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Use of Cellulosic Fibres in Double Layer Porous Asphalt

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Abstract**—**Climate change, namely precipitation patterns alteration, has led to extreme conditions such as floods and droughts. In turn, excessive construction has led to the waterproofing of the soil, increasing the surface runoff and decreasing the groundwater recharge capacity. The permeable pavements used in areas with low traffic lead to a decrease in the probability of floods peaks occurrence and the sediments reduction and pollutants transport, ensuring rainwater quality improvement. This study aims to evaluate the porous asphalt performance, developed in the laboratory, with addition of cellulosic fibres. One of the main objectives of cellulosic fibres use is to stop binder drainage, preventing its loss during storage and transport. Comparing to the conventional porous asphalt the cellulosic fibres addition improved the porous asphalt performance. The cellulosic fibres allowed the bitumen content increase, enabling retention and better aggregates coating and, consequently, a greater mixture durability. With this solution, it is intended to develop better practices of resilience and adaptation to the extreme climate changes and respond to the sustainability current demands, through the eco-friendly materials use. The mix design was performed for different size aggregates (with fine aggregates – PA1 and with coarse aggregates – PA2). The percentage influence of the fibres to be used was studied. It was observed that overall, the binder drainage decreases as the cellulose fibres percentage increases. It was found that the PA2 mixture obtained most binder drainage relative to PA1 mixture, irrespective of the fibres percentage used. Subsequently, the performance was evaluated through laboratory tests of indirect tensile stiffness modulus, water sensitivity, permeability and permanent deformation. The stiffness modulus for the two mixtures groups (with and without cellulosic fibres) presented very similar values between them. For the water sensitivity test it was observed that porous asphalt containing more fine aggregates are more susceptible to the water presence than mixtures with coarse aggregates. The porous asphalt with coarse aggregates have more air voids which allow water to pass easily leading to ITSR higher values. In the permeability test was observed that asphalt porous without cellulosic fibres presented had lower permeability than asphalt porous with cellulosic fibres. The resistance to permanent deformation results indicates better behaviour of porous asphalt with cellulosic fibres, verifying a bigger rut depth in porous asphalt without cellulosic fibres. In this study, it was observed that porous asphalt with bitumen higher percentages improve the performance to permanent deformation. This fact was only possible due to the bitumen retention by the cellulosic fibres.

Keywords**—**Binder drainage, cellulosic fibres, permanent deformation, porous asphalt.

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I. Introduction

THE increase of extreme climate and weather events, such as droughts, floods and heating waves, are having serious impacts in natural and human systems around the world [1], causing negative effects on urban water management, rainwater runoff quality and quantity [2]–[4]. The urbanization increase, because of population growth, has led to soil sealing, leading to profound changes in your morphology and occupation type [5]. The soil sealing leads to the areas reduction more favorable to water infiltration [6]. This reduction affects urban hydrological variations by increasing surface runoff, water quality deterioration and pollutant concentration, reducing groundwater recharge [2], [7], [8]. The answers to the adaptation and mitigation of these events include innovation in environmental tested technologies and infrastructure [1]. In this context, the climate change effect has motivated the interest of several researchers in the rainwater management area using permeable pavements [9], [10].

Permeable pavements have been applied in some of the North America and Europe countries, in parking lots and low traffic roads. These pavements allow to reduce peak floods during periods of heavy rainfall, reduce surface runoff and, consequently, the aquaplaning and spray effect, leading to safer driving, reducing the pollutants concentration in the infiltrated waters, attenuating the island effect of urban heat, reduce stress on drainage systems and reduce tire noise.

The use of porous asphalt (PA) in road pavements surface layers is one of the solutions used worldwide to mitigate the climate change effects and population growth. The porous asphalt has been applied as a surface layer over impermeable base layers. However, in the case of permeable pavements, it is a structure totally constituted by draining layers [9], [11]. Their disadvantages are, on the one hand, the load capacity reduction, mainly in permeable pavements, and on the other hand, periodic maintenance due to clogging [12]–[15].

Porous asphalt is produced with low amount of fine aggregates in order to obtain high void content. This leads to a mastic reduced amount causing a poor binding between the aggregates [16]. To solve this situation, it is used polymer modified bitumen with differentiating characteristics, such as elasticity, aging resistance and plastic deformations, good adhesiveness with the aggregates and the low thermal susceptibility [17], [18]. Furthermore, the additives incorporation, such as cellulosic fibres, leads to an increase of mixture binder amount and, consequently, its performance and durability [19], [20]. According to Satyanarayana et al. [21] and Wambua et al. [22], referenced by Ardanuy et al. [23], the most important advantages of these additives, both vegetable and cellulose, are: wide availability at relatively low cost, recycling ability, biodegradability, non-hazardous nature, zero carbon footprint and interesting physical and mechanical properties (low density and well-balanced stiffness, toughness and strength). The use of cellulosic fibres allows the bitumen absorption increase preventing its loss during storage and transport [24].

Thus, this research aim was to evaluate the porous asphalt performance incorporated with cellulosic fibres compared to porous asphalt without cellulosic fibres, named conventional. The mix design was initially performed for the four mixtures studied and the fibres percentage influence to be used. The porous asphalt performance was evaluated through several laboratory tests (indirect tensile stiffness modulus, water sensitivity, permeability and permanent deformation). With this solution, it is intended to develop resilience and adaptation better practices to the increase of extreme climate changes and respond to the sustainability current demands, through the eco-friendly materials use.

II. Porous Asphalt Design

The materials used in the porous asphalt production were initially characterized. Then, the porous asphalt design was made by the Cantabro test.

The surface layer solution proposed in this paper consists of a double porous layer in order to improve surface runoff and reduce the clogging problem [13], [17]. Thus, in practice, it is first applied layer with coarse aggregate, which increases the air voids content, then the layer with fine aggregate that offers greater comfort to the wearer, reduces noise and at the same time has drainage capacity [17].

In this study, two types of porous asphalt were produced, one without cellulosic fibres (with fine aggregates, PA01, and with coarse aggregates, PA02) and another with cellulosic fibres (with fine aggregates, PA1 and with coarse aggregates, PA2).

A. Aggregates Particles' Size Distribution

This research was developed with granitic natural aggregates, using different fractions (stone dust, gravel 5/10 and 5/15). All mixtures incorporated hydraulic lime. The aggregates particle size distribution was made according to the EN 933-1 standard, by sieving method. Two different grading envelopes were adopted. The PA 12.5 grading envelope was used for the mixture with coarse aggregates, according to the Portuguese Road Administration specifications [25]. Since these specifications do not include any other envelope for porous asphalt, PA 8 grading envelope was adopted for the mixture with fine aggregates, defined in the Swiss SN 640 431-7NA and 430a standards. Regarding the grading envelopes adopted, Table I shows the aggregates particles size distributions.

B. Binder

The binder used in the porous asphalt production was PMB 45/80 Polymer Modified Bitumen, traded with the name of Elaster BM-3b, by CEPSA Portuguesa Petróleos, SA. The recommended temperatures range for the mixing is between 155 to 165 °C and the compacting temperature is between 150 to 160 °C. The bitumen characterization is presented in Table II.

TABLE I
AGGREGATES PARTICLE SIZE DISTRIBUTION

Sieve size (mm)	% Passing		
	Stone dust	5/10 Gravel	5/15 Gravel
16	100	100	100
14	100	100	98
12.5	100	100	95
10	100	97	77
4	100	17	6
2	85	3	3
1	63	1	1
0.5	44	1	1
0.125	14	0	0
0.063	5	0	0

TABLE II
PMB 45/80 BITUMEN PROPERTIES

Properties	Standard	PMB 45/80 Bitumen
Penetration 25 ºC, 100g, 5seg	EN 1426	53 dm
Softening point	EN 1427	63.2 ºC
Elastic recovery	EN 13398	70 %

C. Additive

The additive used in porous asphalt was the cellulosic fibres. These are presented as granules made of natural cellulose fibres with bitumen mixture, traded with the name of Viatop Premium by JRS, J. Rettenmaier & Söhne. Viatop Premium is a pelletized blend of 90 % by weight of ARBOCEL ZZ 8/1 and 10 % by 50/70 bitumen weight. The fibres bituminous coating guarantees a quick and complete dispersion in the mixture having a stabilizing effect due to a dense three-dimensional fibre net. Since the porous asphalt has a structure with few fines and, consequently, a smaller contact surface between the coarse aggregates, the cellulosic fibres use aims to increase the amount of mixture bitumen without checking drainage. These allow, on the one hand, the bituminous binder retention and, on the other hand, help the aggregates coating, meaning the bituminous layer formation with constant thickness. Thus, cellulosic fibres avoid the mastic efficacy loss. The detailed characterization is presented in Table III.

D. Optimum Bitumen Content

The experimental program began with the two porous asphalt mixtures study (coarse and fine) using the PBM 45/80 modified bitumen. These were designed as surface layers, meeting the Table IV requirements according to the Portuguese road administration, the Spanish road administration and Swiss SN 640 standard. There were also considered the studies conducted by the Federal Highway Administration [13], indicating different air voids content from the established in Portugal for these mixtures. Thus, these foreign references were considered due to recently demonstrated experience.

TABLE III
CELLULOSIC FIBRES' CHARACTERISTICS

Granulated characteristics	
Aspect	Cylindrical granules
Fibres content	87 a 93 %
Average length of the granules	2 a 8 mm
Average diameter of the granules	5 ± 1 mm
Bulk density	440 a 520 g/l
Particle size distribution, # < 4,5 mm	max. 10 %
Bitumen included in the granulated characteristics	
Penetration (EN 1426) a 25 ºC	50/70 (0.1 mm)
Softening point (EN 1427)	46/54 ºC
Fibres characteristics	
Basic composition	Technical celulose fibre
Cellulose content	80 ± 5 %
pH Value (5 g/100 ml)	7.5 ± 1,0
Average length of the fibre	1100 µm
Average diameter of fibre	45 µm
Particle density	480 kg/m3

TABLE IV
REQUIREMENTS FOR POROUS ASPHALT MIXTURES

Properties	Air voids content (%)	% Bitumen, min	Wet Cantabro test, max (%)
Portuguese road adminitration	Vmin22-Vmax30	Bmin4.0	≤ 25
SN 640 standard	≥ 20	≥ 5	-
Spanish road administration	> 20	4.3	≤ 35 (T00 a T1) ≤ 40 (T2 a T3)
FHWA, 2015	> 16	-	-

The optimum bitumen content for mixtures without cellulosic fibres is given in the following section. Subsequently, the study is presented for the mixtures with cellulosic fibres, analyzing their influence. Through the binder drainage test was selected cellulosic fibres percentage that had the lowest drainage

E. Optimum Bitumen Content to the Mixtures Without Cellulosic Fibres

The porous asphalt mix design, PA01 and PA02, was obtained taking into account the grading envelopes and the initial bitumen content (with ± 0.5 %) determined through the aggregates specific surface. The optimum bitumen content selection was obtained by meeting the established requirements in Table IV. For this purpose, there were produced eight cylindrical Marshall specimens and bulk density tests were performed according to EN 12697-6 (procedure D) and air voids content according to EN 12697-8. Cantabro test was carried out according to EN 12697-17 and Spanish NLT 362 standard. This test allows to determine the four specimens maintained in air particle loss (PA) for 48 h at 25 °C, and of the four specimens maintained in water particle loss (PS) for 24 h at 60 °C and then heated for further 24 h at 25 °C. The test was carried out in Los Angeles equipment, with 300 rotations, without metal balls. The PS results for each bitumen content must meet the established requirements for the Cantabro test.

The PA01 and PA02 mixtures composition study are shown in Table V and particle size distribution in Table VI. Both tables include porous asphalt mixtures with fibres (PA1 and PA2), since the particle size depends only of aggregates and does not depend on the additive percentage. Despite the point failure in the grading envelope it was opted for these mixtures use to ensure their air voids content.

TABLE V
POROUS ASPHALT COMPOSITION (%)

Materials	PA01	PA1	PA02	PA2
PMB 45/80 bitumen *	4.2/4.7/5.2	4.2/4.7/5.2	4.1/4.6/5.1	4.1/4.6/5.1
Hidraulic lima	2	2	2	2
Stone dust	8	8	4	4
5/15 Gravel	__	__	94	94
5/10 Gravel	90	90	__	__

TABLE VI
POROUS ASPHALT PARTICLE SIZE DISTRIBUTION

Sieve size (mm)	% Passing PA01/PA1	PA 8 Envelope (SN 640)	Sieve size (mm)	% Passing PA02/PA2	PA 12,5 Envelope (CE EP)
16	100	100	20	100	100 – 100
11.2	99	100	12.5	99	90 – 100
8	73	90 - 100	10	79	55 – 75
4	25	15 - 35	4	12	13 – 30
2	12	10 - 17	2	8	11 – 18
0.5	5	4 - 10	1	6	6 – 14
0.063	2	3 - 5	0.063	2	2 - 5

* Weight percentage of total aggregates

The bulk density and air voids content results are shown in Figs. 1 (a) and (b), respectively. The results of the Cantabro test are presented in Table VII. Both porous asphalt mixtures meet the minimum bitumen content and air voids requirement of 16 % according to the FHWA, as well as the result of the wet Cantabro test. For PA01 mixture was adopted a 4.7 % optimum bitumen content, because it presented the best visual aspect and total aggregates coating. For PA02 mixture was considered the 4.6 % optimum bitumen content since it presents the lower result of wet Cantabro test.

F. Cellulosic Fibres Influence by the Schellenberg Method

The cellulosic fibres influence was analyzed by Schellenberg Method according to EN 12697-18 standard through the porous asphalt determination binder drainage. The cellulosic fibres addition allows the use of relatively high binder content, without checking the binder drainage while being stored and/or transported. Besides that, the cellulosic fibres addition does not allow the heterogeneities appearance in the applied layer characteristics, such as very different air voids content and consequent premature degradation. The cellulosic fibres retain the binder and favour aggregates coating, leading to mixtures higher performance and durability. Given this situation, in mixtures with fibres addition, it was chosen the higher bitumen content use.

The mixtures were made with different cellulosic fibres percentages such as 0.0, 0.2, 0.4 and 0.5 % (recommended limit by the manufacturer). The procedure consisted of producing three mixtures specimens for each fibres percentage by heating them for 60 minutes at the test temperature, in this case 180 °C. Through the waste mixture weight ratio after the 60 minutes heating and the mixture weight immediately after being produced, the binder drainage percentage is obtained. The final result was the three specimens average made by percentage of fibres used.

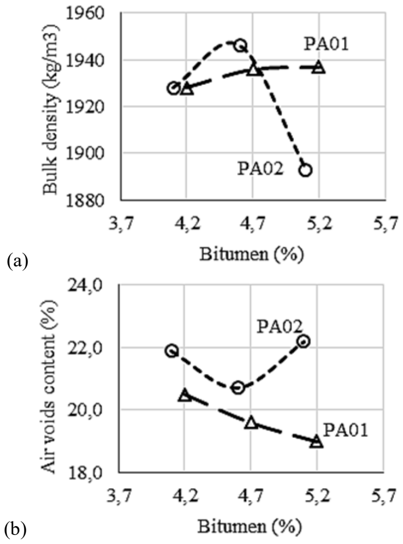

Fig. 1 Bulk density and air voids content results of the porous asphalt without fibres (8 specimens average)

TABLE VII
CANTABRO TEST RESULTS OF THE POROUS ASPHALT WITHOUT FIBRES (8 SPECIMENS AVERAGE)

Porous Asphalt	% PMB 45/80 Bitumen	Cantabro test – dry PA (%)	Cantabro test – wet PS (%)
PA01	4.2	15	14
	4.7	12	15
	5.2	9	16
PA02	4.1	11	13
	4.6	7	8
	5.1	8	15

The mixtures' production with cellulosic fibres addition was carried out with the highest percentages of bitumen obtained in the mixtures without fibres design. This choice was due to the binder retention capacity on the fibres part, preventing the mixtures dry aspect. The 5.2 % and 5.1 % bitumen contents were used for porous asphalt containing more fine aggregates (PA1) and coarse aggregates (PA2), respectively. The obtained results by Schellenberg method are shown in Table VIII where it can be verified that as the percentage of cellulosic fibres increases the binder drainage decreases.

It was found that the PA2 mixture obtained more binder drainage than the PA1 mixture, independently of the used fibres percentage. This may be due to the aggregates use with a bigger nominal size (smaller specific surface) as well as the use of a more discontinuous grading curve. The 0.5 % cellulosic fibres use for PA1 and PA2 mixtures showed a reduction of 0.2 and 0.3 %, respectively, comparing to mixtures with 0.0 % fibres. Taking into account the results, the cellulosic fibres selected percentage as the most suitable for both porous asphalt was of 0.5 %.

TABLE VIII
POROUS ASPHALT WITH CELLULOSIC FIBRES BINDER DRAINAGE RESULTS (3 SPECIMENS AVERAGE)

Porous Asphalt	% PMB 45/80 Bitumen	Cellulosic fibres (%)	Binder drainage (%)
PA1	5.2	0.0	0.284
		0.2	0.164
		0.4	0.149
		0.5	0.102
PA2	5.1	0.0	0.454
		0.2	0.275
		0.4	0.237
		0.5	0.191

G.Optimum Bitumen Content to the Mixtures with Cellulosic Fibres

After selecting the percentage of the most appropriate fibres to porous asphalt mixtures, there were produced bituminous mixtures with fibres, PA1 and PA2, with different bitumen content. The properties determined to obtain the optimum bitumen content were the bulk density, air voids content (the results are presented in Fig. 2) and the particle loss by Cantabro test, wet and dry (the results are presented in Table IX).

The two porous asphalt mixtures with fibres according to the FHWA requirement of 16 % air voids content. Regarding the Cantabro test results in Table IX, it is verified that the most favorable values for the PA1 and PA2 mix are 5.2 and 5.1%, respectively, considered as optimum bitumen contents.

III. POROUS ASPHALT PERFORMANCE

The performance tests studied to characterize the four porous asphalt with 0.5% of cellulosic fibres were: Indirect Tensile Stiffness Modulus (ITSM), water sensitivity, permeability and permanent deformation.

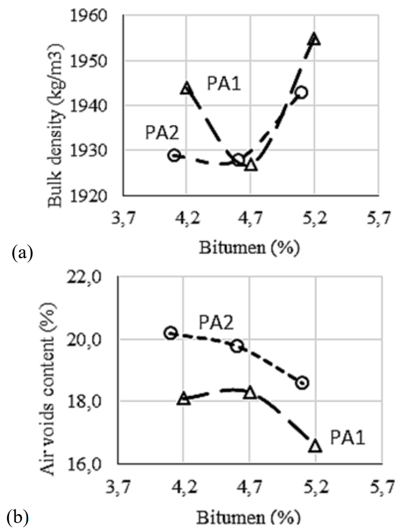

Fig. 2 Bulk density and air voids content results of the porous asphalt with fibres (8 specimens average)

TABLE IX
CANTABRO TEST RESULTS OF THE POROUS ASPHALT WITH FIBRES (8 SPECIMENS AVERAGE)

Porous Asphalt	% PMB 45/80 Bitumen	Cantabro test – dry PA (%)	Cantabro test – wet PS (%)
PA1	4.2	17	30
	4.7	11	36
	5.2	7	28
PA2	4.1	23	31
	4.6	17	17
	5.1	9	21

A. Stiffness

The stiffness was obtained by Indirect Tensile Stiffness Modulus (ITSM) according to EN 12697-26 standard, using Nottingham Asphalt Tester (NAT) equipment. Six cylindrical specimens were made, with an impact compactor by applying 50 blows in each side, for each of the four porous asphalt mixtures optimum bitumen content, totaling 24 specimens, with about 100 mm diameter and different heights.

B. Water Sensitivity Test

The water sensitivity test was performed according to EN 12697-12 standard. Six cylindrical specimens were made for each optimum bitumen content by applying 50 blows in each side. The water sensitivity test results are Indirect Tensile Strength Ratio (ITRS) by EN 12697-12 and Tensile Strength Indirect (ITS) by EN 12697-23.

C. Permeability Test

By performing the permeability test, vertical and horizontal, it was used a variable load device, similar to the LCS permeameter (*Laboratorio de la Cátedra de Caminos de Santander*) developed in Spain, into cylindrical test specimens compacted in the laboratory. In the variable load device used, the permeability was measured by the time it takes to drain a 1735 cm3 water volume through porous asphalt. Four cylindrical specimens were produced for each mixture optimum bitumen content.

The EN 12697-19 standard has a different permeability measuring permeameter. However, the permeability coefficient for both permeameters is determined based on Darcy's law, according to (1).

$$k = \frac{a \times L}{A \times \Delta t} \times \ln\left(\frac{h_1}{h_2}\right) \quad (m/s) \quad (1)$$

where k is the permeability coefficient (m/s), a is cross section area of standpipe (m^2), A is cross section area of specimen (m^2), L is height of specimen (m), Δ_t is time interval taken for water in the standpipe to fall from h_1 to h_2 (s), h_1 is the head at the beginning of time measurement (m) and h_2 is head at the end of time measurement (m).

D. Permanent Deformation Resistance

The permanent deformation resistance to four mixtures was assessed by the Wheel Tracking Test, according to the EN 12697-22 standard, using a small device and the B procedure (in air). Two slabs were prepared for each mixture with 30 x 30 x 4 cm dimensions, compacted with a vibratory compactor. The test ended after the 10 000 cycles were applied.

IV. RESULTS AND DISCUSSION

A. Stiffness

Table X presents the results obtained for the stiffness modulus. The two mixtures groups (with and without cellulosic fibres) presented very similar values between them. The PA1 and PA01 mixtures showed a stiffness slight decrease of about 12.2 %, due to its structure with more mastic, absorbing better the induced stresses, compared to PA02 and PA2 mixtures.

TABLE X
CANTABRO TEST RESULTS OF THE POROUS ASPHALT WITH FIBRES (8 SPECIMENS AVERAGE)

Porous asphalt	% PMB 45/80 Bitumen	Stiffness (MPa)
PA01	4.7	1946
PA1	5.2	1947
PA02	4.6	2282
PA2	5.1	2151

B. Water Sensibility Results

Fig. 3 shows the water sensitivity test results. The wet specimens have lower ITS values than dry specimens. The percentage differences in the four mixtures ITSR values are around 8%. It was observed that porous asphalt containing fine aggregates, PA1 and PA01 are more susceptible to the water presence than mixtures with coarse aggregates. The PA02 and PA2 mixtures air voids content allows water to pass easily leading to ITSR higher values. The SN 640 standard indicates a value for porous asphalt above 70 %. Although the porous asphalt did not accomplish this limit, the results obtained are very close to this value and are considered valid.

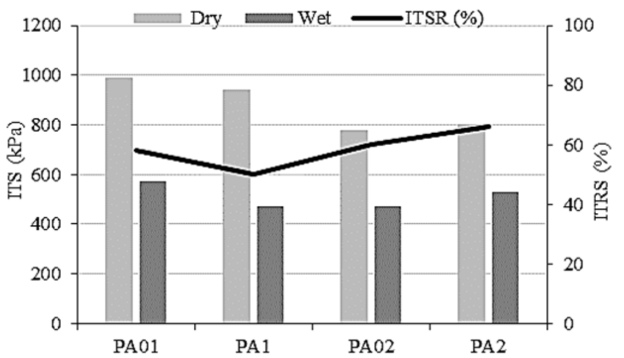

Fig. 3 Water sensitivity results, ITS and ITSR (3 specimens average)

C. Permeability Test

The permeability test results are shown in Fig. 4. Comparing the mixtures with and without cellulosic fibres addition was observed that PA01 and PA02 show lower permeability values than PA1 and PA2. In this case, it was evident that the fibres presence in the mixtures allowed the binder absorption, preventing that it remains dispersed, occupying the air voids content. The PA1 mixture provides the best results for the water flow, being the PA01 mixture the one that shows the lowest values, the high flow time result. This was due to the bigger fine aggregates number in the mixture interfering with their permeability.

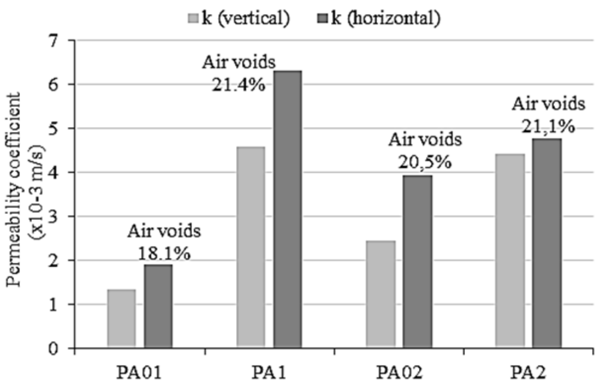

Fig. 4 Permeability results (4 specimens average)

D. Permanent Deformation Resistance

Fig. 5 presents the results obtained from the rut depth. It is observed an improvement in the permanent deformation performance in the mixtures with addition of cellulosic fibres, presenting inferior results to the mixtures without fibres. These good results are related to the bitumen/aggregate adhesion improvement provided by the cellulosic fibres. It is observed that the cellulosic fibres effect is slightly higher in PA1 than in PA2 due to its structure with fewer voids. In this study, the permanent deformation resistance improvement of porous asphalt with fibres with larger bitumen content is clear, as compared to conventional porous asphalt. Thus, the mixtures durability increase is achieved with this bitumen increase.

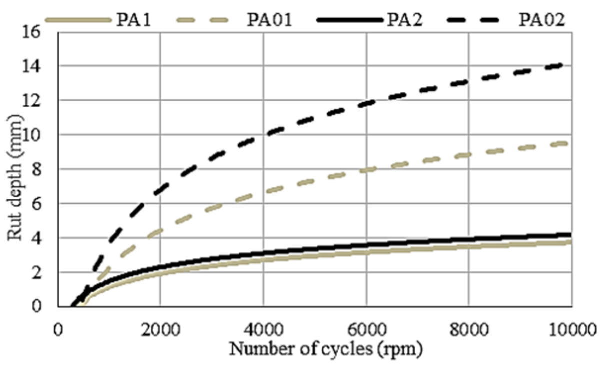

Fig. 5 Wheel tracking test results, at 60 ºC (2 slabs average)

V. Conclusion

This study shows the porous asphalt performance with and without cellulosic fibres addition. Through performed mix design higher bitumen content was obtained for porous asphalt with cellulosic fibres. The cellulosic fibres allowed to increase the bitumen content, enabling its retention and a better aggregates coating and, consequently, a bigger mixture durability. In wet Cantabro test at 60 °C it was found that the porous asphalt with added cellulosic fibres showed bigger particle loss values than the porous asphalt without this addition. It was noted that the water temperature in this test was a significant factor in porous asphalt with cellulosic fibres behaviour.

The cellulosic fibres addition does not induce any significant change in the stiffness modulus obtained in an ITSM test because the results were quite similar.

The water sensitivity results identify the porous asphalt with more fine aggregates with lower ITSR values than the porous asphalt with coarse aggregates, being PA02 and PA2 more resistant in water presence.

In permeability test the mixtures with added fibres present bigger vertical and horizontal permeability comparing to mixtures without fibres. Thus, the fibres use in the mixtures composition improves its performance for runoff in a pavement. The cellulosic fibres incorporation to absorb more binder allows the water drainage between the mixture voids.

In general, the results of permanent deformation resistance indicated porous asphalt with cellulosic fibres better performance by verifying a bigger rut depth to porous asphalt without cellulosic fibres, of 7 mm. In this study, it was observed that porous asphalt with cellulosic fibres has a higher bitumen content, which leads to the permanent deformation resistance improvement.

The porous asphalt durability and mechanical performance increase, promoted by the addition of cellulosic fibres guarantees a good functioning through the aquaplaning phenomena reduction, leading to a higher users safety.

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