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USE OF UNCONVENTIONAL AGGREGATES IN HOT MIX ASPHALT CONCRETE

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Abstract. The study investigates use of dolomite sand waste as filler or/and sand material plus blast oxygen furnace steel slag as fine and coarse aggregate for design of high performance asphalt concrete. Both environmental and economic factors contribute to the growing need for the use of these materials in asphalt concrete pavements. This is particularly important for Latvia, where local crushed dolomite and sandstone do not fulfill the requirements for mineral aggregate in high and medium intensity asphalt pavements roads. Annually 100–200 thousand tons of steel slag aggregates are produced in Latvia. However, it has not been used extensively in asphalt pavement despite of its high performance characteristics. Dolomite sand waste, which is a byproduct of crushed dolomite production, is another widely available polydisperse by-product in Latvia. 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. Various combinations of steel slag, dolomite sand waste and conventional aggregates were used to develop asphalt concrete AC 11 mixtures. The mix properties tests include resistance to permanent deformations (wheel tracking test, dynamic creep test) and fatigue resistance. Laboratory test results showed that asphalt concrete mixtures containing steel slag and local limestone in coarse portion and dolomite sand waste in sand and filler portions had high resistance to plastic deformations and good resistance to fatigue failure.

Keywords: steel slag, dolomite sand waste, permanent deformation, creep test, fatigue.

1. Introduction

Asphalt concrete pavements are constructed of bituminous and polydisperse granular materials. Regardless of the thickness or type of asphalt pavement, the load is transmitted through the aggregate, the bitumen serving as a cementing agent to bind the aggregate in proper position to transmit the applied wheel loads to underlying layers where the load is finally dissipated (Huang 2003; Mallick, El-Korchi 2013).

Local crushed dolomite and sandstone aggregate lacks the desirable qualities for asphalt concrete mix design (Tuminienė 2013). In the meantime, as natural supplies of high quality granular materials used in highways have become less abundant, the highway engineer is faced with the challenge of finding alternative materials to meet the requirements for these materials (Krayushkina *et al.* 2012). Some of these alternatives are fly ash, coal dust, hydrated lime, steel slag etc. The co-products (slag) of iron and steel production have been used commercially since 19th century (Haritonovs *et al.* 2013). 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 (Pasetto, Baldo 2011; Xirouchakis, Manolakou 2011). However, in Latvia, 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 2014). However, the studies have also indicated that, because of the high angularity and texture of the particles, the asphalt often has poor workability (Huang *et al.* 2012; Tan *et al.* 2014). Therefore, the application of slag has more potential in combination with conventional aggregates (Bagampadde *et al.* 1999).

The second most widespread co-product 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 has been 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).

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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.

The goal of this study is to develop high performance properties asphalt mixtures using various combinations of blast oxygen furnace (BOF) steel slag, dolomite sand waste, crushed quartz sand crushed dolomite aggregates and to compare the results with reference asphalt mixture, produced with conventional aggregates. The mix properties tests include resistance to permanent deformations (wheel tracking test, dynamic creep test) and fatigue resistance.

2. Materials

The basic materials used in this study are fractionated steel slag, crushed dolomite aggregate; dolomite sand waste, crushed quartz sand, unmodified bitumen BND 60/90 and SBS modified bitumens. Steel slag was obtained from JSC Liepajas metalurgs (Latvia), dolomite sand waste from Plavinu DM Ltd (Latvia), crushed quartz sand from Jauncerpji Ltd. (Latvia) and crushed dolomite aggregate from AB Dolomitas (Lithuania), 60–90 penetration bitumen from Kirishi refinery (Russia) and SBS modified bitumen from Grupa LOTOS S.A (Poland). Conventional aggregate and unmodified and modified bitumen are used extensively for local mixes.

2.1. Properties of dolomite sand waste

The Council Directive 91/689/EEC on Hazardous Waste and the appropriate Latvian law classify steel slag and dolomite sand waste as non-hazardous solid materials. Chemical analysis of dolomite sand is shown in Table 1. There is no evidence of clay minerals being present in dolomite sand. The X-ray diffraction has been used to obtain mineralogical composition of the investigated dolomite waste (Korjakins *et al.* 2008). The main constituents of waste dolomite are $CaCO_3 \cdot MgCO_3$, which account for more than 92% of the composition.

This material contains more than 10% of fines (below 0.063 mm) and therefore it has to be tested for properties of mineral filler. Fig. 1 presents the gradation of three dolomite sand samples – S_1, S_2 and S_3 from the same stockpile. The fine particles of this material are part of the mixture mineral carcass and contribute to obtain a dense structure by filling the voids between coarse aggregate particles. The mineral filler that is in this material, however, provides more touch points between fine and coarse aggregate thus improving the mechanical properties of the mixture. Another function of the mineral filler is to increase the bitumen viscosity and improve the binder properties.

Table 2 contains test results of conventional sand and dolomite filler for comparison of the properties of

Table 1. Chemical properties of dolomite sand waste

Oxide	Name	%
CaO	Calcium oxide	31.0
MgO	Magnesium oxide	17.0
SiO_2	Silicon dioxide	2.50
Na_2O	Sodium oxide	0.82
Al_2O_3	Aluminum oxide	0.64
K_2O	Potassium oxide	0.76
Fe_2O_3	Iron oxide	0.34

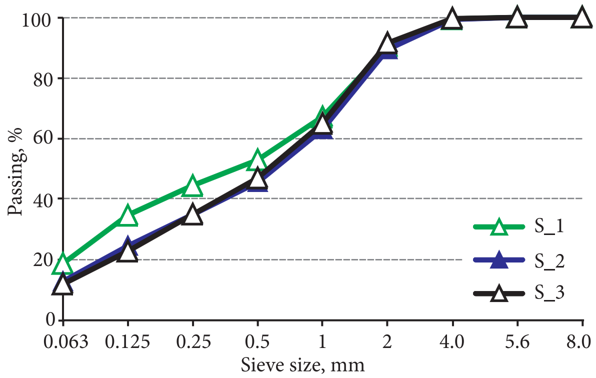

Fig. 1. Particle size distribution of dolomite sand

Table 2. Physical characteristics of dolomite sand

Physical properties	Units	Related standard	Value		
			Dolomite waste sand	Conventional material	
				Crushed quartz sand	Dolomite filler
Sand equivalent test	%	*EN 933-8:2012*	60	91	–
Flow coefficient	s	*EN 933-6:2014*	33	35	–
Water absorption	%	*EN 1097-6:2013*	2.0	0.54	<2.6
Grain density	mg/m^3	*EN 1097-6:2013*	2.80	2.80	2.75
Fine content	%	*EN 933-1:2012*	12–19	0.9	78–88
Methylene blue test	g/kg	*EN 933-9:2009*	0.5	–	0.5
Carbonate content	%	*EN 196-21:2005*	>90	–	>90
Rigden air voids	%	*EN 1097-4:2008*	28–38	–	28–38
Delta ring and ball test	°C	*EN 13179-1:2013*	8–**25**	–	8–25

sand waste's fine portion and filler portion respectively. The properties of the both of these fractions correspond to high quality requirements. Dolomite waste sand test results present excellent angularity with average flow coefficient of 33. Test results show that the fines quality is high – the material has low methylene blue value – 0.5 g/kg, high carbonate content – more than 90%, excellent Rigden air voids and Delta ring and ball tests results.

2.2. Properties of steel slag aggregate

The properties of BOF steel slag correspond to the highest category of *LVE EN 13043:2013 Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and other Trafficked Areas* standard. However, because of high abrasivety of this material, the proportion of it for wearing courses according to Latvian Road Specifications 2012 has been restricted to 20 present. 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 Magnesium sulpahate (MS test) value of 3%, low fines content – 0.5% and slag expansion tests, showed that the expected swelling is negligible (Table 3).

2.3. Bitumen tests

Unmodified bitumen BND 60/90 (penetration grade category in accordance to Russian classification) and SBS polymer modified bitumens was used for the testing. All the test results of the bitumen BND 60/90 and PMB are shown in Table 4.

3. Mix design

Dense graded AC mixtures have been designed by using conventional and unconventional raw materials (Table 5).

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: voids content (V), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) (Roberts *et al.* 2002). Test specimens for Marshall Test were prepared in the laboratory by impact compactor according to *LVS EN 12697-30:2012 Specimen Preparation by Impact Compactor* with 2×50 blows of hammer 140 °C for mixtures with unmodified bitumen and 150 °C for mixtures with SBS modiefied bitumen. The optimal bitumen content was determined by optimisation of the volumetric characteristics (Table 6).

Table 3. Physical and mechanical characteristics of steel slag aggregate

Physical and mechanical properties	Units	Related standard	Value	
			Steel slag aggregate	Crushed dolomite aggregate
Los Angeles (LA) coefficient	%	*EN 1097-2:2010*	19	22
Resistance to wear. Nordic test (A_N)	%	*EN 1097-9:2014*	14.4	15.7
Flakiness Index (FI)	%	*EN 933-3:2012*	2	12
Water absorption	%	*EN 1097-6:2013*	2.4	2.7
Grain density	mg/m^3	*EN 1097-6:2013*	3.25	2.80
Fine content	%	*EN 933-1:2012*	0.5	0.9
Freeze/thawing (MS test)	%	*EN 1367-2:2010*	3	9
Expansion	%	*EN 1744-1:2010*	2	–

Table 4. Typical characteristics of the bitumens

Parameter	Units	Bitumen				Standard
		BND 60/90	PMB 10/40-65	PMB 45/80-55	PMB 25/55-60	
Penetration at 25 °C	dmm	65.0	40.0	50.0	34.0	*EN 1426:2007*
Softening point	°C	50.4	65	58.4	63.5	*EN 1427:2007*
Fraas temperature	°C	–25	–17	–20	–23	*EN 12593:2007*
Kinematic viscosity	mm^2/s	607	2390	1203	1712	*EN 12595:2007*
Dynamic viscosity	Pa·s	340	4166	1074	3021	*EN 12596:2007*
Elastic recovery	%	–	87	88	89	*EN 13398:2012*
Ageing characteristics of bitumen under the influence of heat and air (RTFOT method)						
Loss in mass	%	0.1	0.01	0.02	0.02	*EN 12607-1:2007*
Retained penetration	%	70.8	75	69.7	79.4	*EN 1426:2007*
Increase of a softening point	°C	6.4	7.2	5.9	6.2	*EN 1427:2007*
Fraas breaking point after aging	°C	–20.0	–15	–18	–19	*EN 12593:2007*

Table 5. Compositions of asphalt concrete AC 11 mixes

Mixture	Raw materials, mass %										
	Natural dolomite aggregates, d/D			Crushed quartz sand	Dolomite filler	Stee slag aggregates, d/D				Dolomite sand waste	Bitumen
	2/5	5/8	8/11	0/5		0/5	2/5	5/8	8/11	0/2	
100% co-products	–	–	–	–	–	15.8	11.2	12.1	22.3	31.6	7.0
Combination No. 1	–	–	–	–	2.3	10.8	18.8	10.4	23.6	28.3	6.0
Combination No. 2	4.7	–	–	–	–	–	–	17.9	23.6	48.0	5.8
Reference	13.2	16.1	20.8	36.9	7.6	–	–	–	–	–	5.4

Table 6. Principle properties of asphalt concrete mixes

Parameter	Unit	Standard	Target value	Value			
			AC	100% co-products	Combination No. 1	Combination No. 2	Reference
Voids content (V),	%	*EN 12697-8:2003*	1.5–4	3.0–3.8	2.5–3.5	3.0–3.5	3.3–3.8
Voids in mineral aggregate (VMA)	%		≥15	17.5–18.5	16.0–18.0	17.0–19.0	16.5–17.5
Voids filled with bitumen (VFB)	%		≤86				
Marshall stability	kN	*EN 12697-34:2012*	≥7.0	12.0–13.5	11.5–12.5	11.0–12.5	8.5–9.5
Marshall flow	mm		2–4				
Blows of Marshall hammer		*EN 12697-30:2012*	2×50				
Mix temperature	°C		140 °C (unmod. bit.); 150 °C (mod. bit.)				

Variation of bitumen content, even with similar grading curves, results in high hygroscopicity of dolomite waste material, differences in aggregate bulk density and high bitumen absorption of BOF steel slag material (Sivilevičius, Vislavičius 2008; Sivilevičius *et al.* 2011).

4. Performance evaluation

Three different groups of mixtures were analyzed:

- reference mixtures without co-products (with conventional BND 60/90 and SBS modified bitumens), which were used as a control;
- mixtures containing only BOF slag and dolomite waste sand (with conventional BND 60/90 and SBS modified bitumens);
- combination of conventional and unconventional aggregate (with conventional BND 60/90 and SBS modified bitumens).

Performance tests are time-consuming and the number of combinations is very large; therefore in the first phase the different mixtures were evaluated with axial and triaxial loads. The combinations that have the highest deformation resistance will be tested for rut resistance and fatigue (Fig. 2).

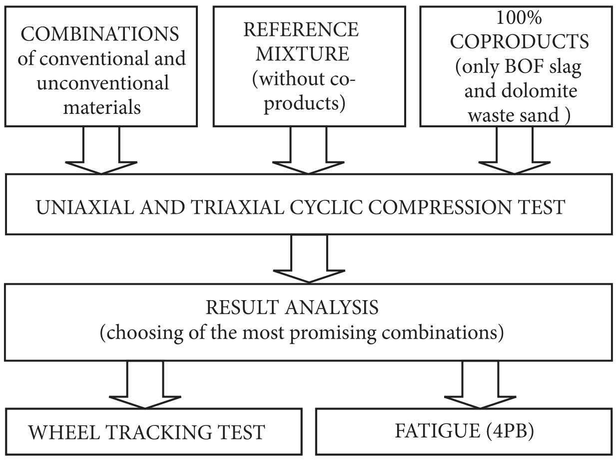

Fig. 2. Performance evaluation plan

4.1. Uniaxial and Triaxial Cyclic Compression test

For this test the standard *LVS EN 12697-25:2006 Cyclic Compression Test* was followed. The Uniaxial and Triaxial Cyclic Compression test is performed using specimens with 101.7 mm diameter and 63.5±2.5 mm height. The laboratory specimens were compacted using Marshall Impact compactor. The applied load had a block – pulse shape with 1 s of loading time and 1 s of rest time. The test duration was 3600 cycles and the test temperature was 40 °C for uniaxial and 50 °C for triaxial loading. The maximum axial stress for uniaxial loading was 100 kPa. The maximum axial stress for triaxial loading was 200 kPa and

100 kPa confining pressure. Figs 3 and 4 show the uniaxial and triaxial test results.

The combination No. 1 with PMB 45/80-55 binder showed a little higher resistance to deformations. In order to reduce the number of tests, the following tests will be performed for the combination No. 1 with unmodified binder BND 60/90 and PMB 45/80-55. In the following stages of the research (research is still in rogress) the rutting resistance and fatigue performance will be evaluated for other combinations as well.

4.2. Wheel tracking test

To perform rut resistance test, a wheel tracking apparatus is used to simulate the effect of traffic and to measure the deformation susceptibility of asphalt concrete samples. Tests were performed according to standard *LVS EN 2697-22:2012 Wheel Tracking Test* method B (small size device in air). This test method is designed to repeat the stress conditions observed in the field therefore it is categorized as simulative. Three rectangular shape specimens for each mixture with the base area of 305×305 mm were prepared by using roller compacto – two for rut resistance test and one for fatigue test. 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/min) under constant temperature (60 °C). The rut depths are monitored by means of two linear variable displacement transducers, which measure the vertical displacements of each of the two wheel axles independently as rutting progresses. Fig. 5 provides a summary of rut resistance properties of the test specimens.

The obtained results demonstrate that the largest rut depth appears for the reference mixture with unmodified bitumen. The results for reference mixture with SBS

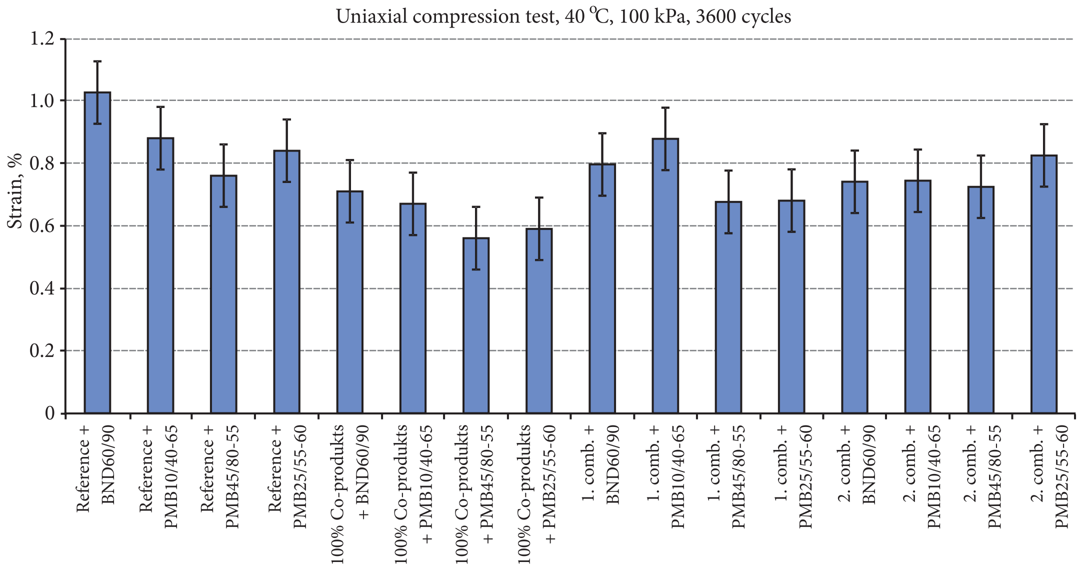

Fig. 3. Uniaxial compression test results

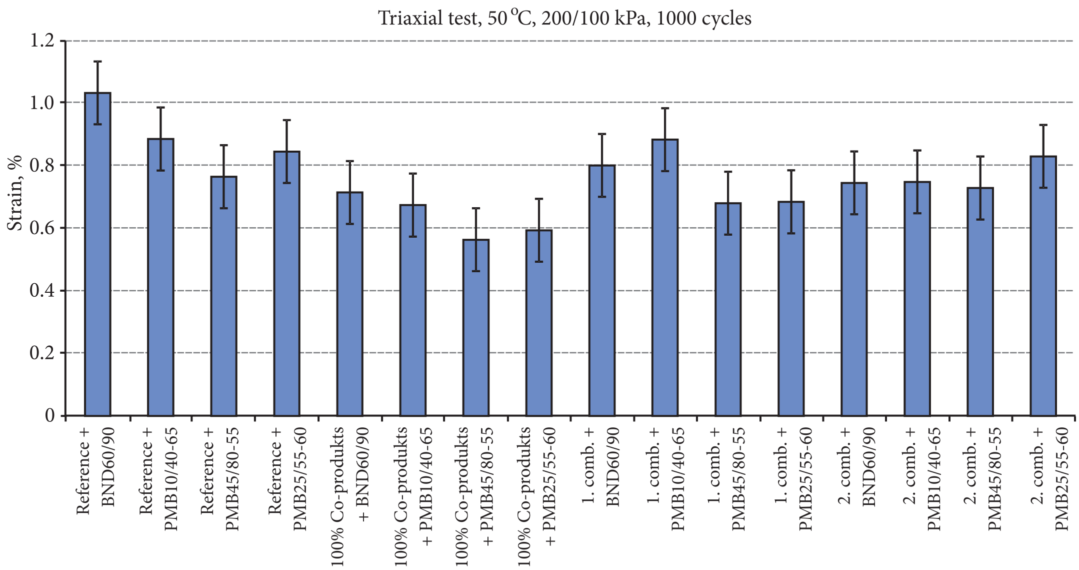

Fig. 4. Triaxial test results

modified bitumen are only slightly better. The asphalt concrete mixture which was produced entirely from co-products (100% combination) shows high resistance to permanent deformations, having an average rut depth value of 1.54 mm and wheel tracking slope of 0.06 mm/1000 cycles using unmodified bitumen B60/90 and average rut depth value of 1.47 mm and wheel tracking slope of 0.03 mm/1000 cycles using modified bitumen PMB 45/80-55. The mixture with combination of co-product and conventional aggregate (combination No. 1) had somewhat worse test results (Table 7).

4.3. Fatigue

To determine the fatigue life of the prepared asphalt concrete mixes, a four point bending fatigue test was conducted. The test was run at 20 °C, 30 Hz (according to *LVS EN 12697-24:2007 Resistance to Fatigue* at 190 μm/m strain level. The beams were compacted in the laboratory by using roller compactor. They were saw cut to the required dimensions of 50 mm wide, 50 mm high and 400 mm long. The failure criterion used in the study is the traditional 50% reduction in initial stiffness. The stiffness reduction curves are shown in Fig. 6. The obtained results indicate that mixture with BOF steel slag and dolomite sand waste (100% co-product) 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 thousand 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 – this will allow determine the relationship between tensile strain at the bottom of the beam and the number of load applications before cracking.

5. Conclusions

1. Physical and mechanical properties of steel slag aggregates and dolomite sand waste are comparable with the characteristics of conventional natural aggregate usually used in transportation infrastructure.

2. The results of wheel tracking test and cyclic compression show that mixtures with high deformation resistance were prepared in laboratory using two types of co-products.

3. The analysis of fatigue resistance results show that 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, mixture from 100% steel slag and dolomite waste sand shows less resistance to fatigue. To verify the findings more extensive laboratory research is needed – this will allow determining the relationship between tensile strain at the bottom of the beam and the number of load applications before cracking.

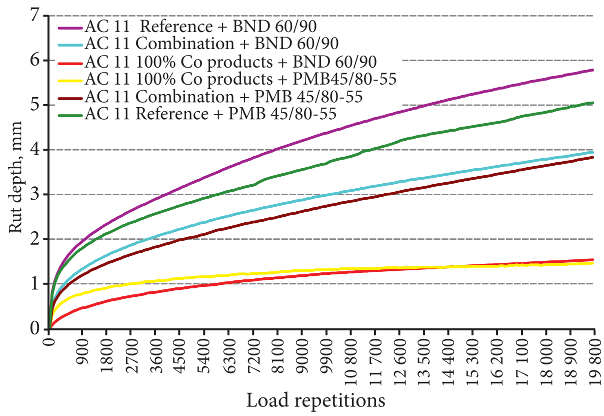

Fig. 5. Wheel tracking test results

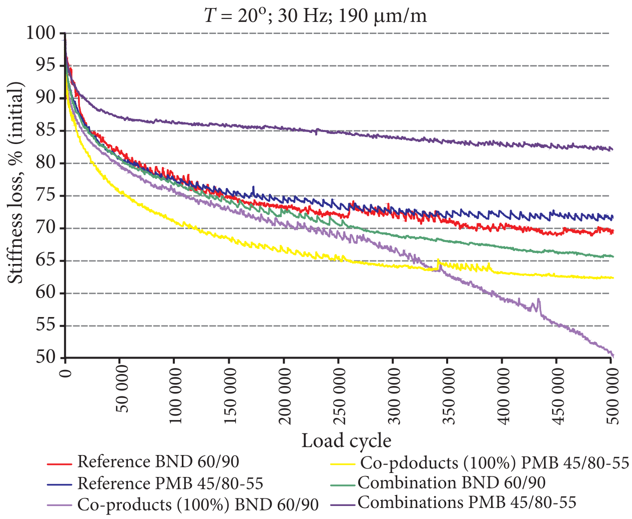

Fig. 6. Fatigue test results – stiffness reduction curves

Table 7. Numerical values of Wheel Tracking Test

Parameter	Unit	Standard	Mixture					
			100% co-products		Combination No. 1		Reference	
			B60/90	PMB 45/80-55	B60/90	PMB 45/80-55	B60/90	PMB 45/80-55
Wheel tracking slope (*WTS*$_{AIR}$)	mm/1000 cycles	*EN 12697-22:2012* B method	0.06	0.03	0.19	0.22	0.29	0.28
Rut depth (*RD*$_{AIR}$)	mm		1.54	1.47	3.94	3.83	5.78	5.05
Proportional rut depth (*PRD*$_{AIR}$)	%		3.85	3.93	9.85	9.58	14.45	12.63

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