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Influence of wax additives on the properties of porous asphalts

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ABSTRACT

An experimental work evaluating the application of Warm Mix Asphalt technologies to Porous Asphalts in severe cold climate is reported. Volumetric tests as well as water permeability, Cantabro and Indirect Tensile Strength tests were performed on samples of a selected porous asphalt, with and without the Sasobit wax. Mixing and compacting temperatures were varied during the tests. Permeability and ITS tests were repeated after a severe water/temperature conditioning process. In general, the results con- firmed that WMA technology is applicable to porous asphalts in a cold climate, allowing the lowering of compaction temperatures by about of 20° C without any significant decrease in performance.

Keywords:
Porous Asphalt, Warm Mix Asphalt, Wax, Compaction temperature, Water/Temperature conditioning

1. Introduction

Modern Porous Asphalts (PA) are the result of more than 20 years of specific research aimed at increasing their drainage capability in order to increase traffic safety and environmental quality. Years and years of experience have shown their benefits including hydroplaning reduction, pollutant filtration, and excellent friction resistance [1]. Rolling noise is also significantly reduced [2]. All these benefits depend on the high void content (20% or greater) that characterizes these asphalts and on the void structure. As for the drainage, the larger the pores and the greater their connection, the higher the drainage capability [3]. To absorb noise at different frequencies, the voids must have variable dimensions [4]. To filter pollutants within the porous layer, the voids must be gradually reduced in the lower part [5]. To enhance skid resistance, the maximum grain size should be reduced so decreasing the void dimensions [6]. It is evident that many of these characteristics conflict with each other. All these factors provided the framework of needs that has led the research into these asphalts in recent years. Many porous asphalts have been produced in the recent past with the aim of balancing these various needs [7–9]. A specific porous asphalt was developed for this research in order to evaluate both the potential of draining rainfall and of noise absorption when combined with the use of Warm Mix Asphalt (WMA) technologies. This is a well known technology developed to deal with environmental and economic issues related to pavement construction.

This technique allows the production of asphalt mixes suitable for use at lower construction temperatures. WMA technologies improve mixture workability through the addition of organic, chemical, water-based, or hybrid additives [10–15]. These technologies work mainly by reducing the binder viscosity, which increases the ability to flow or pour the mixture. This allows the aggregates to be properly coated with asphalt binder at lower temperatures, thus reducing fuel consumption, lowering plant emissions and reducing energy costs by decreasing production temperatures by 30o–50o C in comparison to traditional hot mix asphalt (HMA). In addition, when applying WMA techniques in cold weather conditions, the increase in the workability of the material makes the drop of temperature with time less important as a result of the decrease in the viscosity of the binder. This also allows longer haulage distances, reduces the risk of compaction problems and requires less time to cool the laid material before opening it to traffic or laying the next layer [10].

The WMA technique also improves workability during construction by allowing the mixture to be properly transported, paved and compacted at lower temperatures, thus improving worker conditions through decreased smoke and odours [16].

The lower mixing temperatures may also reduce the aging of the binder leading to increased fatigue life [17]. Moreover, lower binder viscosities allow the use of higher percentages of reclaimed asphalt pavement (RAP) in WMA. This reduces the production of additional aggregate and binder [18].

The aim of this work is to evaluate how the advantages given by the use of this technique, in particular using the wax Sasobit, modify the physical and mechanical characteristics of the porous asphalt under study.

Many works on WMA technologies referring to the application of different types of additives have been published in the literature in recent years.

Zhao et al. [19] studied the effects of various warm additives on the rutting performance of traditional asphalt mixture with different binders and mixing temperature applications. Lowering mixing temperatures can increase the rutting susceptibility due to less aging occurring in the binder during mixing. The results indicated that the addition of warm wax additive can stiffen the binder and increase the mixture rutting resistance, while chemical additives do not soften the binder, nor do they stiffen the binder.

The study conducted by Capitão et al. [20] confirmed that resistance of WMA to cracking at low temperature is apparently generally good, but slightly lower than that observed for similar HMA. It appears that permanent deformation behaviour of WMA is highly dependent on how much the production temperature is lowered. For high levels of temperature reduction, WMA performance is consistently reduced. Sasobit wax additive seems to be the only one that does not follow this tendency, as the crystallisation of this wax improves resistance to deformation at high temperatures.

Several studies have also been conducted on porous asphalts. They mainly involved the investigation of mechanical properties of mixtures containing various additives. Almost all the works agree in suggesting that, due to the low mixing temperature, the mixtures are more prone to moisture damage. The moisture sensitivity of porous asphalt is of fundamental concern because the presence of water can affect both binder cohesion and adhesion between the bitumen and aggregate, causing accelerated stripping.

Hamzah et al. [21] investigated the stripping resistance of warm porous asphalt mixes by using a specially designed dynamic stripping machine. Porous asphalt specimens incorporating Sasobit wax additive were used and subjected to a strength test (indirect tensile strength ratio, ITSR) indicating that the dynamic action of water significantly reduces the resistance to stripping of porous asphalts.

Regarding the durability, abrasion resistance is also a parameter for investigating the moisture susceptibility. Hamzah et al. [22] used the Cantabro Particle Loss test as an indicator of cohesion for evaluating the stripping resistance of porous asphalt samples prepared with different additives and subjected to dynamic strip- ping machine conditioning.

Goh and You [23] (2012) characterized the mechanical proper- ties of porous asphalt pavement mixtures containing reclaimed asphalt pavement (RAP) and a WMA additive. They found that WMA mixes containing RAP had ITS values significantly higher than mixes with RAP alone (without WMA additives). Recent studies have shown that using Warm Mix Recycled Asphalt (WMRA) it is possible to achieve good results with high RAP percentages [24], even up to 100% [25], without affecting the Superpave mix design [26].

Finally, Jamshidi et al. [27] report on the state of art on the performance of Warm Mix Asphalt containing Sasobit. They found that in order to optimize the performance of Sasobit-modified asphalt binders, careful selection of the binder type and source as well as Sasobit content are essential. Construction temperatures, aggregate type and source, aggregate gradation, filler type and anti-stripping agent type are also key points.

2. Research objectives and scope

An attempt was made to produce a PA with WMA technologies that would be suitable for climates with hot summer, cold winter and number of freeze-thaw cycles more than 100 per year (e.g. central Europe, Poland severe climate). Thus, the main objective of this paper is to evaluate the feasibility of the application of WMA technologies to Porous Asphalt for its use in climates that experience low temperatures. The study investigated the possibility of obtaining the required volumetric and mechanical characteristics at lower production temperatures than traditional PA, by evaluating:

- The differences in density and void content,
- The differences in Cantabro test results,
- The differences in ITS results, also before and after the severe water/temperature conditioning process required by the Polish standard PN-EN 12697-12:2008,
- The differences in hydraulic conductivity, also before and after the water/temperature conditioning process.

3. Experimental work

In order to achieve the results mentioned above, one PA mix was selected and prepared using both traditional and WMA technologies, with the Sasobit wax additive used in the latter. In the preparation of the samples, the aggregate temperature was varied based on the target production temperature, while the binder temperature was kept constant for both PA and WMA-PA mixtures.

3.1. Material selection

The gradation curve of the PA selected for the experiments is presented in Fig. 1. A polymer modified binder PmB 45/80-65 produced in Poland (by Lotos Group), was used for the preparation of all the specimens. In order to reduce the number of variables, the binder content was kept constant and equal to 5.2% of the aggregate weight.

Cellulose fibre was also added to both the WMA-PA and traditional PA (0.4% of aggregate weight). Finally, Sasobit additive was added to the binder (2.5% of binder weight) and also dopes of adhesion (0.3% of binder weight) by hand mixing with glass stirring rods at the binder temperature to achieve ideal mixing viscosity.

3.2. Research plan

In order to evaluate the difference between WMA-PA and traditional PA, volumetric tests as well as permeability, Cantabro and ITSR tests were performed. With this aim, 45 Marshall samples of PA and 55 Marshall samples of WMA-PA were produced.

3.2.1. Mix preparation

Asphalt mixes were prepared by initially pre-heating aggregates for four hours in an oven at mixing temperature. The asphalt binder was blended after heating at 150 °C which corresponds to its ideal mixing viscosity specified by the producer. The binder was initially mixed with coarse particles only, while the fine aggregate were added after the coating of the coarse aggregate had occurred. After mixing, the mixes were conditioned in an oven for one hour at the compaction temperature. Table 1 shows the mixing and compaction temperatures used in this research.

The compaction temperature was always set 10°C lower than the mixing temperature. Compaction was conducted by applying 50 blows of a Marshall hammer per side in accordance with UNI EN 12697-34 and then specimens were left to cool overnight at room temperature.

3.2.2. Tests

The density and air void content were determined using the geometric method for all specimens. As shown in Table 1, 10 samples of WMA-PA and 10 samples of PA were used to perform the Cantabro and ITSR tests.

Indirect Tensile Strength before and after conditioning was determined according to PN-EN 12697-12:2008, the Polish version of the European EN 12697-12 standard and specifically according to instructions published by the Polish General Director for National Roads and Motorways. In PN-EN 12697-12:2008 the limit value for ITSR is 90%. According to these instructions, six samples were compacted for each mixture using a Marshall compactor. The samples were divided into two subsets of three samples each: an unconditioned subset and a moisture conditioned subset. Each mixture was evaluated following the procedure outlined below:

- measure ITS for the unconditioned subset;
- place the three samples of the second subset in water in a vac- uum for their immersion;
- place the same samples in a water bath at 40 oC for 68–72 h;
- place the wet samples in stretch bags at -18 oC for 16 h;
- immediately place the cold samples in water at 60 oC for 24 h;
- measure ITS for the conditioned samples;
- calculate the ITSR using Eq. (1):

$$ITSR = 100\ ITSw/ITSd \tag{1}$$

where: ITSw = Indirect Tensile Strength of conditioned specimens;
ITSd = Indirect Tensile Strength of unconditioned specimens.

Fig. 2 shows the samples after ITS tests.

In order to investigate the differences between the hydraulic conductivity of WMA-PA and PA, before and after conditioning, the permeability test was performed on those mixes. With this purpose five more samples of WMA-PA and five more samples of PA where prepared at 135° C and 165° C, respectively.

The scope was to address the same void content for the WMA- PA and the PA samples, so that the same permeability should also be expected for the WMA-PA and the PA samples. If this is not the case, the only reason for the difference must be the internal structure of the pores due to the presence of the wax in the mix. Surprisingly, while the five PA samples showed void content values about the expected 26.5%, the five WMA-PA samples showed a different void content, about 28.5%. Thus, a statistical analysis was performed to determine whether the difference between the samples subjected to the mechanical tests and those subjected to permeability tests is significant. A One-Way ANalysis Of VAriance (ANOVA) at 95% confidence level was adopted. Table 2 shows that for both cases (PA and WMA-PA mixes) the variance between groups is greater than the variance within groups and the F-value is greater than the corresponding value in the distribution table.

The results of ANOVA show a statistically significant difference between the groups. Based on this result the initial intent was modified and only the difference between conditioned and unconditioned samples was investigated separately for WMA-PA and PA samples.

Thus, permeability tests were performed on both WMA-PA and PA samples before and after conditioning. Specifically, the tests had the aim of verifying the differences in terms of the internal pore structure, before and after conditioning. Table 3 summarizes the results of the first set of PA and WMA-PA samples.

The test results of the second set of PA and WMA-PA samples are summarized in the following Table 4.

4. Discussion of the results

4.1. Effect of temperature on volumetric characteristics

The density and the air void content of both mixtures were estimated based on the geometric method. Fig. 3 presents the density- temperature curve and Fig. 4 shows the plot of void content versus temperature. In both cases, the curve relative to WMA-PA is down shifted with respect to that of the PA for the temperature. Fig. 4 also shows the plot of air voids which reflects the reduction in the compaction temperature.

The air voids decrease as the compaction temperature increases for both mixtures. This can be explained in terms of increased binder stiffness as its temperature reduces making it more difficult to compact. However, samples incorporating Sasobit exhibit a greater susceptibility to compaction temperature compared to specimens of traditional PA. This is a confirmation that the Sasobit additive increases the ability to change the consistency of mixtures. From the slope of the lines, the shift in temperature is not constant, becoming greater at higher temperatures. At the void content of 26.5%, which is also a desirable void content for porous asphalt mixes, the plot shows the largest gap between the compaction temperatures of WMA-PA and PA. The best performance in terms of the equilibrium between a good void content and the best temperature reduction is therefore achieved at 135 °C and 165 °C for WMA-PA and for PA, respectively.

4.2. Effect of temperature on mechanical resistance

4.2.1. Cantabro test

The Cantabro test was used to evaluate particle loss of unconditioned samples of PA and WMA-PA mixtures with varying com- paction temperatures. Figs. 5 and 6 show the plot of the Cantabro test results, with a general trend in which the Cantabro Index (Ic) decreases with increasing compaction temperature. Samples incorporating Sasobit exhibit a slightly greater susceptibility to compaction temperature compared to specimens of traditional PA. Fig. 5 also shows that there is not a clear shift factor between the two regression lines. It is possible, in fact, to draw a unique regression line as shown in Fig. 6. In this case the regression line fits the experimental points very well ($R^2 = 0.93$). On looking at this curve, it is possible to say that the Cantabro test result depends more on the temperature than on the presence of the wax in the mix.

Fig. 7 shows the relationship between void content and Ic both for WMA-PA and traditional PA. Both regression lines show that when void content increases, the Ic increases as well. There is also a shift factor of about Ic = 15% between the two lines.

For a given level of void content the mixes incorporating Sasobit showed higher values of Ic. Therefore, on merging the results of the plots in Figs. 4, 6, and 7, it appears that on decreasing temperature, the void content increases as well as the Ic. The temperature acts firstly on the void content and the latter acts differently for the WMA-Pa and for the PA.

Thus, the increase in air void content is the major cause of the specimen disintegration. However, at same void content the WMA-PA mixture seems to be weaker than PA. This indicates that the use of Sasobit seems to worsen the resistance of the mixture, probably because it worsens the cohesive properties of the binder.

4.2.2. Indirect tensile strength and indirect tensile strength ratio

ITS and ITSR were calculated according to the PN-EN 12697-12 on both PA and WMA-PA samples in order to evaluate the water susceptibility of the mixes in cold climates.

The Fig. 8 illustrates that the ITS of all dry samples, with and without Sasobit, is linearly correlated to compaction temperature, with a higher correlation coefficient for WMA-PA mixture. The general trend shows that the ITS increases as the compaction temperature increases for both mixtures. However, the WMA-PA regression line lies approximately 100 kPa above the PA regression line, thus for a given temperature the WMA-PA samples show higher values of ITS. It appears that the use of the waxes allows each given ITS value to be achieved with a lower compaction temperature. This result seems to confirm that Sasobit additive can raise the ITS value of mixtures with respect to that of the traditional one [28].

Fig. 9 illustrates the results of the ITS test on conditioned samples of PA and WMA-PA mixtures. Also in this case the ITS value increases with increasing compaction temperature for both mixtures. On comparing these ITS results with those in Fig. 8, it is possible to appreciate how after conditioning all samples exhibit a reduction in resistance, due to the very aggressive water conditioning method adopted.

Samples treated with Sasobit seem to suffer the conditioning effects more than those traditionally mixed. On average, WMA- PA reduces the resistance by approximately 140 kPa, while PA reduces it on average by approximately 90 kPa. Similar results have also been found elsewhere [14,28].

As a result of this effect, the regression lines of WMA-PA and PA in Fig. 9 appear to be in continuity with each other on varying the temperature. In other words the shift factor of about 100 kPa observed in Fig. 8 disappears. It is possible to imagine that this phenomenon is due to the break in the bond structure given by the wax during the freezing cycle, so cancelling the positive effect of the additive.

Taking into account the above mentioned factors, it is possible to draw a unique regression line for WMA-PA and PA samples as in Fig. 10. The relationship between compaction temperature and ITSw, in fact, is still very strong (R2 = 0.92), more than when the two sets of samples are considered separately (R^2 = 0.86 and 0.84, respectively).

The above mentioned is confirmed by the plot of ITSR against compaction temperature. The results presented in Fig. 11 show that the specimens without Sasobit can better resist moisture dam- age compared to WMA-PA specimens. This means that the additive has an unappreciable influence on the mixture in terms of ITS - ITSR. It is also noticeable that the two curves are almost horizontal and are separated by approximately 15%. On one hand this high- lights the difference in water susceptibility and on the other hand, surprisingly, indicates that the ITSR is almost independent of the temperature, for both samples. This finding seems to contradict the previous and common result, according to which, like ITS, ITSR also depends on temperature and is usually linearly correlated with it [21]. This will be further investigated in future research.

The crack paths of the samples after the ITS tests (see Fig. 2) seem to suggest that the rupture occurred due to cohesive failure. This is in agreement with Wasiuddin [29] who indicates among the causes of failure the loss in cohesion of the samples including Sasobit.

4.2.3. Permeability tests

In order to evaluate the effects of the additive and conditioning on the permeability of specimens, specific tests were performed on PA and WMA-PA samples according to the European specification UNI EN 12697-19-2004. The results of the vertical and horizontal permeability tests are reported in the previously mentioned Table 4.

Vertical permeability. Fig. 12 presents the results of the vertical permeability test for PA and WMA-PA samples, respectively. As expected, WMA-PA samples, which are characterized by higher air void content than the PA samples, have higher permeability values.

On comparing the permeability loss after conditioning, it can be observed that WMA-PA mixtures have a slightly greater loss than PA (about 6.5% and 4.3%, respectively).

This result suggests that after conditioning there is a modification in the internal structure causing both a loss of mechanical resistance and of permeability. This phenomenon could be attributed to the variation in the pore structure, probably due to the grains and binder ruptures that lead to an increase in the tortuosity of the pathways between the connected air voids in the specimen.

The results seems to confirm that the shape of flow channels as well as the average effective porosity of the entire channel are likely to be responsible for hydraulic conductivities, as similarly stated elsewhere [30,31].

In any case, both mixtures, before and after conditioning, meet the minimum coefficient of permeability, 10–2 cm/s, which is typically used to ensure adequate water drainage from the road surface [23].

Horizontal permeability. Horizontal permeability tests were also conducted according to the UNI EN 12697–19-2004 specifications.

The results of these tests are shown in Table 4. Comparing the results of the vertical and horizontal tests, it can be appreciated that the horizontal permeability is higher than the vertical permeability. This is evidence of the existence of anisotropy in the samples as regards the water permeability. This result was found by the Authors in past researches on PA [32,33] even if the horizontal permeability was found to be approximately 40% lower than the vertical permeability. This aspect is worthy of further research in order to better understand the anisotropic behaviour of PA. As for HMAs, recent research has also shown that there is a strong anisotropy in regard to the water permeability, given that the horizontal permeability is several times higher than the vertical permeability [34,35]. Further study of the anisotropy assessment method and its effect on compaction can be found elsewhere [36,37].

The following results of horizontal permeability tests, before and after conditioning, clearly show the difference in behaviour of the two mixtures.

As shown in Fig. 13, the kh of WMA-PA before conditioning is approximately 3 times greater than PA. For both of the mixtures, the kh values decrease after conditioning. This decrease is much more noticeable in

WMA-PA: so much so that the permeability of the two mixes after conditioning is almost equivalent.
This seems to suggest that in the unconditioned state the wax, on acting on the fluidity of the bitumen, guarantees a high percent- age of interconnected voids. The higher reduction in the WMA-PA of the Kh after conditioning confirms what was observed for the vertical permeability; it could be due to a greater number of internal ruptures occurring in the WMA-PA mixes.
In summary, it seems that the bonds structure given by the wax is weak in respect to the effects of conditioning. The ITS and the permeability tests both show similar results: WMA-PA samples after conditioning have a greater decrease in ITS compared to PA samples; similarly, the WMA-PA samples after conditioning have a greater decrease in permeability compared to the PA samples.
In both the ITS and the permeability tests, after conditioning the WMA-PA samples show results comparable to those of the PA samples. Hence, the wax additive seems to have a positive effect which vanishes after the conditioning cycles, without becoming negative.

5. Summary and conclusions

This paper reports an investigation on the application of WMA technology applied to porous asphalts. With this aim, two sets of specific porous asphalt mixtures were studied and tested: one was produced with Sasobit waxes (WMA-PA), the other was the reference mix produced with the traditional hot mix asphalt technology (PA). The mixes were produced by varying the mixing and compacting temperatures in order to evaluate the influence of the temperature on the performance of the mixes. Volumetric and physical measurements were first performed and then ITS, Cantabro and permeability tests were conducted. In order to evaluate the water susceptibility of WMA-PA and PA, the ITS and the permeability tests were also repeated after a conditioning cycle performed according to the standard PN-EN 12697-12:2008, the Polish version of the European standard EN 12697-12
Analysis of the results of these tests leads us to the following conclusions:

- When the wax is introduced, the characteristics of the mix are more susceptible to the compaction temperature, for example when the WMA-PA samples showed steeper curves of the void content and density with respect to temperature.
- The levels of density and void content of both mixtures are
dependent on compaction temperature. However, different behaviour can be observed for HMA and WMA. WMA mix with wax additive exhibits levels of density and void content equal to HMA but at a lower temperature. The difference is approximately 20° C.
- As for the Cantabro test, as expected, the Cantabro Index
decreases with increasing compaction temperature. When the temperature increases, the void content decreases and the Cantabro index improves. The WMA-PA samples perform worse than the PA samples. For a given void content, the WMA-PA mixture is 35% weaker than the corresponding PA, resulting in the worsening of the cohesive properties of the WMA-PA mixtures with respect to those of the PA mixtures. Samples incorporating Sasobit, probably due to the low production temperature, also exhibit a slightly greater susceptibility to compaction temperature as compared to the specimens of traditional PA.
- As for the ITS tests, the tensile strength (ITSd) increases as the
compaction temperature increases for both types of mixture. Also in this case there is a shift between the ITSd vs. temperature curves of the two mixes, with the WMA-PA regression line about 100 kPa above the PA regression line. Thus, for a given temperature the WMA-PA samples show higher values of ITSd. On the other hand, it can be stated that using the waxes it is also possible to achieve a given ITSd value with a compaction temperature 25° C lower.
- As regards the water susceptibility, both mixture types suffer the effects of the water/temperature conditioning. The tensile strength after conditioning (ITSw) for all the compaction temperatures is always less than the ITSd, both for WMA-Pa and PA. The ITSw increases with temperature as well as the ITSd, but without a shift factor between the two types of mixture. Hence the samples treated with Sasobit seem to suffer the conditioning effects more than those traditionally mixed. This is probably due to the larger number of internal ruptures occur- ring in the WMA-PA mixtures caused by the break of the bond structure given by the wax.
- The results show that WMA-PA at -18 °C exhibits similar or better performance than the PA control mix. At the same com- paction temperature, higher values of ITS can be observed in the WMA-PA samples than in PA in both conditions (wet and dry). Although WMA mixtures are produced at a relatively low temperature and the bonding at the binder coated aggregate inter- face is still in question, the wax seems to

improve the performance of porous asphalt because makes it possible to obtain comparable values of ITS, especially in dry conditions, at lower production temperatures with significant environmental benefits.

This confirms the results of other studies available in the literature, according to which low temperature cracking as well as fracture temperatures were slightly decreased by adding Sasobit and in general, the stiffening effect of Sasobit-associated aging reduces the fracture temperatures in WMA mixtures.

- As regard the ITSR, this parameter appears to be almost independent of the sample preparation temperature for both mixture types. When compared with the compaction temperature values of PA and WMA-PA, as can be seen in Fig. 11, a constant trend of ITSR values to variable temperatures (from 135 °C to 165 °C for PA, from 95 °C to 135 °C for WMA-PA). On the other hand, it seems to be influenced by the wax incorporated in the WMA because at the same temperature (135° C) and the same other parameters, the ITSR is higher for the PA mixture.
- As expected, WMA-PA samples, which are characterized by a higher air void content than the PA samples, have higher water permeability values.
- As regards the vertical water permeability, the WMA-PA samples suffer the conditioning effects more than the PA samples.
- As for the horizontal water permeability, it is greater than the vertical permeability thus confirming the presence of an anisotropy in the mix, mainly related to the compaction procedure. After conditioning, the horizontal permeability decreases as well as the vertical permeability. For the WMA-PA samples this decrease in the horizontal permeability is substantial as observed for the ITS test. This seems to confirm that the conditioning process causes the break of the bond structure given by the wax which results in a modification of the internal pore structure of the mixture which in turn increases its resistance to water filtration.
- In any case, the results of vertical and horizontal permeability tests, before and after conditioning, show results above the thresholds required by the technical norms.

These results confirm that WMA technology is applicable in cold climates, allowing porous asphalt to be laid at a temperature of approximately 20° C less than usual without a significant decrease in performance. However, other studies are needed to characterize such mixes in more detail.

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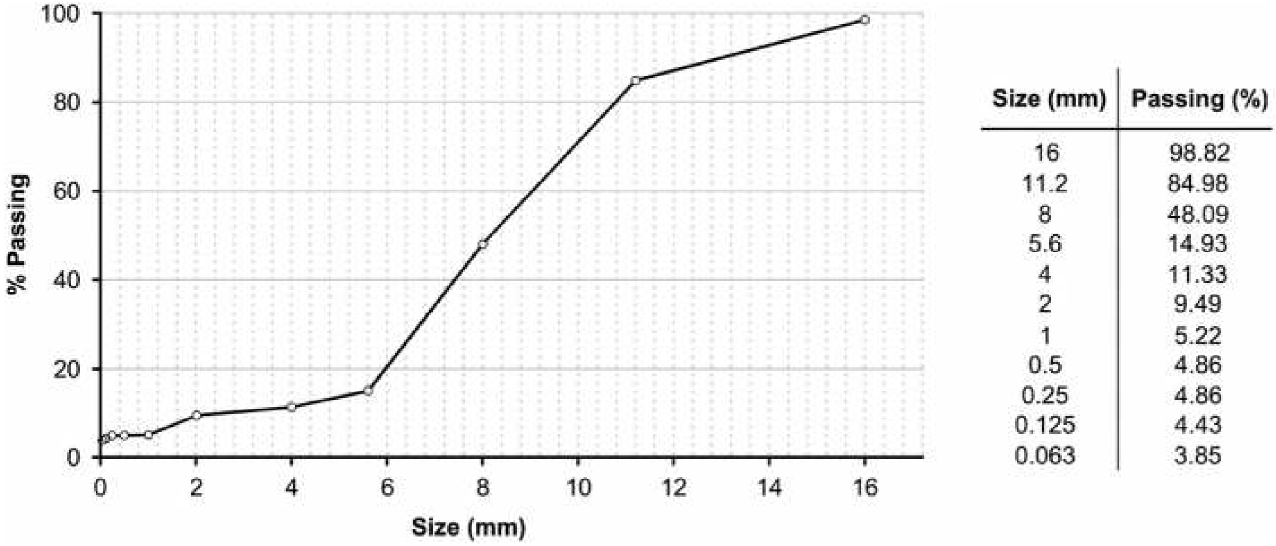
FIGURES



Size (mm)	Passing (%)
16	98.82
11.2	84.98
8	48.09
5.6	14.93
4	11.33
2	9.49
1	5.22
0.5	4.86
0.25	4.86
0.125	4.43
0.063	3.85

Fig. 1. Aggregate size distribution of the PA used in the study.

Fig. 2. Some samples after the ITS test.

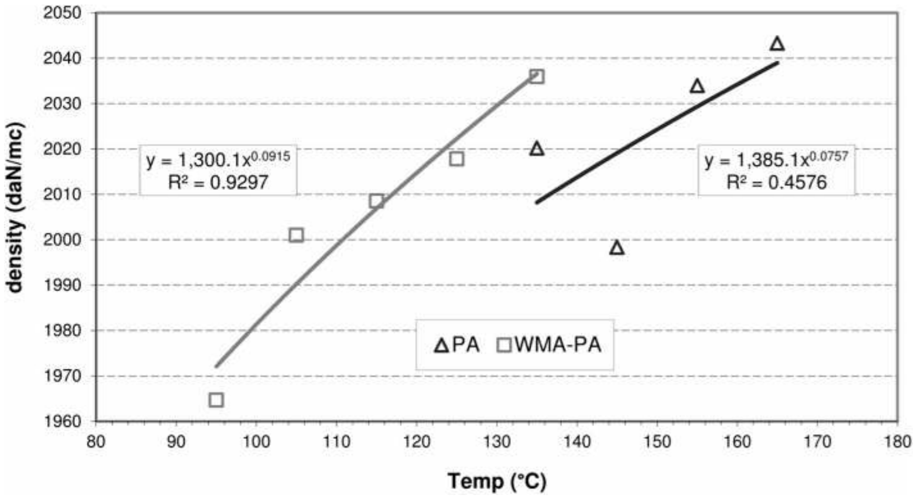


Fig. 3. Density at varying compaction temperatures.

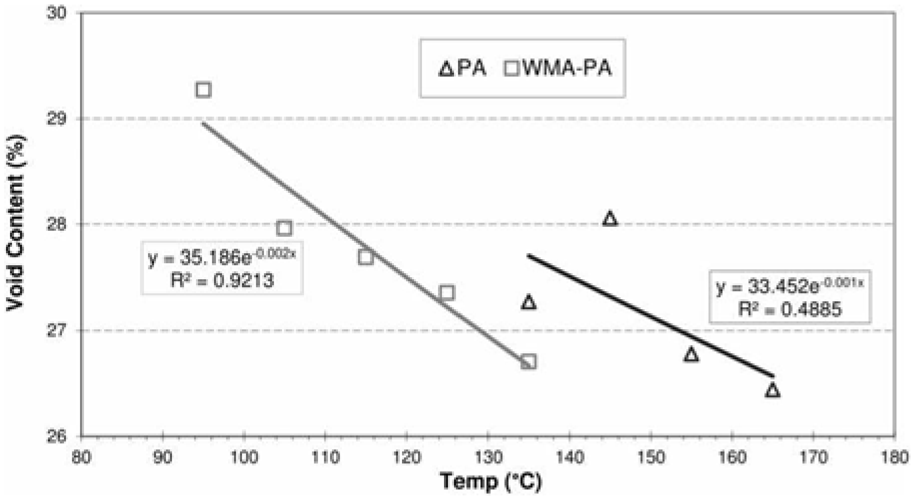


Fig. 4. Void content on varying compaction temperatures.

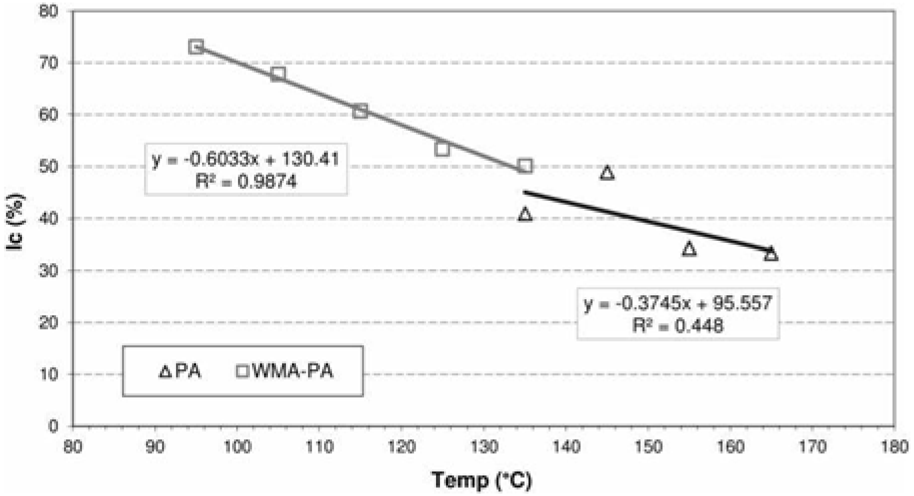


Fig. 5. Cantabro index on varying compaction temperatures.

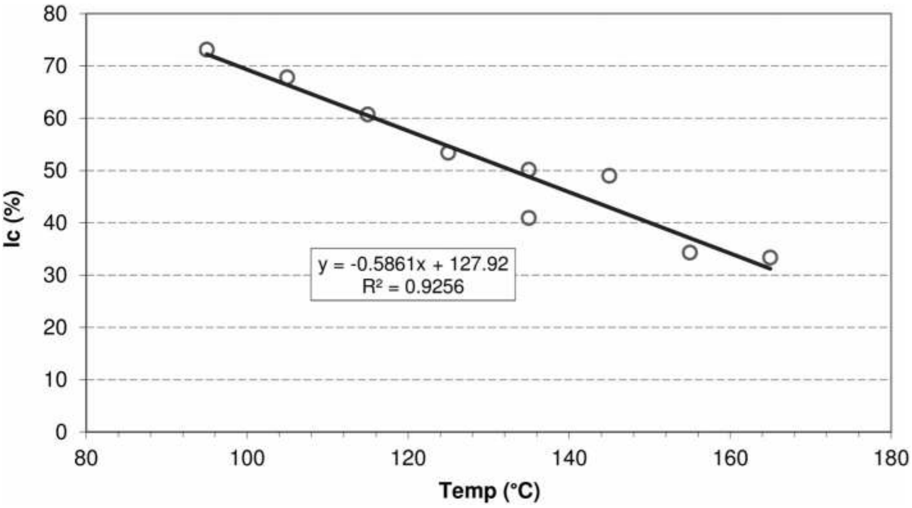


Fig. 6. Cantabro index vs. Compaction temperature, regardless of the type of mixture.

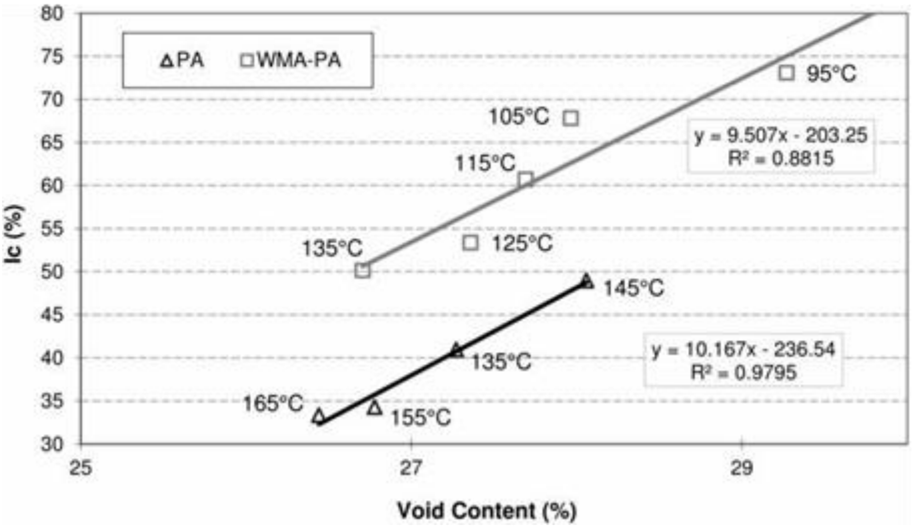


Fig. 7. Void content vs. Cantabro index.

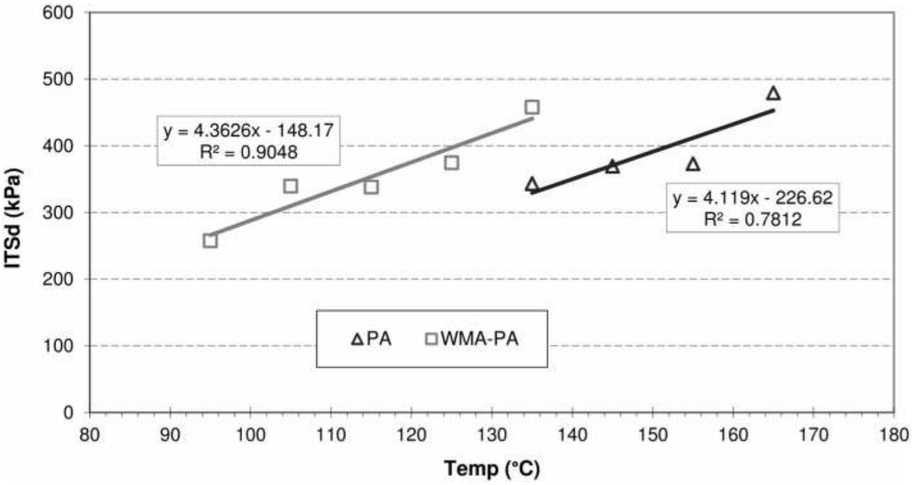


Fig. 8. ITSd vs. Compaction temperature.

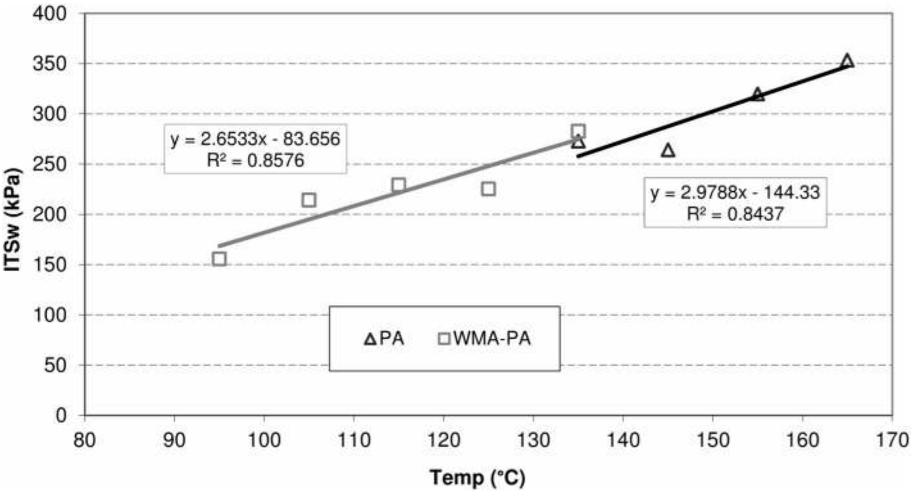


Fig. 9. ITSw vs. Compaction temperature.

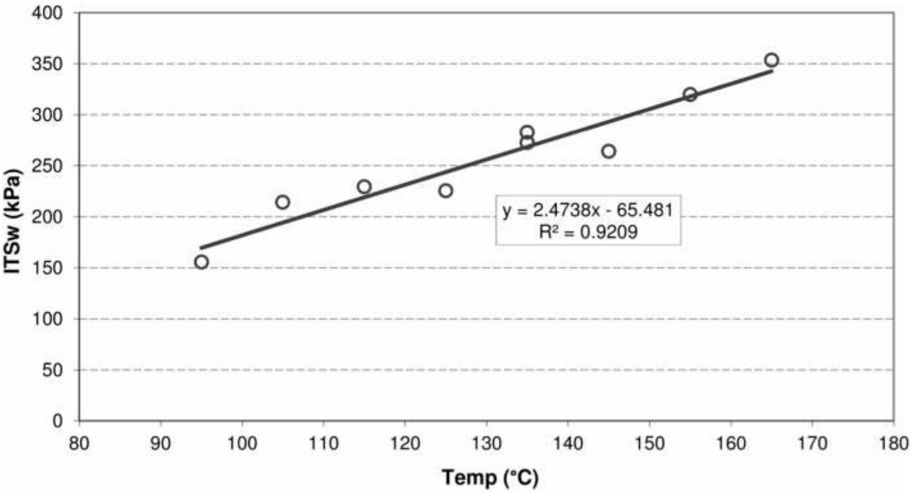


Fig. 10. ITSw vs. Compaction temperature, regardless of the type of mixture.

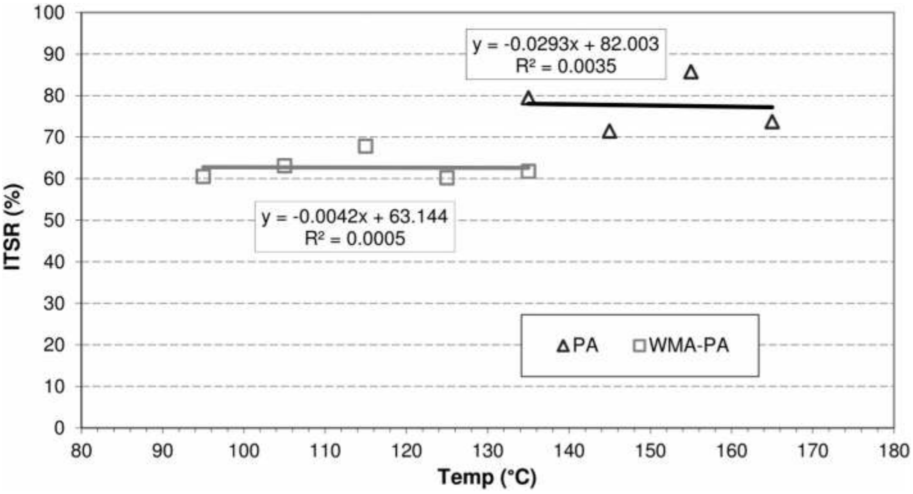


Fig. 11. ITSR vs. Compaction temperature.

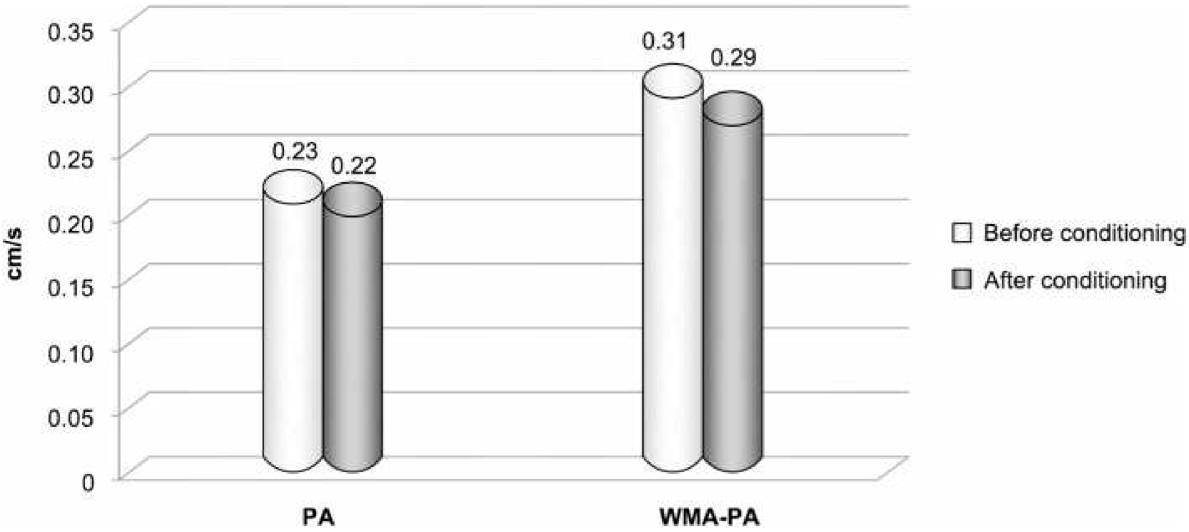


Fig. 12. Comparison between vertical permeability of PA and WMA-PA samples, before and after conditioning.

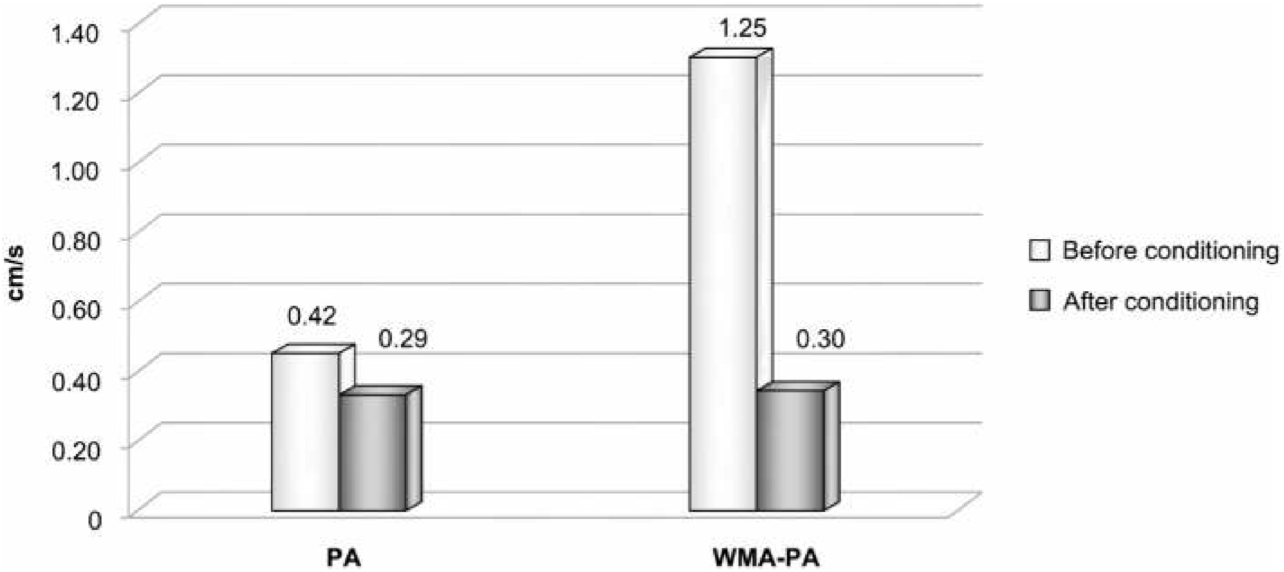


Fig. 13. Comparison of horizontal permeability of PA and WMA-PA samples, before and after conditioning.

TABLES

Table 1
Mixing and compaction temperatures for PA and WMA-PA samples.

PA Temp. (°C)			WMA-PA Temp. (°C)		
Binder Mixing	Aggregate Mixing	Sample Compaction	Binder Mixing	Aggregate Mixing	Sample Compaction
150	145	135	150	105	95
150	155	145	150	115	105
150	165	155	150	125	115
150	175	165	150	135	125
			150	145	135

Table 2
Results of the ANOVA test.

	PA					WMA-PA			
	Deviance	Degrees of Freedom	Variance	F		Deviance	Degrees of Freedom	Variance	F
Between Groups	1.39	1	1.39	6.06	Between Groups	15.19	1	15.19	24.49
Within Groups	3.90	17	0.23		Within Groups	9.92	16	0.62	

Table 3
Mechanical tests results.

Mixtures	Comp. Temp. (°C)	Density (g/cm^3)		Void Content (%)		Cantabro Index (%)		ITSd (kPa)	ITSw (kPa)	ITSR (%)
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	Mean	Mean
PA	135	2.020	13.42	27.27	0.48	40.94	6.81	343	273	79.5
	145	1.998	21.55	28.06	0.78	48.96	9.99	369	264	71.5
	155	2.034	13.54	26.78	0.49	34.29	3.20	373	320	85.7
	165	2.043	13.60	26.44	0.49	33.34	4.14	479	353	73.7
WMA-PA	95	1.965	22.47	29.27	0.81	73.09	20.42	257	156	60.5
	105	2.001	19.41	27.96	0.70	67.82	9.31	340	214	63.1
	115	2.009	12.73	27.69	0.46	60.72	3.16	338	229	67.8
	125	2.018	16.83	27.36	0.61	53.39	11.68	375	225	60.2
	135	2.036	22.87	26.71	0.82	50.14	5.31	458	283	61.7

Table 4
Permeability tests results.

Mixtures	Comp. Temp. (°C)	Void Content (%)		Vertical Permeability (before conditioning) (m/s)		Vertical Permeability (after conditioning) (m/s)		Horizontal Permeability (before conditioning) (m/s)		Horizontal Permeability (after conditioning) (m/s)	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
PA	165	26.98	0.47	0.0023	0.0002	0.0022	0.0002	0.0042	0.0014	0.0029	0.0016
WMA-PA	135	28.78	0.97	0.0031	0.0003	0.0029	0.0004	0.0125	0.0036	0.0030	0.0007