN 933-3</i>	2	–	12	–
Flow coefficient (<i>E_{CS}</i>)	<i>LVS EN 933-6</i>	43*	33	–	35
Water absorption, %	<i>LVS EN 1097-6</i>	2.4	–	2.7	5.4
Grain density, Mg/m ³	<i>LVS EN 1097-6</i>	3.25	2.80	2.80	2.70
Fine content, %	<i>LVS EN 933-1</i>	0.5	18.6	0.9	0.9
Freeze/thawing (<i>MS</i>), %	<i>LVS EN 1367-2</i>	3	–	9	–
Expansion, %	<i>LVS EN 1744-1</i> p.19.3	2	–	–	–
Methylene blue test (<i>MB</i>), g/kg	<i>LVS EN 933-9</i>	–	0.5	–	–
Carbonate content, %	<i>LVS EN 196-21</i>	–	> 90	–	–
Rigden air voids, %	<i>LVS EN 1097-4</i>	–	28–30	–	–
Delta ring and ball test, °C	<i>LVS EN 13179-1</i>	–	11	–	–

NOTE: * BOF steel slag 0–5 mm.

Table 3. Conventional and co-product aggregate gradation

Sieve, mm	Passing, %									
	Conventional aggregate					Co-product aggregate				
	BOF steel slag		Dolomite waste sand			Crushed dolomite			Crushed quartz sand	
	0/5	2/5	4/8	8/11	0/2	2/5	5/8	8/11	0/5	
11.2	100	100	100	81.8	100	100	100	90.7	100	
8.0	99.9	100	94.6	17.9	100	100	88.4	16.1	100	
5.6	99.2	99.2	47.6	4.7	100	93.0	11.7	4.1	98.4	
4.0	95.6	62.4	16.3	2.0	99.5	57.6	3.1	1.7	89.6	
2.0	66.4	22.4	4.4	1.3	90.1	9.1	1.8	1.3	71.9	
1.0	39.3	14.1	3.6	1.2	67.1	2.7	1.5	1.3	55.0	
0.5	21.6	10.1	3.4	1.2	52.9	2.0	1.3	1.1	34.9	
0.250	11.4	7.5	2.8	1.0	44.4	1.8	1.2	1.0	10.5	
0.125	6.0	5.1	2.0	0.8	34.6	1.7	1.0	0.9	1.4	
0.063	3.5	3.6	1.4	0.8	18.6	1.4	0.9	0.7	0.7	
Category	G _A 90	N/A	G _c 90/20	N/A	G _r 85	G _c 90/15	G _c 85/15	G _c 90/20	G _A 90	

NOTE: N/A – not applicable.

Table 4. Typical characteristics of the bitumen *BND 60/90* and *PMB 45/80-55*

Parameter	Bitumen		Standard
	<i>BND 60/90</i>	<i>PMB 45/80-55</i>	
Penetration at 25 °C, dmm	65.0	59.0	<i>LVS EN 1426</i>
Softening point, °C	50.4	67.7	<i>LVS EN 1427</i>
Fraas temperature, °C	–25.0	–16.0	<i>LVS EN 12593</i>
Kinematic viscosity, mm ² /s	607	–	<i>LVS EN 12595</i>
Dynamic viscosity, Pas	340	–	<i>LVS EN 12596</i>
Elastic recovery, %	–	88	<i>LVS EN 13398</i>
Ageing characteristics of bitumen under the influence of heat and air (RTFOT method)			
Loss in mass, %	–0.1	0	<i>LVS EN 12607-1</i>
Retained penetration, %	70.8	40.0	<i>LVS EN 1426</i>
Increase of a softening point, °C	6.4	1.9	<i>LVS EN 1427</i>
Fraas breaking point after aging, °C	–20.0	–	<i>LVS EN 12593</i>
Retained elastic recovery, %	–	84	<i>LVS EN 13398</i>



Fig. 3. Test equipment for wheel tracking test



Fig. 4. Roller compactor

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 Bituminous Mixtures – Material Specifications – Part 1: Asphalt Concrete* and the complementary Latvian criteria specified in *Autoceļu specifikācijas 2010* [Road Specifications 2010]. 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) (Roberts et al. 2002). Test specimens for Marshall Test had the shape of cylinder with diameter of 101 mm and height range from 62.5 mm to 64.5 mm. All of them were prepared in the laboratory by impact compactor according to the *LVS EN 12697-30 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 30: Specimen Preparation by Impact Compactor* with 2×50 blows of hammer 140°C temperature.

Three different groups of mixtures were analysed:

- two reference mixtures without coproducts (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 unconventional aggregates in the mixtures, the 2nd and 3rd groups of mixtures were prepared by using only conventional bitumen. Each group of mixtures is 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 optimising the volumetric characteristics and considering resistance to deformation with wheel tracking test. This variation of bitumen content even having similar grading curves can result in high hygroscopicity of dolomite waste material, differences in aggregate bulk density and high bitumen absorption of BOF steel slag material (Sivilevičius et al. 2008, 2011; Vislavičius, Sivilevičius 2013).

4. Performance evaluation

4.1. Resistance against permanent deformations

Resistance against permanent deformation was determined according to the standard *LVS EN 12697-22 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 22: Wheel Tracking 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 is 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/m) under constant temperature (60°C) (Fig. 3). 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.

Rectangular shape specimens with the base area of 305×305 mm were prepared for the test by using roller compactor according to the *LVS EN 12697-33 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 33: Specimen Prepared by Roller Compactor* (Fig. 4). Thickness of the tested specimens conforms to that of the traditional pavement surface layer – 40 mm. The test assesses three parameters:

- Wheel Tracking Slope (WTS_{AIR} , mm/1000cycles) which is defined as increase in the depth of wheel track per 1000 test cycles;
- Rut Depth (RD_{AIR} , mm) 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.

Fig. 5 reports the evolution of the loading cycles – rut depth curves during the test conducted. The wheel tracking slope has been calculated by using the following equation:

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

where WTS_{AIR} – the wheel tracking slope, mm/1000cycles; d_{5000} and d_{10000} – the rut depths after 5000 and 10000 load cycles, mm.

The experimentally obtained curves illustrate asphalt as typical visco-elastic-plastic material. The 1st phase has a decreasing wheel tracking slope (creep rate), whereas, the 2nd has a constant wheel tracking slope.

The requirements for wheel tracking slope in Latvia are regulated by the requirements of *Autoceļu specifikācijas 2010* [Road Specifications 2010]. All of the mixtures fulfilled requirement to the category of $WTS_{AIR}0.3$ for road with high traffic volume. The results are presented in Table 5.

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 unmodified bitumen. The results for reference mixture with SBS modified bitumen are only slightly better (5.05 mm to 0.28 mm/1000 cycles). The asphalt concrete mixture which was produced entirely from coproducts 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 coproduct and conventional aggregate had somewhat worse test results: 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. In a dense graded asphalt concrete the aggregates and bitumen both have an active role in forming the structure. Therefore, the test results confirm that high resistance to rutting is attained by using modified bitumen as well as aggregates with rough surface texture which promises more aggregate interlock and surface friction. It is also important that the combination of steel slag with mineral aggregates allowed reducing the bitumen content by significant 1% (from 7% to 6%). The optimisation of the bitumen content was performed by utilization of fatigue and rutting test results. Low bitumen amount reduces the fatigue performance, while highly increases the rutting.

4.2. Fatigue

Fatigue properties were determined using four point bending test device (4PB) (Fig. 6). This method consists of a cyclic bending of prismatic specimen at a constant strain amplitude. The beams were compacted in the laboratory by using roller compactor. They were saw cut to the required

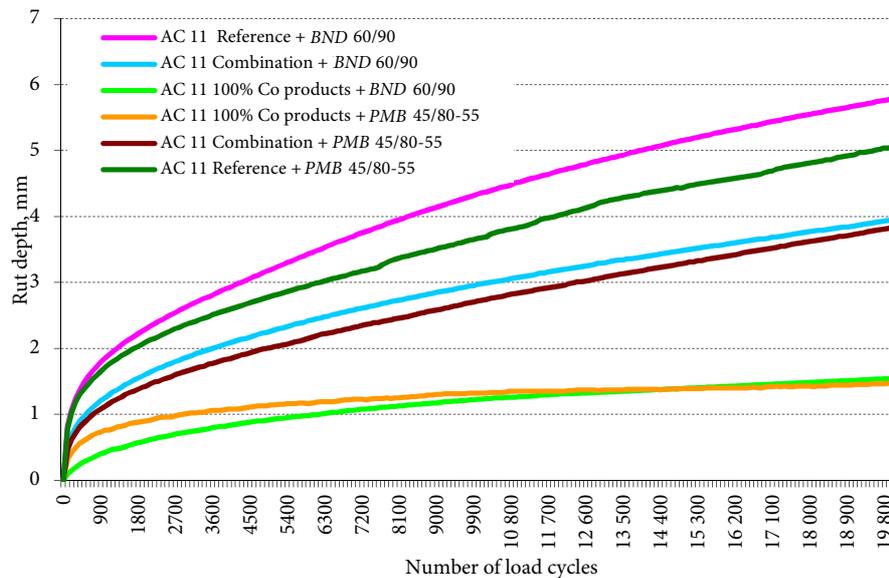


Fig. 5. Wheel tracking test curves

Table 5. Characteristics of wheel tracking test

	Asphalt mixes					
	Reference (natural dolomite aggregate)		Co-products, 100%		Combination of co-products and natural aggregate	
Bitumen	BND 60/90	PMB 45/80-55	BND 60/90	PMB 45/80-55	BND 60/90	PMB 45/80-55
WTS_{AIR} , mm/1000 cycles	0.29	0.28	0.12	0.03	0.19	0.22
RD_{AIR} , mm	5.78	5.05	1.54	1.47	3.94	3.83
PRD_{AIR} , %	14.45	12.63	3.85	3.68	9.85	9.58

dimensions of 50 mm wide, 50 mm high and 400 mm long. Resistance to fatigue was determined at 20 °C and 30 Hz according to the *LVS EN 12697-24 Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 24: Resistance to Fatigue*.

Fatigue life is defined as the number of cycles which corresponds to 50% decrease of initial stiffness modulus. In this study the fatigue was determined by applying half million load cycles to the beam. The results are given in Fig. 7.

The results indicate that the mixture with BOF steel slag and dolomite sand waste (100% coproduct) showed less resistance to fatigue compared to results for mixture made with conventional aggregates and combined mixture. The mix designs that include exclusively dolomite aggregates as well as the combination of dolomite and slag in coarse portion plus waste sand in fine aggregate portion exhibit slightly higher fatigue life compared to other combinations. The fatigue life exceeded 500 000 cycles for all the combinations with the exception of 100% by-product mixtures made with BND 60/90 bitumen. However, to verify the findings more extensive laboratory research is needed.

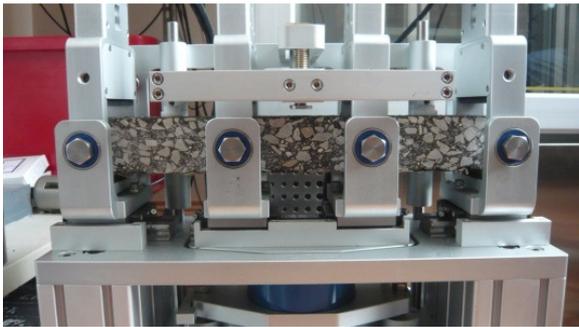


Fig. 6. Test equipment for fatigue test

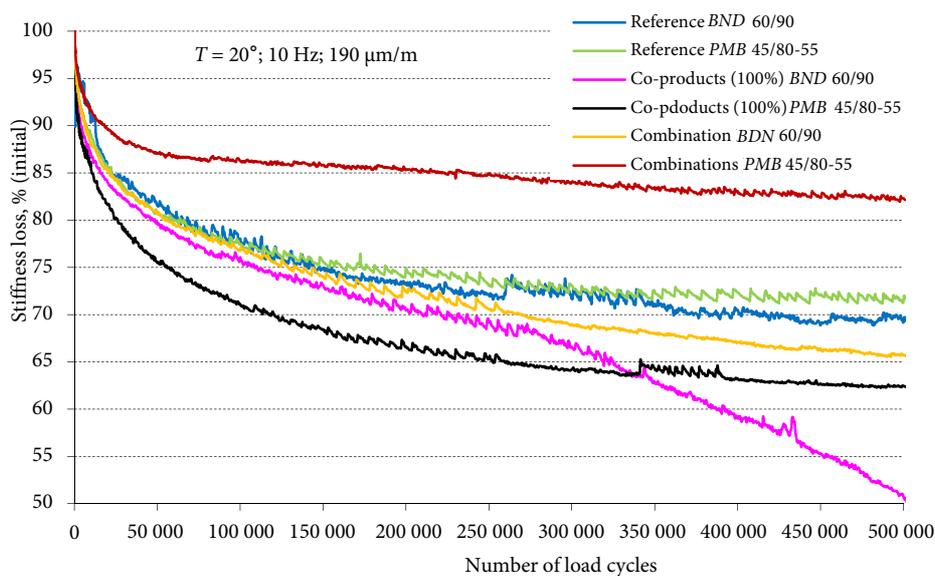


Fig. 7. Fatigue test results

5. Conclusions

BOF steel slag aggregates meet the *Autoceļu specifikācijas 2010* [Road Specifications 2010] requirements in Latvia to 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 the average LA value of 19, excellent shape (FI_2) and texture characteristics. The values of these parameters are higher than those for conventional dolomite and granite aggregates that are used in Latvia. The main disadvantages of the material are high density which raise the transportation costs and large porosity that forces to use the increased bitumen dosage.

Dolomite sand waste fulfills the highest standard *LVS EN 13043* category in terms of angularity having an average value of flow coefficient of 33 which also satisfies the *Autoceļu specifikācijas 2010* [Road Specifications 2010] requirements to sand. The dolomite waste sand has high filler content – 18.6% and, therefore has to be tested for the properties of filler. The research showed high quality of this material having low methylene blue value ($MB_{f0.5}$), high carbonate content (CC_{90}), excellent Rigden air voids ($V_{28/38}$) and Delta ring and ball ($\Delta_{R\&B} 8/25$).

Mixture from 100% steel slag and dolomite waste sand that was prepared using unmodified bitumen BND 60/90 shows high resistance to permanent deformation $WTS_{AIR}0.12$. However, this combination has high optimum binder content – 7%. Mixture from steel slag and dolomite aggregate in coarse portion plus 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 that for the reference mixtures made 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 a combination of conventional aggregate and co-products has also significantly lower bitumen content which lowers the production costs compared to the mixture made entirely from co-products.

The mixtures made with steel slag and local limestone in coarse portion plus dolomite sand waste in sand and filler portions exhibit slightly higher fatigue resistance than the conventional mixtures. However, the mixture from 100% steel slag and dolomite waste sand shows less resistance to fatigue.

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 optimization 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.

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