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Performance of Warm Mix Recycled Asphalt containing up to 100% RAP

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HIGHLIGHTS

- Warm Mix Recycled Asphalt (WMRA) with asphalt emulsion containing up to 100% RAP.
- Low temperature production and use of large amounts of Recycled Asphalt Pavement (RAP).
- Characterize the performance of Warm-Mix Recycled Asphalt.

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ABSTRACT

The asphalt industry has been under pressure to reduce its emissions. This can be achieved, from one hand, by decreasing the mixing and laying temperatures of asphalt mixtures. On the other hand, recycling of Reclaimed Asphalt Pavement (RAP) is a viable solution that allows reducing waste production and resources consumption. This paper presents a study that combines Warm Mix Asphalt with the use of RAP aggregates. These mixtures, while being produced at lower temperature than traditional Hot Mixtures contain 100% RAP. Several Warm Mix Recycled Asphalt (WMRA) were prepared with 100% RAP and different emulsion contents and their behaviour was assessed by means of laboratory tests such as water sensitivity, stiffness, fatigue resistance and rutting resistance. The obtained results show that these WMRA may be successfully used in road pavements in substitution of conventional Hot Mix Asphalts.

1. Introduction

The sustainability concept is broad enough to encompass almost every aspect of life. Many industries incorporate best practices to help ensure quality of life for generations to come. The asphalt industry makes no exception. On many levels, asphalt production, laying and its many different applications can contribute to sustainability in ways not obvious to the general public. Asphalt is 100% recyclable and can be used in the old roads repair or construction of new ones [1]. This measure reduces the landfill use and the natural resources such as aggregates and bitumen [2].

In most European countries the reclaimed asphalt amount and the production of asphalt containing RAP continue to grow regularly [3]. Across Europe, a number of studies have been conducted with the overall objective of stimulating the reuse of RAP, in many cases with RAP contents as much as 60% [4–6]. In these studies, RAP is not seen as a waste, but as a material carrying valuable characteristic and that can preserve virgin aggregates for the next generations.

Hot Mix Asphalt (HMA) plant recycling is presently a common practice. However, in most cases, the RAP percentage in the new asphalt mixture is limited due to difficulties in mixing the RAP with the virgin materials, without an excessive increase of the mixing temperatures, which would accelerate the binder ageing process and also increase energy consumption and emissions during manufacture. Thus, in practice, the RAP amount in hot mix recycling is limited to less than 30%, in most cases, although there are examples of using higher values, on special equipment such as parallel drums [7].

The concern in developing road pavement techniques involves reducing environmental, economic and social costs. It also refers to the development of mixtures produced at a lower temperature than the traditional Hot Mix Asphalt. For that, several techniques are used to reduce the binder effective viscosity enabling aggregates full coating at lower mixing temperatures [8–10].

WMA technologies can be, basically, classified in three main groups [11–15]: organic additives, chemical additives and foaming

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technologies. Most of the available literature highlights the WMA advantages, which include the following [16,17]: lower energy consumption in mix production, reduced emissions and better working conditions because of the gaseous emissions absence.

Many authors have approached the Warm-Mix Recycled Asphalt (WMRA) use [8–17]. The technology presented in this paper is based on the asphalt emulsion use at ambient temperature instead of bitumen [18]. The main principle is the use of 100% RAP, heated between 100 and 140 °C (drying) and adding a small percentage of asphalt emulsion at ambient temperature (generally below 25 °C). This new technology involves a reduction in mixing energies and consequently, the emission of CO_2. Furthermore, 100% recycled aggregates reduces the materials quantity doomed to landfills [6].

The present study comprises a comparative analysis between different mixtures of WMRA and HMA. The specimens were produced in the laboratory and several physical and mechanical tests were performed to compare the different mixtures mechanical properties.

2. Materials and mix design

The RAP used in this study was obtained from two different Portuguese main roads (EN244 and EN346). These roads are secondary with T5 level traffic, corresponding to Annual Average Daily Traffic of 150–300 vehicle traffic. Both RAPs residual bitumen content was obtained by the centrifuge extractor method (EN 12697-1). The extracted bitumen was then characterised by penetration value and softening point (Table 1). As can be observed, the EN346 recovered bitumen is significantly hard, which is due to the ageing process throughout the pavement life. RAP aggregates gradation was also assessed after bitumen extraction. RAPs characteristics were taken into account for the WMRAs mix design.

The aggregate used in conventional HMA and in the gradation correction of the recycled mixtures were granites. The WMRA with asphalt emulsion design procedure was basically the same used for Hot Mix Recycled Asphalt (HMRA) and can be summarized as follows: (1) defines the mixture composition; (2) determines the optimum asphalt emulsion content; (3) conducts laboratory performance tests.

The WMRA composition was defined taking into account the limits for a base layer specified by the Portuguese Road Administration [19]. Mixtures containing 100% RAP were first designed mixtures WM244 and WM346. Afterwards, mixtures WM244-C and WM346-C were designed correcting the gradation curve by means of virgin aggregates in order to meet the Portuguese grading specifications (Table 2). Different mixtures (HMA and WMRA) grading curves and grading limits are shown in Fig. 1.

The total binder content is calculated by applying an analytical empirical method that uses the following Eq. (1):

$$pb_R = 0.035 \times a + 0.045 \times b + K \times p_{200} + F \quad (1)$$

where pb_R is the total binder content (%); a is the percent of mineral aggregate retained on 2.36 mm sieve (%); b is the percent of mineral aggregate passing 2.36 mm sieve and retained on 75 μm sieve (%); p_{200} is the percent of mineral aggregate passing 0.075 mm sieve (%). K is a constant equal to 0.15 for 11–15% passing 75 μm sieve, 0.18 for 6–10% passing 75 μm sieve and 0.20 for 5% or less passing 75 μm sieve; F is the absorption factor of aggregates 0–2%, default is 0.7% [20].

The newly added bitumen percentage can be calculated with Eq. (2):

$$pb_N = pb_R - pb_F \times TR \quad (2)$$

where pb_N is the percentage of new bitumen (%); pb_R is the total binder content (%); pb_F is the percentage of bitumen in reclaimed material (%) and TR is the recycling rate (%). pb_R and pb_N have been calculated as shown and are reported in Table 3.

The new bituminous binder used for the WMRAs was a recycling asphalt emulsion. Due to the high content of fines in the RAP an asphalt emulsion with high stability is required. HMA mixture was produced with a traditional bitumen 35/50. The asphalt emulsion and bitumen properties are shown in Table 4.

The asphalt emulsion contains polyamines additives, which enhance its stability and provide a high cohesion to the recycled mixture, through the aged bitumen of RAP regeneration. The additives used have also permitted that the mixing temperature was between 100 and 120 °C, improving the aggregate coating, the mixture workability and its compaction.

The asphalt emulsion has a 61.5% of residual bitumen. The initial content of asphalt emulsion to be added to the recycled mixtures was calculated by means of Eq. (3).

$$E = \frac{pb_N}{X} \times 100 \quad (3)$$

where E is the initial content of asphalt emulsion (%); pb_N is the percentage of new bitumen (%) and X is the residual bitumen of the asphalt emulsion (%). The results are presented in Table 5.

To complete the mix design phase an estimate of asphalt binders blending was conducted taking into account the penetration of the new and old binders. Eq. (4) was adopted.

$$\lg pen_R = TR_b \times \lg pen_F + (1 - TR_b) \times \lg pen_N \quad (4)$$

where pen_R is the penetration of the binder in the recycled mixture (a minimum value of 30 was considered) (0.1 mm); pen_F is the penetration of the binder recovered from the reclaimed asphalt (0.1 mm); pen_N is the penetration of the new added binder (0.1 mm); TR_b is the binder recovered rate (%). Thus, the total binder content pb_R can be obtained from Eq. (5).

$$pb_R = \frac{TR \times Pb_F}{TR_b} \quad (5)$$

where pb_R is the total binder content (%); pb_F is the percentage of bitumen in reclaimed material; TR is the recycling rate (%) and TR_b is the binder recovered rate (%). TR_b and pb_R results from different mixtures are presented in Table 6.

The results showed in Tables 5 and 6 are variable. This is due to penetration of aged binder that presented low values, especially in the WM346 mixture. Several mixtures with different asphalt emulsion contents were prepared in order to evaluate the aggregate coating. Some mixtures were rejected because they have shown excess or scarcity of asphalt emulsion. The study moved on with the asphalt emulsion content presented in Table 7.

Table 1
Properties of the RAPs recovered bitumen.

RAP	Penetration at 25 °C, 100 g (0.1 mm) [EN 1426]	Softening point (°C) [EN 1427]	Bitumen content (%) [EN 12697-1]
EN244	19	69.6	4.8
EN346	4	85.7	4.8

Table 2
Experimental asphalt mixtures composition.

Mixtures	RAPs (%)	Crushed sand 0/5 (%)	Coarse aggregate 6/15 (%)	Coarse aggregate 15/25 (%)
WM244	100	–	–	–
WM244–C	75	–	–	25
WM346	100	–	–	–
WM346–C	80	–	–	20
HMA	–	40	30	30

3. Methods

The methodologies used for the experimental work are shown below. A primary study was carried out to obtain the optimal content of asphalt emulsion for different mixtures with and without natural aggregates. This study was based on the Indirect Tensile Stiffness Modulus (ITSM) test and on the volumetric properties determination as well as their water sensitivity, permanent deformations and fatigue resistance.

3.1. Indirect Tensile Stiffness Modulus (ITSM) test

The bituminous mixtures stiffness modulus is one of the most important properties for the asphalt pavements design [21–23]. Several mixtures were made with different asphalt emulsion contents. The RAP and aggregates were heated at 130 °C and the asphalt emulsion was added at ambient temperature. The specimens were compacted with Marshall compaction hammer by applying 50 blows to each side. ITSM test was conducted according to EN 12697-26, using the Nottingham Asphalt Tester. The test conditions were as follows: rise time 124 ms, Poisson ratio 0.35, transient peak horizontal deformation 5 με and test temperature

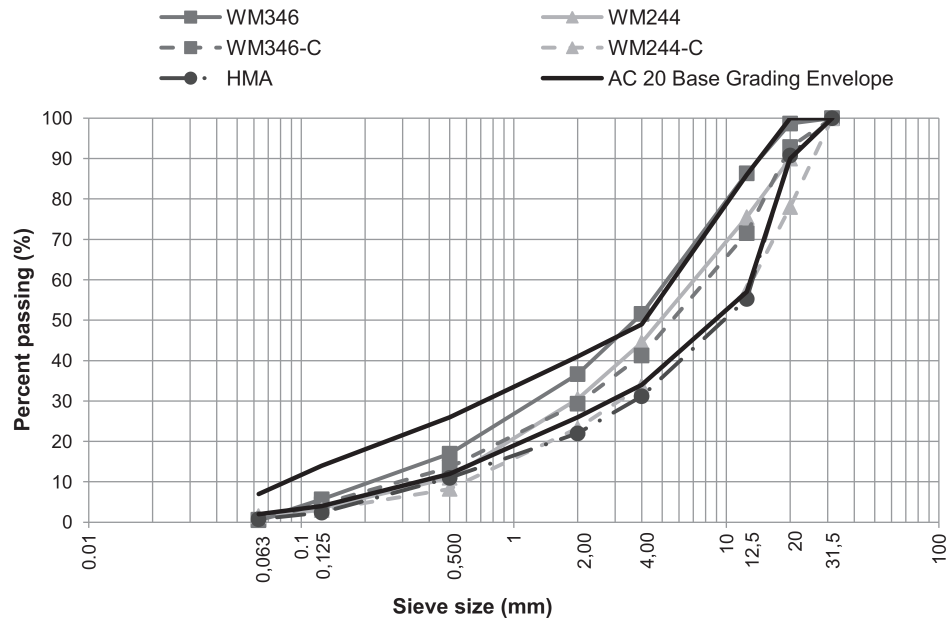

Fig. 1. Mixtures gradation curves and grading limits.

Table 3
Results obtained with Eqs. (1) and (2).

Parameter	WM346	WM244	WM346-C	MW244-C	HMA
a	63	53	71	65	75
b	35	38	27	28	23
p_{200}	2	9	2	7	2
K	0.2	0.18	0.2	0.18	0.2
pb_R	4.9	5.9	4.8	5.5	4.8
pb_F	4.8	4.8	4.8	4.8	–
TR	100	100	80	75	–
pb_N	0.1	1.1	1.0	1.9	–

Table 4
Asphalt emulsion and bitumen 35/50 properties.

Properties	Standard	Asphalt emulsion	Bitumen 35/50
Sedimentation after 5 days (%)	EN 12847	25.4	–
Particle polarity	EN 1430	Positive	–
Residue on sieving, 0.5 mm sieve (%)	EN 1429	0.0	–
Breaking value (g)	EN 13075-1	210	–
Distillation: Bitumen, m/m (%)	EN 1428	61.5	–
Distillation residue: Penetration, at 25 °C (0.1 mm)	EN 1426	103	40
Softening Temperature (°C)	EN 1427	46.0	51.2

Table 5
Asphalt emulsion initial content.

WM346 %	WM244 %	WM346-C %	WM244-C %
0.1	1.8	1.6	3.1

Table 6
Asphalt emulsion initial content by Eq. (5).

	WM346 %	WM244%	WM346-C %	WM244-C %
TR_b	0.38	0.73	0.38	0.73
pb_R	12.64	6.58	10.11	4.93
E	12.75	2.89	8.64	0.22

Table 7
Asphalt emulsion content used in mix design.

WM346 (%)	WM244 (%)	WM346-C (%)	WM244-C (%)
2.0	1.0	2.0	2.0
3.0	2.0	3.0	–
4.0	3.0	4.0	–

20 °C. Specimens were tested at different ages, namely: 1, 7, 14, 21 and 28 days.

3.2. Water sensitivity

The water sensitivity evaluation is essential when studying asphalt recycled mixtures, since this property is directly related to the behaviour and durability of these materials during the road pavement life. The water sensitivity evaluation was determined by EN 12697-12 standard. Six cylindrical specimens of each asphalt mixture type were compacted with Marshall compaction hammer by applying 50 blows to each side. For each type of mixture three specimens with similar characteristics according to their height and bulk density were assigned in two groups. One of the test groups was conditioned in air (dry group) at 20 °C temperature. The specimens from the other group were immersed in water at 20 °C (wet group) and subjected to vacuum soaking. They were subsequently kept in a 40 °C water bath, for a period of 68–72 h. After conditioning, the specimens were tested to determine the Indirect Tensile Strength (ITS) at a 15 °C temperature, as recommended in EN 13108-20. Then it was calculated each group average value and the Indirect Tensile Strength Ratio (ITSR), which corresponds to the ratio between the ITS of the wet group (ITS_w) and the dry group (ITS_d) of specimens, was calculated. In the present study, the indirect tensile test was carried out according to EN 12697-23 standard, after the specimens volumetric characterization.

3.3. Permanent deformations

Permanent deformations were determined by wheel-tracking test, according to EN 12697-22 standard, small size device, procedure B in air. The specimens submitted for testing have a 50 mm thickness. WM244 and WM244-C mixtures samples were obtained with the roller compactor equipment while for the other warm mixtures and the conventional HMA specimens were obtained by a vibratory compactor. Before testing, the specimens were pre-heated at a 45 °C temperature according to EN 13108-20 standard.

This device consisted of a loaded wheel that repeatedly passed over the test specimen. The load applied was 700 N at a frequency of 26.5 ± 1.0 load cycles/minute. The test ended after 10,000 cycles or until the deformation depth reached 20 mm. The main parameters obtained from this test were the Wheel Tracking Slope in air (WTS_{AIR}), calculated between 5000 and 10,000 cycles and the mean Rut Depth in air (RD_{AIR}). The temperature selected for the test was 45 °C, as being representative of the hot summer days that would influence the resistance to mixtures permanent deformations.

3.4. Fatigue resistance

Fatigue resistance of all studied mixtures was determined using the Four-Point Bending (4 PB) test procedure, according to EN 12697-24 standard. The tests were carried out at 20 °C, using a frequency of 10 Hz and in strain control mode. The equipment used a servo pneumatic actuator and digital data acquisition and control system. The loading system was able to apply a sinusoidal signal repeated at a given frequency. The maximum deformation sustained by each specimen was measured by a LVDT that was located at mid-span of the beam allowing, through the theory of elasticity, the maximum tensile strain determination.

The bituminous mixture fatigue resistance is generally expressed by a relationship between the applied tensile strain (ε) and the number of load repetitions to failure (N) (stiffness reduction to half of its initial value) [24–26] as presented in Eq. (6)

$$\varepsilon = A \times N^{B} \quad (6)$$

where N is the number of cycles; ε is the tensile strain ($\mu\varepsilon$) and A, B are experimentally determined coefficients.

Two important parameters are adopted to represent the bituminous mixture fatigue resistance: N_{100}, which is the cycles number to reach the extension of 100 $\mu\varepsilon$ and ε_6 which is the strain at 10^6 cycles.

The specimens were obtained from slabs compacted with different methods which were later cut into prismatic specimens with the dimensions required for the execution of the 4PB test.

4. Results and discussion

4.1. Indirect Tensile Stiffness Modulus (ITSM) test

Stiffness modulus results correspond to a 5 values average for each different mixture and they are presented in Fig. 2.

The optimum emulsion content was selected according to the mixtures stiffness. As can be seen in Fig. 2, the optimum asphalt emulsion content for WM346 was 3%. For mixture WM346-C it was 2% but to allow full aggregates coating it was decided to use 3%. For mixtures WM244 the optimum asphalt emulsion content was 2%. These optimum asphalt emulsion contents were used in the specimens' preparation to the water sensitivity, permanent deformation and fatigue resistance tests, described in the following sections. The reason why HMA mixture presents higher stiffness values in about 50% relating to the RAP mixtures is due to the used binder (bitumen and emulsion, respectively), to the production temperature and natural aggregates.

4.2. Water sensitivity

The bulk density (EN 12697-6, procedure B) and air voids content (EN 12697-8) of the tested specimens and the water sensitivity test results (EN 12697-12) were presented in Table 8.

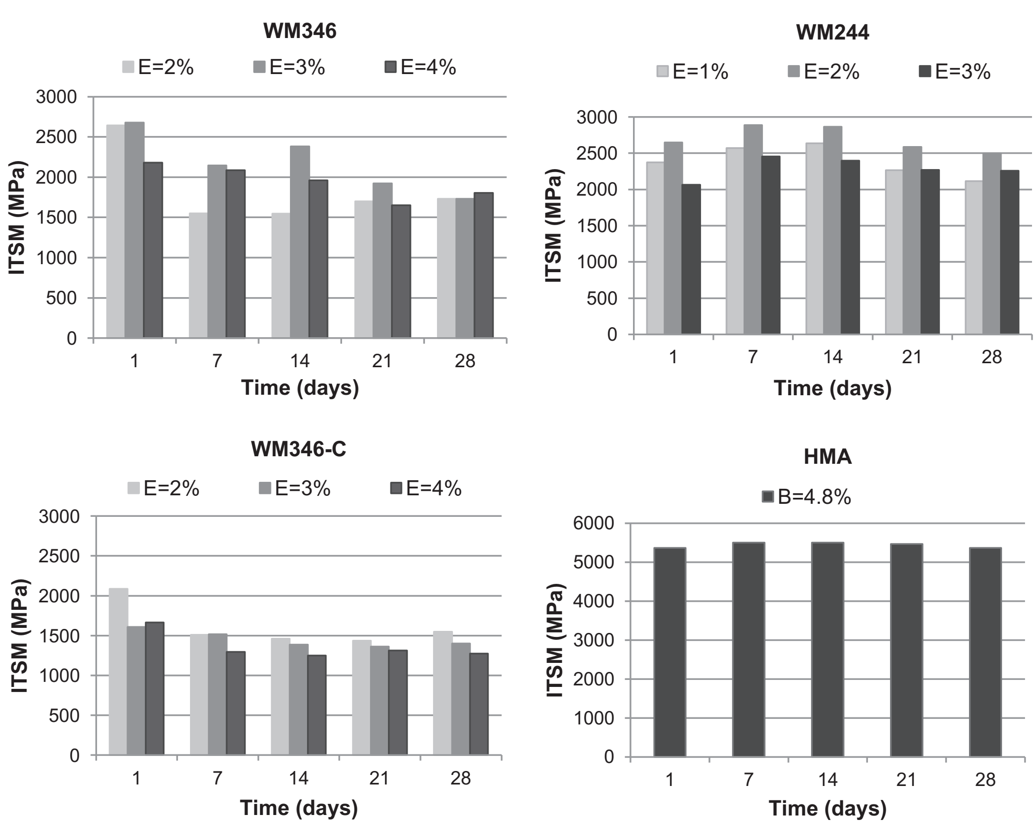

Fig. 2. Stiffness modulus for the studied mixtures.

Table 8
Bulk densities, air voids content and water sensitivity.

Properties	WM346	WM244	WM244-C	WM346-C	HMA
Bulk density (kg/cm^3)	2433	2410	2405	2213	2402
Air voids content (%)	3.0	2.5	2.0	8.0	3.0
ITSR (%)	93	100	91	68	89

Table 9
Wheel tracking test results.

Mixture	WTS_{AIR} ($mm/10^3$ cycles)	RD_{AIR} (mm)
WM346	0.37	4.72
WM244	0.31	7.48
WM346-C	0.31	3.15
WM244-C	0.25	5.46
HMA	0.13	2.44

Concerning the volumetric properties, the mixture with natural aggregates correction (WM346-C) presented higher air voids content than that of 100% RAP mixtures influencing the ITSR results. WM346 and HMA showed values within the Portuguese limits specifications (3–6%).

Overall, it was found that all mixtures have good water sensitivity results, although the warm mixtures with natural aggregates were more sensitive to the water presence. The remaining mixtures with 100% RAP had a better performance.

4.3. Permanent deformations

The permanent deformations results of each studied mixture and the conventional mixture produced with bitumen 35/50 result were presented in Fig. 3 and Table 9.

Comparing the 100% RAP mixtures and mixtures with natural aggregates it was verified that these showed better results than the mixtures with 100% RAP for the same asphalt emulsion content. The warm mixtures WM346 and WM346-C showed a better behaviour due to the old bitumen stiffness, reducing the permanent deformations.

4.4. Fatigue resistance

Fatigue testing results for warm recycled mixtures with 100% RAP (WM244 and WM346) and mixtures with grading correction (WM244-C and WM346-C) are presented in Fig. 4 and Table 10 together with the results for the conventional Hot Mix Asphalt (HMA).

The fatigue resistance of warm recycled mixtures with 100% RAP had the best results, being similar to those obtained for the HMA. The bitumen amount in the total recycled mixtures allowed the increase of their fatigue resistance. According to some authors

Table 10
Fatigue law coefficients obtained for different mixtures.

Mixture	A	B	N_{100} (cycles)	ε_6 ($\mu\varepsilon$)
WM346	1953	−0.151	3.53E+08	243
WM244	2397	−0.162	3.28E+08	256
WM346-C	3759	−0.230	7.05E+06	157
WM244-C	1746	−0.152	1.49E+08	214
HMA	1589	−0.139	4.38E+08	233

[6], this could result also from the fines high content which are presented in the RAP due to the bituminous mixture milling from the road pavement. This aspect was further strengthened in mixtures with natural aggregates, in which it was verified a decrease in fatigue resistance.

5. Conclusions

Low consumptions and emissions during production and laying and high recycling rate (100%) are the most important benefits of the WMRAs presented in this study. At the same time, when RAP high proportions are used, this material characterization is relevant in the mix design process, especially in the asphalt emulsion amount considered.

The simple mix design method based on ITSM tests was here used with success. Nevertheless, the amount of tests carried out and the mixtures number studied were still not enough to assess the viability of using the method as a standard procedure for warm mixtures with high RAP recycling rates.

The WMRA comparative study with a conventional HMA using the same testing machine and test method was justified in order to support the pavement engineers when choosing between alterna-

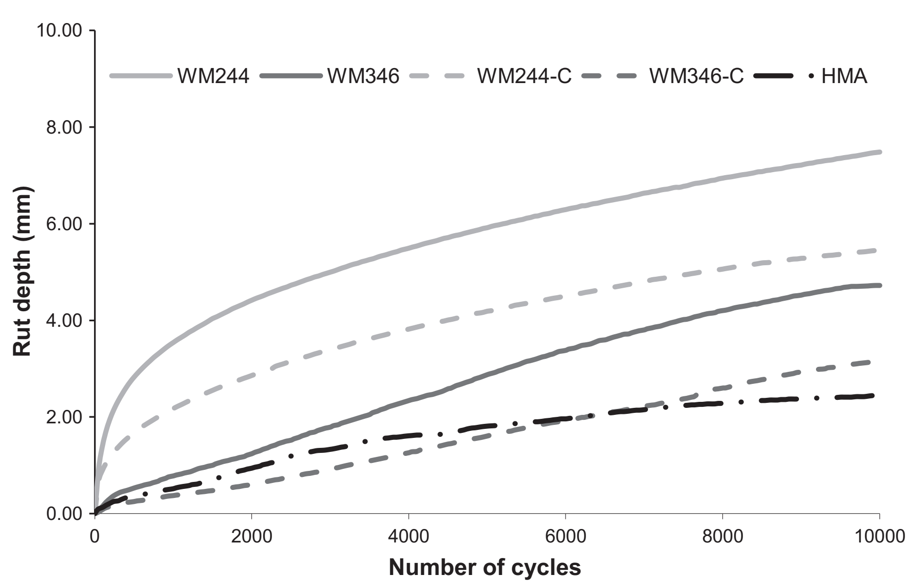

Fig. 3. Wheel tracking test results obtained for the studied mixtures.

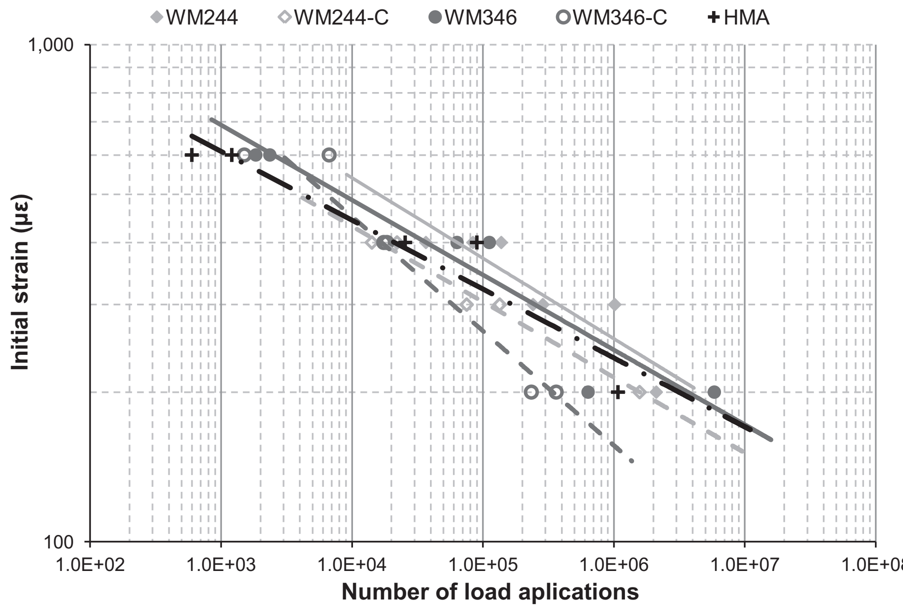

Fig. 4. Fatigue test results obtained for the studied mixtures.

tive solutions of pavement rehabilitation: i.e. recycling or overlaying with new bituminous mixtures.

The WMRA overall laboratory performance compared to the conventional HMA showed better results in terms of water sensitivity, while fatigue resistance was proven to be similar. In terms of rutting resistance mixture WM346-C was the most stable material. It should be kept in mind that the adopted RAP contained very hard bitumen influencing the wheel tracking test result that provided similar results to those of a conventional hot mixture.

Knowing the environmental advantages of using lower temperatures for the asphalt mixtures production and, simultaneously, the recycled aggregates use such as RAPs, will require the standards development that allow these technologies correct assessment. Thus, it would serve as an incentive for its use in road pavement works by the state, local governments and industry.

References

[1] EAPA, Asphalt the 100% Recyclable Construction Product, European Asphalt Pavement Association, 2014. June 2014.
[2] EAPA, Arguments to Stimulate the Government to Promote Asphalt Reuse and Recycling, European Asphalt Pavement Association, 2008. 21 May 2008.
[3] EAPA, Asphalt in Figures 2013, European Asphalt Pavement Association, 2013. Version 27 November 2014.
[4] C. Celauro, C. Bernardo, B. Gabriele, Production of innovative, recycled and high-performance asphalt for road pavements, Resour. Conserv. Recycl. 54 (6) (2010) 337–347, http://dx.doi.org/10.1016/j.resconrec.2009.08.009.
[5] M. Dinis-Almeida, J.P. Castro Gomes, M.L. Antunes, L. Vieira, Mix design and performance of warm-mix recycled asphalt, Proc. ICE Construct. Mater. (2013), http://dx.doi.org/10.1680/coma.12.00054.
[6] H.M.R.D. Silva, J.R.M. Oliveira, C.M.G. Jesus, Are totally recycled hot mix asphalts a sustainable alternative for road paving?, Resour Conserv. Recycl. 60 (2012) 38–48, http://dx.doi.org/10.1016/j.resconrec.2011.11.013.
[7] M. Tusar, E. Nielsen, F. Batista, M.L. Antunes, K. Mollenhauer, S. Vansteenkiste, I. Carswell, D. Kuttah, L. Viman, A. Waldemarson, Optimization of Reclaimed Asphalt in Asphalt Plant Mixing. Re-Road End of Life Strategies of Asphalt Pavements, European Commission DG Research, 2012.
[8] E. Sanchez-Alonso, A. Vega-Zamanillo, D. Castro-Fresno, M. DelRio-Prat, Evaluation of compatibility and mechanical properties of bituminous mixes with warm additives, Constr. Build. Mater. 25 (5) (2011) 2304–2311, http://dx.doi.org/10.1016/j.conbuildmat.2010.11.024.
[9] H. Silva, J. Oliveira, J. Peralta, S. Zoorob, Optimization of warm mix asphalts using different blends of binders and synthetic paraffin wax contents, Constr. Build. Mater. 24 (9) (2010) 1621–1631, http://dx.doi.org/10.1016/j.conbuildmat.2010.02.030.
[10] M.F.C. van de Ven, K.J. Jenkins, J.L.M. Voskuilen, R. Van Den Beemt, Development of (half-) warm foamed bitumen mixes: state of the art, Int. J. Pavement Eng. 8 (2) (2007) 163–175.
[11] B. Kheradmand, R. Muniandy, L. Hua, R. Yunus, A. Solouki, An overview of the emerging warm mix asphalt technology, Int. J. Pavement Eng. (2013), http://dx.doi.org/10.1080/10298436.2013.839791.
[12] J. Oliveira, H. Silva, L. Abreu, J. Gonzalez-Leon, The role of a surfactant based additive on the production of recycled warm mix asphalts – less is more, Construct. Build. Mater. 35 (2012) 693–700, http://dx.doi.org/10.1016/j.conbuildmat.2012.04.141.
[13] B. Prowell, G. Hurley, B. Frank (Eds.), Warm-mix asphalt: best practices, second ed., Quality Improvement Series 125, National Asphalt Pavement Association, Lanham, MD, 2011.
[14] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm mix asphalt: an overview, J. Cleaner Product. 24 (2012) 76–84, http://dx.doi.org/10.1016/j.jclepro.2011.11.053.
[15] A. Vaitkus, V. Vorobjovas, L. Ziliut, The Research on the Use of Warm Mix Asphalt for Asphalt Pavement Structures, Road Department, Vilnius Gediminas Technical University, Vilnius, Lithuania, 2009.
[16] M.M.A. Aziz, M.R. Hainin, H. Yaacob, S.M. Feizabadi, M. Shokri, M.N.M. Warid, Performance of warm-mix asphalt in the highway industry, Mater. Res. Innovations 18 (S6) (2014), http://dx.doi.org/10.1179/1432891714Z.000000000965. S6-245–S6-249.
[17] EAPA, The Use of Warm Mix Asphalt, European Asphalt Pavement Association, 2014. October 2014.
[18] M. Dinis-Almeida, J.P. Castro Gomes, M.L. Antunes, Mix design considerations for warm mix recycled asphalt with bitumen emulsion, Constr. Build. Mater. 28 (2012) 687–693, http://dx.doi.org/10.1016/j.conbuildmat.2011.10.053.
[19] Estradas de Portugal (Ed.), Caderno de Encargos Tipo Obra, Vol. V:03 – Pavimentação – Cap. 14. 03 – Características dos Materiais (janeiro), Estradas de Portugal, S.A., 2012 (in Portuguese).
[20] Asphalt Institute (Ed.), Superpave Mix Design, Superpave Series N° 2 (SP-2), 1997.
[21] S. Al-Busaltan, H. Nageim, W. Atherton, G. Sharples, Green bituminous asphalt relevant for highway and airfield pavement, Construct. Build. Mater. 31 (2012) 243–250, http://dx.doi.org/10.1016/j.conbuildmat.2011.12.065.
[22] H. Nageim, S. Al-Busaltan, W. Atherton, G. Sharples, A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials, Constr. Build. Mater. 36 (2012) 743–748, http://dx.doi.org/10.1016/j.conbuildmat.2012.06.032.
[23] J. Neves, A.G. Correia (Eds.), Evaluation of the stiffness modulus of bituminous mixtures using laboratory tests (NAT) validate by field back-analysis, International Conference on the Bearing Capacity of Roads, Railways and Airfields, 7, Trondheim, Norway, 2005.
[24] G. Dondi, M. Pettinari, C. Sangiorgi, S.E. Zoorob, Traditional and dissipated energy approaches to compare the 2PB and 4PB flexural methodologies on a warm mix asphalt, Constr. Build. Mater. 47 (2013) 833–839, http://dx.doi.org/10.1016/j.conbuildmat.2013.05.091.
[25] G. Dondi, P. Tataranni, M. Pettinari, C. Sangiorgi, A. Simone, V. Vignali, Crumb rubber in cold recycled bituminous mixes: comparison between traditional crumb rubber and cryogenic crumb rubber, Constr. Build. Mater. 68 (2014) 370–375, http://dx.doi.org/10.1016/j.conbuildmat.2014.06.093.
[26] M. Pettinari, G. Dondi, C. Sangiorgi, O. Hededal, The effect of cryogenic crumb rubber in cold recycled mixes for road pavements, Constr. Build. Mater. 63 (2014) 249–256, http://dx.doi.org/10.1016/j.conbuildmat.2014.04.060.