Journal of Geotechnical and Transportation Engineering
Volume 4 | Issue 1
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Received 4/20/2018 Accepted 6/1/2018
Published 7/1/2018
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Using of Circular Road Simulator to Evaluate Performance of Asphalt Mixtures made of Industrial By-Products

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Abstract

It is well known that the use of by-products (recycled), instead of natural materials help toward more environmentally friendly roads by easing landfill pressures and reducing demand of extraction. Correspondingly, this paper deals with evaluating the mechanical performance of new developed hot mix asphalt (HMA) mixtures made of alternative materials (up to 98% industrial waste materials). The paper sheds light on the long-term performance of the new developed mixtures using the accelerated load testing facilities available at VTI (the Swedish National Road and Transport Research Institute). The materials, methods and results given in this article are part of ALTERPAVE European -project findings. In this project, different types of industrial by-products, namely, reclaimed asphalt pavement (RAP), foundry sand and steel slag) have been used in different fractions to find the composition of the best asphalt mixtures made mainly of industrial wastes that can substitute the asphalt mixtures made of natural aggregates. Using the circular road simulator (CRS), twenty- eight asphalt slabs were prepared using natural and industrial by-products and tested under different testing conditions. The CRS test has been used to assess the surface deterioration, wear and the changes in macrotextures of the tested asphalt slabs under wheel loading in dry or wet conditions and under different testing temperatures to simulate summer and winter seasons. In addition, studless and studded tires have been used to traffic the asphalt slabs during the CRS testing to simulate the current roads conditions in different European countries. The test results demonstrated that by controlling the homogeneity of recycled material and by using rejuvenators of suitable quality and quantity, it is possible to obtain paving mixtures with high content of recycled materials that can satisfactory substitute the conventional asphalt mixtures made of natural materials.

Keywords: Accelerated load testing; Foundry sand; Hot mix asphalt; Reclaimed asphalt pavement; Steel slag.

1. Introduction

It is well known that the construction and maintenance of European roads consume large amounts of quarried aggregates. Based on European Aggregates Association annual review [1], the European aggregates industry covers a demand of 2.7 billion tonnes of aggregates produced every year. About 10% of the produced aggregates from the European aggregates industry goes to asphalt products. According to European Aggregates Association annual review 2017, every new 1 km of roadway requires up to 30,000 tonnes of aggregates. The use of by-products (recycled), instead of primary (natural), materials help easing landfill pressures and reducing demand of extraction. In spite of the fact that one of the major challenges of pavement engineering world-wide is to meet the ever-increasing demand of economic and physical resources related to construction by means of environmentally sustainable technologies, concerns over inferior road performance have hindered the widespread use of secondary aggregates in such applications. This is especially the case in surface layers of asphalt pavements that may represent a value application for recycled solid waste materials [2]. In such a context, several studies have been focused on using different types of road paving technologies based on the use of asphalt mixtures containing recycled materials. A variety of recyclable materials in asphalt mixtures have been used and studied such as rubber from end-of-life tires [3, 4,5 and 6], reclaimed asphalt pavement [7, 8, 9, 10 and 11], waste glass [12], steel slag [13, 14 and 15], plastic [16 and 17], by-product gypsum [18 and 19], asphalt roofing shingles [20, 21, 22 and 23] and others.

The shortage in natural aggregate is not the only problem which was behind the increase in the cost of asphalt mixtures, but the shortage and high costs of asphalt and polymers have encouraged the engineers to utilize alternative bio-oils (derived from bio-based raw materials) to be used as alternative oils in hot mix asphalt manufacturing [24].

In fact, field studies have indicated that asphalt mixtures made of alternative aggregate and bio binders should be studied further in terms of long-term performance to evaluate their suitability to substitute conventional asphalt materials [25 and 26].

Correspondingly, this paper deals with evaluating the mechanical performance of new developed hot mix asphalt (HMA) mixtures made of alternative materials (up to 98% industrial waste materials) using the VTI's circular road simulator. The materials, methods and results given in this article are part of ALTERPAVE European -project findings. After characterizing all the natural and the recycled materials to be used in manufacturing ALTERPAVE asphalt mixtures, the aggregate and asphalt binder compositions of different suggested hot mix asphalt (HMA) mixtures have been developed in asphalt laboratory at University of Cantabria (UC).

Particularly, this paper focuses on the findings gathered from an accelerated circular road simulator test. The asphalt mixtures previously validated at lab scale (at University of Cantabria) have been tested using the VTI's circular road simulator to determine the surface pavement deformations, wear and texture depending on the different existing climate conditions (wet/dry environments, high medium or low temperatures, etc.) and on the possible use of studded winter tires.

2. Material characterization

The types and properties of the materials used to prepare the asphalt mixtures for the CRS tests are presented in the following paragraphs;

2. 1. Asphalt binder

A conventional Swedish 50/70 binder and polymer modified binder PMB 45/80 – 65 have been used to prepare asphalt specimens for CRS test at VTI. The properties of the conventional binder and the polymer modified binder used in preparing the asphalt mixtures for the CRS test are illustrated in Tables 1 and 2 respectively.

Table 1: Properties of conventional binder 50/70 used to prepare asphalt specimens for CRS test at VTI.

	Result	Standard
Softening point (°C)	50.4	EN 1427 [27]
Penetration at 25°C (0.1 mm)	59	EN 1426 [28]

Table 2: Properties of Polymer modified binder PMB 45 / 80 – 65 used to prepare asphalt slabs for CRS test at VTI.

	Result	Standard
Softening point (°C)	64.5	EN 1427 [27]
Penetration at 25°C (0.1 mm)	62	EN 1426 [28]

2. 2. Aggregates

The required quantities of each type of aggregate used for the CRS test have been sent to VTI from UC in Spain as described below. In ALTERPAVE project, it has been recommended to fulfil the standard grading limits (in volume percentage) considering, first of all, the RAP gradation, secondly, the by-products gradation and lastly the natural aggregates gradation. The approach considered in the ALTERPAVE project entails that the alternative and natural aggregate should comply with the same technical requirements. The requirements that are demanded for the coarse and fine aggregate vary with the specific country in Europe, more details about the technical and Environmental requirements on the materials used in this project is given in Kuttah et al. [29].

2. 2. 1. Natural aggregates

The Spanish Ophitic aggregate has been used as the course aggregate in some mixtures, while the limestone aggregate has been used as the fine aggregate and filler. Note that the percentage of natural aggregates in some alternative mixtures were less than 2%.

2. 2. 2. By-Products aggregate

Different types and percentages of alternative materials have been used in preparing the asphalt samples for the CRS tests including reclaimed asphalt pavement (RAP), electric arc furnace (EAF) slag, basic oxygen furnace (BOF) slag and foundry sand.

2. 3. Rejuvenators

Rejuvenators are used to mitigate the effect of the changes in chemical and physical properties of the asphalt binder due to in-service aging and restore some of the properties of the aged binder in the RAP. The maximum RAP percentage adopted in this study was about 35%, correspondingly, it has been decided to use rejuvenators in order to reinstate the penetration grade of the aged asphalt binder to the target penetration grade of the new neat asphalt binder for a given application.
Four types of rejuvenators used as additives were examined in ALTERPAVE projects, two of them has been selected to be used for the mixtures prepared for the circular road simulator test at VTI. These two rejuvenators are bio-oils (plant-based), namely RS and RVE.

3. Mixtures summary

Based on the laboratory tests carried out at UC and discussed in detail in Kuttah et. al. [29], Tables 3 and 4 below illustrates a summary of the composition of sixteen asphalt mix designs developed with the recommended percentages of binder contents.

Table 3: A summary of aggregates composition of asphalt mixtures

Mix. No.	EAF slag (%)	BOF slag (%)	Ophiti Agg.[1] (%)	RAP (%)	F-sand[2] (%)	Lime - stone (%)	Rejuv.[3]
M01	50.5	-	-	35.5	12.1	1.9	RS
M02	60.5	-	-	21.7	14.9	2.9	RS
M03	-	50.1	-	35.3	12.8	1.8	RS
M04	50.1	-	-	35.3	-	14.6	RS
M05	59.9	-	-	21.5	-	18.6	RS
M06	-	-	44.10	39.5	-	16.4	RS
M07 old	50.5	-	-	35.5	12.1	1.9	RVE
M07 new	50.5	-	-	35.5	12.1	1.9	RVE
M08	60.5	-	-	21.7	14.9	2.9	RVE
M09	-	50.1	-	35.3	12.8	1.8	RVE
M10	50.1	-	-	35.3	-	14.6	RVE
M11	59.9	-	-	21.5	-	18.6	RVE
M12	-	-	44.10	39.5	-	16.4	RVE
M13	50.5	-	-	35.5	12.1	1.9	-
M14	76.3	-	-	-	19.2	4.5	-
R01	-	-	66.50	-	-	33.5	-
R02	-	-	66.50	-	-	33.5	-

[1] Ophitic aggregate
[2] Foundry sand
[3] Rejuvenator

Table 4: A summary of binder characteristics of the asphalt mixtures

Mix. No.	Neat binder per weight (%) EN 12697-39 [30]	RAP binder per weight (%)	Total binder per weight (%) EN12697-39 [30]	Neat binder per volume (%)	RAP binder per volume (%)	Total binder per volume (%)	Bulk density (Mg/m^3) EN 12697- 6 [31]
M01	3.2	1.4	4.6	8.6	3.9	12.5	2.805
M02	3.3	0.9	4.2	9.1	2.4	11.6	2.848
M03	3.4	1.4	4.8	8.4	3.6	12.0	2.59
M04	2.4	1.4	3.8	6.3	3.9	10.2	2.775
M05	2.9	0.9	3.8	8.1	2.4	10.5	2.87
M06	2.2	1.6	3.8	5.2	3.9	9.1	2.481
M07 old	3.2	1.4	4.6	8.4	3.9	12.3	2.649
M07 new	3.2	1.4	4.6	8.4	3.9	12.3	2.759
M08	3.8	0.9	4.7	10.5	2.4	12.9	2.84
M09	3.9	1.4	5.3	9.7	3.6	13.2	2.582
M10	2.4	1.4	3.8	6.3	3.9	10.2	2.777
M11	2.7	0.9	3.6	7.5	2.4	9.9	2.859
M12	3.0	1.6	4.6	7.2	3.9	11.0	2.482
M13	3.3	1.4	4.7	8.9	3.9	12.8	2.802
M14	4.5	0.0	4.5	13.0	0.0	13.0	2.983
R01	4.3	0.0	4.3	10.5	0.0	10.5	2.522
R02	4.3	0.0	4.3	10.4	0.0	10.4	2.498

Note that the aggregate composition of the mixtures from M01 to M06 is the same as for mixtures from M07 to M12, but the only difference is the type of the rejuvenator used.
Since it is possible to test only twenty-eight asphalt slabs simultaneously using the VTI's circular road simulator, fourteen asphalt mixtures have been chosen among the mixtures given in Table 3, namely, M01, M02, M03, M04, M05, M06, M07, M08, M010, M011, M012, M013, Reference 01, and Reference 02. Two identical asphalt slabs were prepared for each chosen mixture and tested using the VTI's CRS.

4. The circular road simulator test

Under controlled conditions, the CRS implements an accelerated test that simulate the effect of traffic on pre- manufactured slabs of different types of roads materials (specially asphalt coatings) to record the corresponding wear, deformations and texture developments under different loading and environmental conditions, see Figure1. Furthermore, the CRS test has been used to link the laboratory test results to the field observations and to assess the impacts of new tires, tire inflation pressures, load limits, etc on the asphalt mixtures or other road materials.
The VTI's CRS has six axles (of which four wheels are in operation) running on a circular test track. A separate DC motor is driving each wheel and the speed can reach up to 70 km h-1. The diameter of the track is 5.25 m, giving an average track length of about sixteen meters. The maximum width of the track is about 0.85 m. The track consists of twenty-eight test slabs that can be manufactured in the Lab. Before the test stars, the axles are lowered down, and the desired axle loads are achieved. Moreover, the temperature and relative humidity in the simulator hall can be controlled via an internal air cooling system. The temperature in the hall can be varied from -5 to + 40 ° C and during the test, the samples surfaces can be sprinkled with water. The measurements of cross sections made with a laser profile measurement beam that can provide more than 400 data points per slab with 0.01 mm accuracy. For each tested slab, three cross sectional profiles are usually measured.

In addition, one of the wheels is provided with texture development measurement indicators to measure the mean profile depth (MPD) along the track.
As highlighted previously, a total of fourteenth asphalt mixtures have been tested at VTI testing facility. Twelve of these asphalt mixtures contained industrial wastes in different compositions and quantities, while the other two mixtures were made totally of natural materials for comparison purposes.
In this study, the CRS test has been used to assess the surface deterioration, wear and the changes in macrotextures of the tested asphalt slabs under wheel loading in dry or wet conditions and under different testing temperatures to simulate summer and winter seasons. In addition, studless and studded tires have been used to traffic the asphalt slabs during the CRS testing in order to simulate the current roads conditions in different European countries since many countries permit the use of studded tires during winter for safer winter driving; e.g. Sweden, Finland, Denmark, Norway, France, Ireland, and other countries.

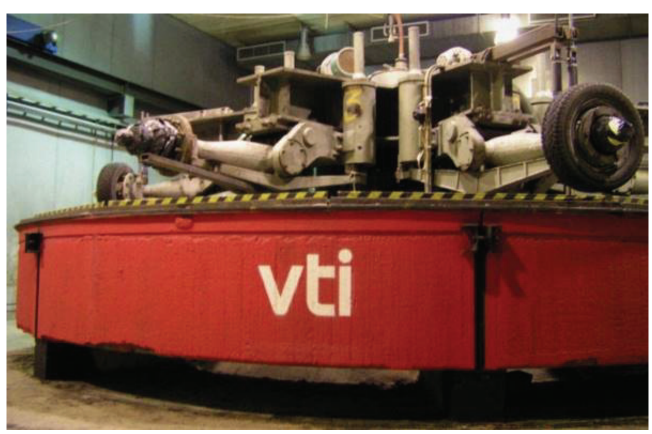

Fig. 1: The VTI's Circular Road Simulator, photo after VTI Image Database, 2016

Table 5: The CRS Testing Program.

The phase nummber	Phase period (Duration)	The total number of revolutions in each phase	The measurements have been carried out at the end of the following accumelative number of	Type of the measurment		Type of the tire	Testing temperature (C°)	Wheel Speed (km/h)	Testing with or without sprinkling of water
				Profile	*Texture*				
One	Very short phase (Pre-loading)	2000	100	Yes	Yes	Studless (winter tire)	0	30	without water
One			2000	Yes	Yes				
Two	Long phase	168000	40000	Yes	Yes	Studless (summer tire)	30	60	without water
Two			122000	Yes	Yes				
Two			170000	Yes	Yes				
Three	Medium-Long phase	120000	210000	Yes	No	Studless (winter tire)	Started with -2 (the test temperature should not exceed +2 during the test)	70	Daily, the test is started in the morning at dry conditions for the first few revolutions. Afterward the water is added and the test proceeds . At the end of the day, the water is discharged. This procedure was repeated for 5 to 6 consecutive days.
Three			290000	Yes	Yes				
Four	Medium-Long phase	90 000- 120000	380000	Yes	Yes	Studded tire	Started with -2 (the test temperature should not exceed +2 during the test)	70	The same as for phase three

4. 1. General test preparation

The CRS has been carried out according to the testing program described in Table 5. The selected fourteen asphalt mixtures have been prepared in the pavement technology laboratory at VTI under controlled conditions following the adopted mix designs described in Table 3 above.

During the manufacturing of the asphalt mixtures the natural and alternative aggregates (except the RAP) were heated up to 185°C for 5.5 hours approximately. The RAP was heated up to 110°C for a maximum time of 2 hours. When the RAP had been taken out of the oven, the rejuvenator was poured above it with a little sprayer directly in the mixer drum. The asphalt binder was heated up to 150°C for approximately 3 hours and then added to the mixture. The mixer drum was previously heated at 150°C (the same temperature of the asphalt binder). Then all the aggregates and asphalt binder mixed for about 5 minutes, although the time depends on the quantity and the type of sample to be manufactured.

After preparing the fourteen selected mix designs, two asphalt slabs of each mixture have been prepared and compacted in rectangular steel slabs each having a dimension of (750 * 480* 40) mm. The preparation of each asphalt plate has been started by heating the asphalt mixtures to the desired temperature in a huge oven at VTI's facility and placing the desired quantity of the asphalt mixture under consideration in the middle of the steel mould and then spread the asphalt mixture to fill in the steel mould.

Then, a roller compactor has been used to compact and force all the desired asphalt mixture inside the steel plate, see Fig.2 A.

After removing each asphalt plate from its mould, the asphalt slabs have been sawed to trapezoidal shapes to fit the circular path of the CRS and then dried, see Fig 2 B. Then, all the twenty-eight asphalt slabs glued on the circular track by a special glue. Asphalt slabs with expected similar wear resistance have been placed side by side to reduce the expected differences in surfaces' levels between the adjacent asphalt slabs during testing and hence minimize the jumping of the machines wheels during operation, see Fig.2 C. The joints between the slabs have been sealed with a sealing mixture.

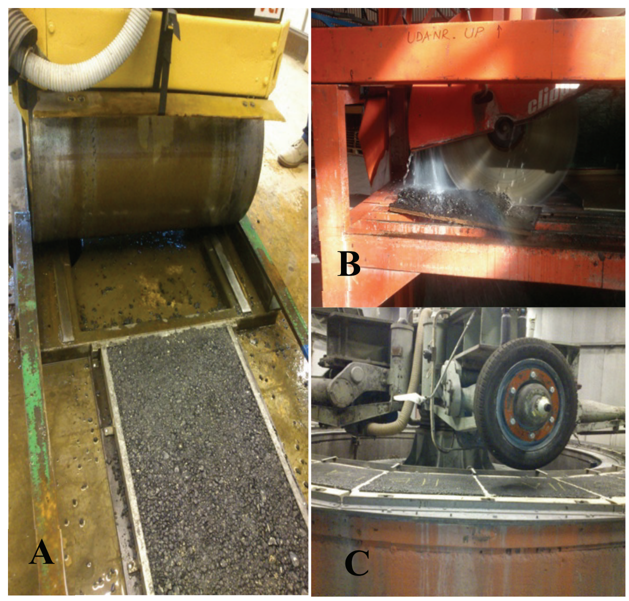

Fig. 2: CRS test preparation, A- compacting the asphalt slabs, B- sawing the asphalt slaps, C- fitting and gluing of the asphalt slabs on the circular track of the CRS

4. 2. Measurements related to CRS test

Surface deformations, wear and macrotexture measurements have been taken at various traffic intervals during the CRS test according to the schedule given in Table 4.

The surface deformations and wear measurements have been taken by passing a laser beam over three predefined lines on the surface of each tasted asphalt plate fixed on the CRS track. The laser beam measures the deformations along these lines after predetermined traffic intervals. The surface deterioration or wear has been determined as the difference between the profile at zero CRS revolutions and the profile after a predetermined number of CRS revolutions.

The macrotextures of the tested asphalt slabs have been measured in terms of mean profile depth values (MPD) using a laser texture scanner system after predetermined traffic intervals applied using the circular load simulator. According to ISO 13473-2 [32], the pavement macrotexture is characterized by a deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0,63 mm to 50 mm of center wavelengths.
The used device scans the material surface to measure the mean profile depth (MPD) which is defined as the average value of the profile depth over a 100-mm long baseline.

5. Testing results and discussion

The results of the CRS test have been analysed to evaluate the technical performance of the alternative asphalt mixtures as compared to the performance of the control conventional mixtures. As described previously, various measurements have been considered during the accelerated CRS testing. The results corresponding to these measurements are described and discussed below:

5.1. Surface deterioration and wear measurements results

In order to get a good correlation between the number of CRS revolutions and the type of the mixture, the average surface deterioration and wear of each two identical asphalt slabs (i.e. made of the same mix design) has been considered and hence the results have become more correlated to the type of the mix, as presented in Fig.s 3 and 4.
Note that the profile measurements have been carried out more frequently at the beginning of the CRS test and less frequently during the course of the test. The surface deterioration and wear measurements given in this study represent those measured under the wheel only and not for the whole width of the slabs.
Fig. 3 shows the correlation between the type of the asphalt mixture and the corresponding surface deterioration after different CRS traffic intervals up to 290 000 revolutions, during which, the summer and winter conditions in European countries have been simulated using summer and winter friction tiers.
In Fig. 3, the surface deteriorations refer to the difference in the profiles after the polishing phase (at the end of phase 1 after 2000 CRS revolutions) and the profile after a predetermined number of CRS revolutions using studless tires (i.e. to the end of phase 3 at 290000 CRS revolutions).
It can be seen from this figure that in terms of surface deterioration the asphalt slabs of R1 (reference mixture of natural materials) has performed best, but some of the asphalt slabs made of by-products materials, namely mixtures 12 and 7 old, have performed as well as R2 (the other reference mixture). Note that at the end of 290 000 CRS revolutions, the surface deteriorations reported for mixtures 12, 7 old and 1 were only 0.5 mm (or less) higher than the surface deterioration reported for mix R1.
Regarding the ability of the developed asphalt mixture to resist the wear caused by studded tires used in Nordic European countries during winter, Fig. 4 illustrates the effect of the number of CRS revolutions with studded tires on the wear characteristics of the different asphalt mixtures. The wear shown in Fig. 4 refers to the changes in profile and the corresponding deterioration took place only during the fourth phase of the CRS traffic loading (i.e. between 290 000 and 380 000 CRS revolutions) where studded tires were used.

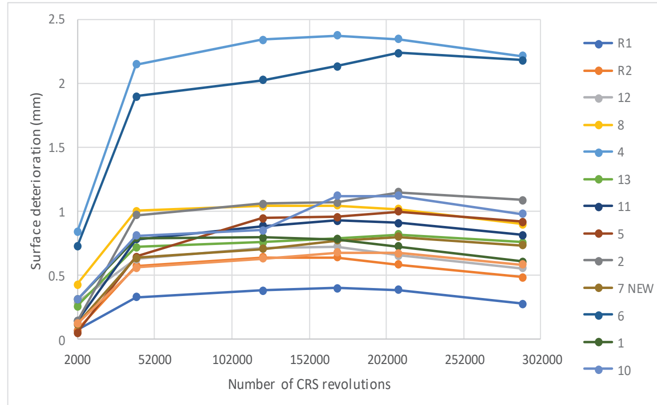

Fig. 3: Effect of CRS traffic on the surface deterioration characteristics of the tested asphalt mixtures.

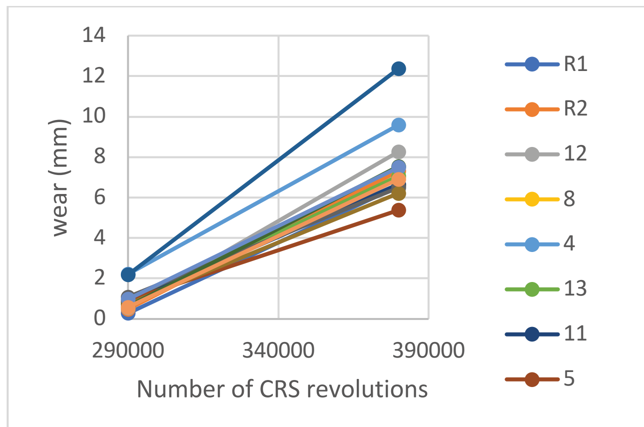

Fig. 4: Effect of CRS traffic on the wear characteristics of the tested asphalt mixtures.

It can be seen from this Fig. 4 that asphalt mixtures made of by-products (industrial wastes) showed very good resistance against loading with studded tires and some of them performed even better than the reference asphalt mixtures made totally of natural materials. According to Fig. 4, the best performed mixtures are mix 5 followed by mixtures 2, 7 new, 8, 11, R1, 13, 7old, 10, R2, 1, 4, 12 and 6 in sequence.

5.2. Macrotexture scanning results

The MPD values have been measured on the surfaces of the tested asphalt slabs at the end of 0, 2000, 40000, 122000, 170000, 290000, and 380000 CRS revolutions according to the testing program described previously in Table 4.
To reduce, as much as possible, the effect of RAP and manufacturing characteristics on the MPD values of the two asphalt slabs made of the same mix design and to get a good correlation between the number of CRS revolutions and the type of the mixture, the average MPD values of each two identical asphalt slabs (i.e. made of the same mix design) has been considered and hence the results have become more correlated to the type of the mix.
Fig. 5 shows the correlation between the type of the asphalt mixture and the MPD values after different CRS traffic intervals up to 290 000 revolutions, during which, the summer and winter

conditions in European countries have been simulated using summer and winter friction tiers.

observed that some asphalt mixtures made of high percentages of by-products (namely mixture 5 followed by mixtures 2, 7 new, 8, 11) performed better than the reference asphalt mixtures.

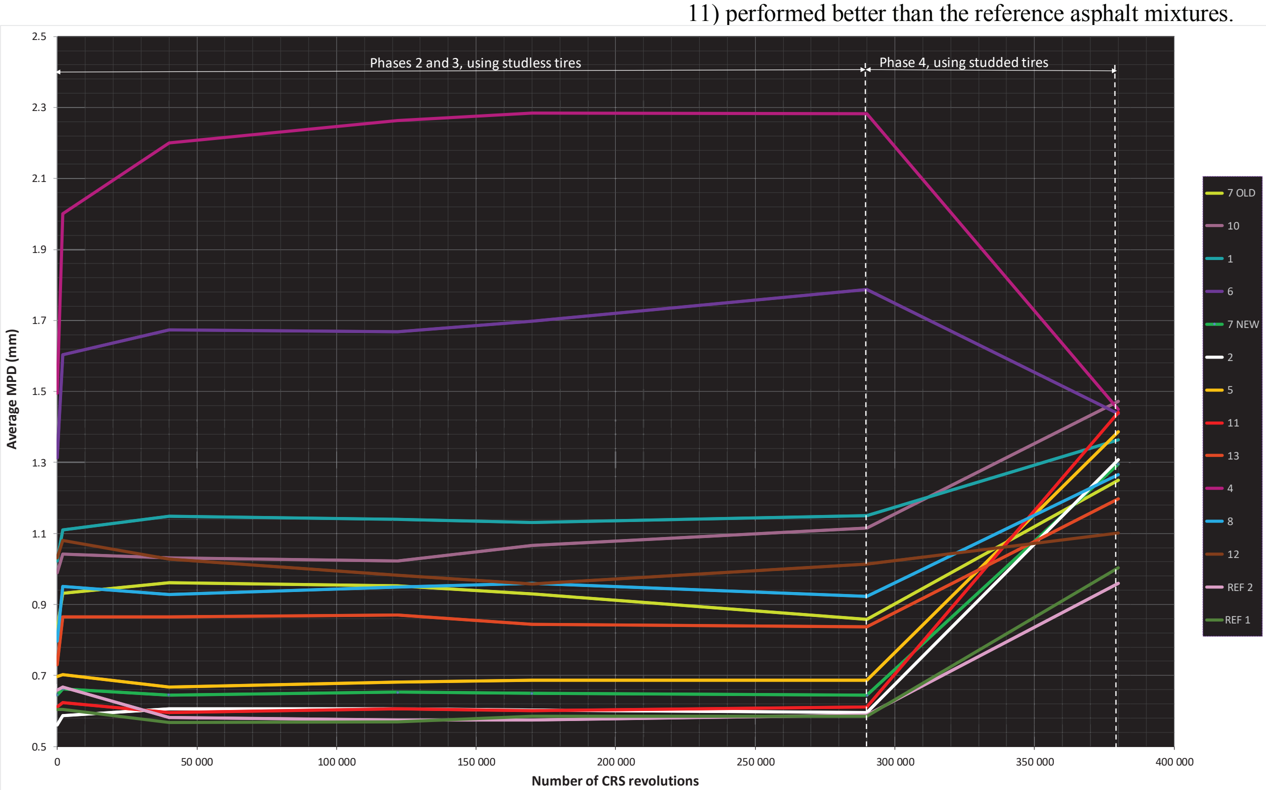

Fig. 3: Correlation between the average MPD values and the number of CRS revolutions for the tested asphalt mixtures.

It can be concluded from Fig. 5, that the changes occurred in the MPD values of the asphalt slabs between 2000 CRS revolutions and 290 CRS 0000 have been lowest for mixtures 2, 7 new, 13, 11, 5, R1 and 1. This means that these mixtures have resisted best the changes in its macrotextures due to trafficking with studless tires based on the average MPD data.
Moreover, the mixtures that have resisted best the changes in their macrotextures under studded tires (usually used during winter in Nordic European Countries) traffic loading between 290000 CRS revolutions and 380 000 revolutions (during the fourth phase), have been considered as the best based on MPD values evaluation. Considering this definition, the best mixtures with minimum changes in their MPD values during the fourth phase of CRS traffic loading have been mixtures 12, 1, 8, 6, 10, 13, R2, 7 old, R1, 7new, 5, 2, 11, 11 and 4 in sequence.

6. Conclusions

It can be concluded from this study that by controlling the homogeneity of recycled material and by using rejuvenators with adequate quality, it is possible to obtain paving mixtures with high content of recycled materials (up to 98%) that can substitute conventional asphalt mixtures made of natural materials.
Based on the CRS test results, it has been noticed that the asphalt slabs of R1 (reference mixture of natural materials) has performed best, but some of the asphalt slabs made of by-products materials, namely mixtures 12 and 7 old, have performed as well as R2 (the other reference mixture). Regarding the ability of the new developed asphalt mixture to resist the wear caused by studded tires used in Nordic European countries during winter, it has been

With respect to the macrotextures properties of the tested asphalt mixtures, it can be concluded that the changes occurred in the MPD values of the asphalt slabs loaded from the beginning of phase 2 to the end of phase 3 (i.e. from 2000 CRS revolutions to 290 0000 CRS revolutions) have been lowest (and hence better) for the Alternative mixtures 2, 7 new, 13, 11, 5, as compared to the reference mixtures R1 and R2. In addition, the mixtures that have resisted best the changes in their macrotextures under studded tires' traffic loading during the last phase (i.e. between 290000 CRS revolutions and 380 000 revolutions) with minimum changes in their MPD values during the fourth phase of CRS traffic loading have been also those made of high percentages of by- products namely mixtures 12, 1, 8, 6, 10, 13.

Acknowledgment

This paper is based on the work done in the framework of ALTERPAVE European project https://www.giteco.unican.es /proyectos/ALTERPAVE/index.htm. The author would like to thank the European Commission for their financial support of ALTERPAVE project-31109806.0006 through the Infravation Funding Program. Furthermore, the author would like to thank ALTERPAVE project partners, namely from University of Cantabria- the project coordinator- (Spain), Western Research Institute (USA), Acciona (Spain) and Impresa Bacchi (Italy) for the effective business communication throughout the project.

List of abbreviations

BOF	Basic oxygen furnace slag
CRS	Circular road simulator
EAF	Electric arc furnace slag
MPD	Main Profile Depth
PMB	Polymer modified asphalt binder
RAP	Reclaimed Asphalt Pavement
UC	University of Cantabria
VTI	The Swedish National Road and Transport Research Institute

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