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EFFECTS OF RECLAIMED ASPHALT, WAX ADDITIVE, AND COMPACTION TEMPERATURE ON CHARACTERISTICS AND MECHANICAL PROPERTIES OF POROUS ASPHALT

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Abstract. This paper describes physical and mechanical properties of porous asphalt mixtures with various RAP amount (0%, 10%, 20%, 30%) containing one WMA additive (organic wax). The samples were prepared using the Marshall compactor at two different temperatures (125 °C, 145 °C) by fabricating six series of porous mixtures. Air void content, particle loss, stiffness modulus, indirect tensile strength, and indirect tensile strength ratio were measured

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and the effects of RAP, wax, and compaction temperatures were evaluated, considering the results of statistical analyses. Based on the performed tests, it has been concluded that high RAP contents (30%) in WMA-RAP PAs result in decreased porosity, permeability, and moisture resistance, and in increased cohesiveness, stiffness, and indirect tensile strength compared to the reference PAs. On the other hand, for low RAP contents (10%), WMA-RAP PAs show lower cohesiveness and indirect tensile strength, at the same time demonstrating an increase in porosity, permeability, moisture resistance, and stiffness. Reduced compaction temperatures (125 °C) particularly affect the cracking resistance.

Keywords: porous asphalt, reclaimed asphalt pavement, sustainable asphalt mixture, warm mix asphalt technology, wax additive.

Introduction

Ensuring pavement sustainability is one of the main goals in the road infrastructure planning and management systems (Radziszewski et al., 2016), especially from a life-cycle perspective (Santos et al., 2017). Several technologies have been implemented for this purpose, such as warm mix asphalts (WMAs) and the application of the reclaimed asphalt pavement (RAP) in the production system.

In particular, warm mix asphalts (WMAs) allow limiting the HMA production temperature (e.g., Tatari et al., 2012), while preserving acceptable mechanical properties (e.g., Capitão et al., 2012; Jamshidi et al., 2013; Xiao et al., 2015). WMA technology improves HMA workability based on viscosity changes as a result of the action of organic, chemical, or water-based additives (e.g., Król et al., 2015; Choudhary et al., 2018). For example, long chain additive waxes in a molten form can be added to the aggregate blend or to the HMA mixer (Hurley & Prowell, 2005).

Recycling of the hot mix asphalts (HMAs) through using reclaimed asphalt pavement (RAP) for the production of new pavements is aimed at preserving limited sources of the aggregate and at reducing the amount of virgin asphalt binder. In fact, during the last decades, the content of RAP obtained from road milling or discharged from plant processing in HMA mixtures has been increased to save energy and materials (Lee et al., 2015), still allowing to maintain appropriate mechanical properties of asphalt for road pavement construction (e.g., Kowalski et al., 2016a; Behnood et al., 2015; Su et al., 2014).

The two technologies can be combined (WMA-RAP), and the WMA offers a possible advantage of adding higher percentages of RAP in the mix design process, which should necessarily consider the properties and composition of the added RAPs (see Al-Qadi et al., 2007). The effect of WMA-RAP technology on pavement performance has been recently reviewed by Guo et al. (2020), who considered different types of additives involved in the WMA production process. The results of the previous research showed that wax additive stiffens the mixture (see e.g., Frigio et al., 2016), which can be observed considering the indirect tensile strength results, especially at low temperatures (Mallick et al., 2008). In addition, the presence of RAP may further stiffen the material and lead to improved moisture resistance – as RAP percentages increase, the tensile strength ratio also increases (Middleton & Forfylow, 2009). The organic wax-modified asphalt mixtures exhibit good rutting resistance as compared to the asphalt mixtures with other WMA additives. In addition, it has been demonstrated that RAP improves mixture resistance to moisture action and permanent deformation. However, RAP negatively influences thermal cracking resistance (Ranieri et al., 2017).

However, most of the previous research (including the above-mentioned studies) about WMA-RAP is dedicated to the mixes to be used for impervious pavements. Since porous asphalts (PAs) are widely used solutions, which can offer the advantage of stormwater collection (see e.g., Ranieri et al., 2002; Ranieri et al., 2014; Garcia et al., 2019), while in other regions they are primarily used to limit tire/pavement noise (see e.g., Kowalski et al., 2009; Kowalski et al., 2015; Kowalski et al., 2016b), studying the performance of different WMA-RAP porous asphalt mixtures (porous asphalts obtained by adding reclaimed asphalt pavements through a “warm” mix design process) is of utmost interest as well. In this case, the problem of stormwater management (or noise reduction) can be addressed in combination with the issue of overall pavement sustainability.

While some studies already demonstrated the successful use of the WMA technology to produce PAs (e.g., Ranieri et al., 2014; Ranieri et al., 2017) or the possibility of adding RAP in the PA mix design process (e.g., Praticò et al., 2013); there is less evidence about WMA-RAP PAs, in particular about the effect of different RAP percentages and additives on WMA-RAP PA performance. In this regard, a summary of results from the previous research about WMA-RAP PAs is reported as follows.

Goh & You (2012) found a higher indirect tensile strength of WMA-RAP PAs (treated with zeolite, with 15% RAP added and compacted at 110 °C) with respect to both the reference RAP-HMA and WMA (with 0% RAP), and a slight decrease in the dynamic modulus compared to the reference RAP HMA. Frigio & Canestrari (2018) studied WMA-RAP PAs treated with different additives (organic wax, chemical additive and zeolite), with 15% RAP added and compacted at 120 °C. As a result of the study, RAP-WMA mixtures showed decreased ITS values (both in dry and wet conditions) and resistance to crack propagation compared to the reference RAP-HMA. Adequate water resistance is guaranteed only in the case of chemical additives, compared to the reference HMA. In another study on similar WMA-RAP PAs, Frigio et al. (2016) found lower stiffness values and extensive long-term aging effects compared to the reference HMA, and higher stiffness and lower fatigue slope parameters in the case of mixtures supplemented with organic wax as compared to other additives. Considering WMA-RAP PAs with the added 15% RAP, compacted at 120 °C and treated with chemical additives, Frigio et al. (2017) found lower stiffness values and significant water susceptibility compared to the reference HMA (with 0% RAP). Moreover, better performance in terms of water susceptibility for mixtures with the added surfactants and adhesion enhancers with respect to viscous regulators was reported.

It is evident from the highlighted results of the previous studies that there is insufficient research reporting on the characteristics and mechanical properties of WMA-RAP PAs. Moreover, these studies have used a constant amount of RAP (15%) and a compaction temperature slightly variable (between 110 °C and 120 °C), while using several additive types. Hence, it is necessary to analyze the effects of different RAP contents and compaction temperatures in producing WMA-RAP PAs.

For the above-mentioned reasons, this study aims at answering the following research questions:

- Are there any significant changes in the WMA-RAP PAs characteristics and mechanical properties if different RAP contents and compaction temperatures are considered?
- Which factors have the most significant effects on each characteristic and mechanical property of WMA-RAP PAs – the use of RAP, different compaction temperatures, or the use of additives?

For this purpose, five porous asphalt mixtures were prepared, tested, and compared with a control HMA porous mix (the “ECD” mix, previously used for research purposes by Ranieri et al., 2010). The ECD control mix is a composite that combines the high draining capacity with a reduced thickness that allows for material savings and easier maintenance.

For this study, the wax additive was selected among all existing WMAs because it lowers the viscosity of asphalt bitumen and the working temperatures can be significantly decreased (Capitão et al., 2012). Moreover, the organic wax can provide an increased stiffness to WMA PAs among other possible additives (Frigio et al., 2016).

A detailed test program was conducted in view of the research questions posed, as described in the next section. The test program is focused on the study of macro-characteristics and mechanical properties of WMA-RAP PA mixtures. Accurate investigation of the mixture morphology conducted in the dedicated studies (see e.g., Król, 2014; Krol et al., 2018) is outside the scope of this research. Macro-characteristics (air void content, permeability) and mechanical properties (particle loss, stiffness, indirect tensile strength, moisture susceptibility) of WMA-RAP PA mixtures prepared as indicated in the following section are studied with the aim to highlight the significant effects of RAP, different compaction temperatures and wax treatment on the studied materials.

1. Materials and methods

1.1. Materials

The characteristics of the mixtures designed for research purposes are presented below.

1.1.1. Tested mixtures

Six different porous asphalt mixtures were produced:

- #0 (ID = "0"): reference baseline PA mixture compacted at 145 °C;
- #1 (ID = "W_R10_T125"): PA WMA-RAP mixture, with 10% RAP content and wax additive, compacted at a lower temperature (125 °C) because of the presence of wax;
- #2 (ID = "W_R20_T125"): similar to mix #1, with 20% RAP content;
- #3 (ID = "W_R30_T125"): similar to mix #1, with 30% RAP content;
- #4 (ID = "R20_T145"): PA added with RAP and compacted at standard temperature (145 °C);
- #5 (ID = "W_R20_T145"): similar to mix #4, but with wax additive (WMA-RAP mix).

Mixtures from 1 to 5 were designed in order to study how physical characteristics and mechanical properties of asphalt are influenced by:

- variation in RAP content in WMA-RAP PAs (specifically comparing Mixtures 1, 2, 3);
- variation in compaction temperature in WMA-RAP PAs (comparing Mixtures 2, 5);
- presence of wax additives in PAs with RAP (comparing Mixtures 4, 5).

1.1.2. Characteristics of baseline materials

The baseline porous asphalt mixture used in this study was designed according to the "ECD" gradation previously used by Ranieri et al.

(2010). The aggregate blend was composed of basalt and gabbro. Other mixtures were prepared by adding reclaimed asphalt pavement (RAP).

The used RAP source originally came from a Stone Mastic Asphalt (SMA) pavement, acquired from a Polish road. The binder originally used in this SMA was highly polymer modified.

The selected gradation curves of different mixture types (with different percentages of RAP ranging from 10% to 30%) are presented in Figure 1. They were chosen to be as close as possible to the minimum and the maximum size passing as reported in the ECD granulometric specification, indicated in the figure. In particular, the aggregate gradation was chosen for each mixture type in order to reach the trade-off between the optimum asphalt content minimization and the adherence to the required mix design. It can be noticed that the curve representing 30% RAP is the farthest from the ECD gradation required due to the high presence of fine material in the used RAP. Once that and the RAP aggregate gradation have been determined, RAP aggregates

Table 1. Granulometric composition of the aggregate blend of the different mixtures and bitumen characteristics

Aggregate			Mixes			
Name	**Size, mm**	**Density, g/cm^3**	**Mix 0% RAP**	**Mix 10% RAP***	**Mix 20% RAP***	**Mix 30% RAP***
Filler	<0.063	2.73	6%	5%	1%	0%
Basalt	0.063–2	3.03	4%	0%	1%	0%
Basalt	2–5.6	3.05	0%	0%	0%	0%
Basalt	5.6–8	3.09	20%	18%	0%	0%
Gabbro	8–11.2	2.99	70%	67%	70%	70%

Bitumen	
Type	Polymer-modified bitumen 45/80-65 (EN 14023 EU Standard)
Content	5.2% (of the aggregates weight)
Main characteristics	45–80 mm^{-1} penetration at 25 °C (PN-EN 1426) softening point at 65 °C (PN-EN 1427) ≤0.5% mass change after ageing (PN-EN 12607-1) ≥60% remaining penetration at 25 °C (PN-EN 12607-1, PN-EN 1426), increase of ≤8 °C of the softening point after ageing (PN-EN 12607-1, PN-EN 1427) flash point at ≥235 °C (PN-EN 13398) Fraas breaking point at ≤–15 °C (PN-EN 12593) ≥70% elastic recovery at 25 °C (PN-EN 13398)

*The RAP aggregate size gradation is 8–11.2 mm: 15%, 5.6–8 mm: 24%, 2–5.6 mm: 32%, 0.063–2 mm: 15%, <0.063 mm: 14%.

were blended with the virgin aggregates to meet the overall mixture gradation requirements. Clearly, the total amount of material for the production of each specimen changed as the amount of added RAP increased.

The final granulometric composition of the aggregate blend of the different mixtures is reported in Table 1, together with information about the bitumen used as a binder.

All specimens were prepared by using polymer-modified bitumen 45/80-65 (complying with EN 14023 European standard) produced in Poland by Lotos Group. This binder content was set as the reference content for all the prepared samples, considering both 6% of the binder already included in the RAP and the virgin binder added to the mix design. The percentage of the binder was not varied across the sample mixes to reduce the number of study variables (such variability may affect physical and mechanical properties, see Čygas et al., 2011).

Cellulose fibers (stabilizer) were added to the mixtures in the amount of 0.4% by aggregate weight. An adhesion agent was also used (0.3%, related to the bitumen weight). Finally, an organic wax additive (Sasobit®) was added to the binder in the amount of 2.5% by the binder weight.

The aggregates were placed in an oven for four hours. After the mixing process, Marshall samples were produced at two different compaction temperatures (125 °C and 145 °C). Mixture compaction was ensured by application of 50 blows of Marshall hammer per sample side.

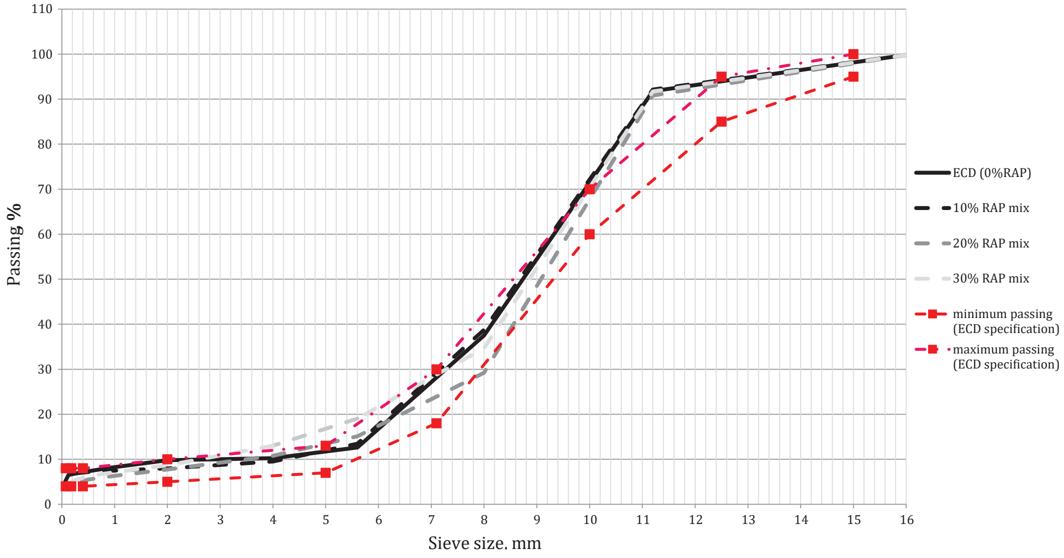


Figure 1. Mixture gradation plot

1.2. Methods

The testing methods used are aimed at inquiring into the variation in physical characteristics and mechanical properties of PAs due to the variation in RAP, wax additive, and compaction temperature.

1.2.1. Testing variation in physical characteristics

Air void content. According to PN-EN 12697-8 specification, the air void content (*Vm*) was calculated on four specimens of each mixture. It was calculated from the maximum density and the bulk density of the specimen.

Permeability. Permeability was estimated using the following index (Ranieri et al., 2010):

$$\mathrm{PI} = P_2 \cdot P_5 \cdot D_{\max}, \tag{1}$$

where:

PI – Permeability Index, the permeability decreases as this index increases;

P_2 – percentage of the aggregate passing to the sieve 2 mm, %;

P_5 – percentage of the aggregate passing at the sieve 5 mm, %;

$D_{\max}$ – maximum diameter of the aggregate, mm.

The higher the calculated PI index, the lower is the permeability of the mixture according to the following experimental relationship (Ranieri et al., 2010):

$$k_{\mathrm{v}} = 0.008 \cdot \exp(-3.8396 \cdot \mathrm{PI}), \tag{2}$$

where k_{v} is the vertical permeability, m/s.

1.2.2. Testing variation in asphalt mechanical properties

Particle loss. The Cantabro test is often used for PAs for measuring the durability and the potential for aggregate loss from mixtures (see Tao & Mallick, 2009). The particle loss of porous asphalt mixtures was calculated on three specimens for each mixture according to PN-EN 12697-17 standard. The particle loss was assessed by the loss of sample mass after 300 turns in the Los Angeles machine.

Stiffness. Stiffness was measured according to the specifications of the European test Standard EN 12697-26. The 25 kN Universal Testing Machine was used on two specimens for each mixture. At a temperature of 12 °C, five load pulses were applied to the specimen and the variation of the applied load and horizontal diametric deformation was measured for each load application. The stiffness modulus was obtained for each load pulse according to Equation 3:

$$S = \frac{F(v + 0.27)}{Z \cdot h}, \tag{3}$$

where:

S = measured stiffness modulus, MPa;

F = peak value of the applied vertical load, N;
z = amplitude of the horizontal deformation, mm;
h = mean thickness of the specimen, mm;
ν = Poisson ratio.

Cracking potential. The indirect tensile strength (ITS) is a reliable indicator of the asphalt mixture cracking potential (Watson et al., 2004): the higher the ITS, the higher the potential resistance to cracking. For this purpose, a compression (flow/stability) Marshall testing machine was used according to EN 12697-23 on three specimens for each mixture. For each test specimen, the indirect tensile strength was calculated (that is, the maximum tensile stress calculated from the peak load applied at break).

Moisture susceptibility. Moisture susceptibility is the tendency of HMA mixtures to lose the adhesion bond between the asphalt and aggregate particles; it is one of the greatest concerns related to pavement performance independently of its mix design. Testing mixes with and without moisture conditioning can aid in measuring their resistance to moisture susceptibility. Hence, three additional freeze-conditioned specimens for each mixture were prepared besides the unconditioned specimens described above. The conditioning was performed by storing water-saturated samples for three days in a water bath at 40 °C, then they were protected from losing the water by a soft plastic bag and placed in a freezer at −18 °C for one day. Finally, they were placed again in the bathtub at 25 °C for another day. Once tested, all samples were loaded diametrically until failure. The Indirect Tensile Strength Ratio (ITSR), used to assess the resistance to moisture susceptibility (the higher the ITSR, the higher the moisture resistance), was determined by Equation 4:

$$\mathrm{ITSR} = \frac{\mathrm{ITSwet}}{\mathrm{ITSdry}} \cdot 100, \tag{4}$$

where:

ITSR = indirect tensile strength ratio, %;
ITSwet = average ITS on the wet group, kPa;
ITSdry = average ITS on the dry group, kPa.

1.2.3. Statistical analyses

A one-way analysis of variance (ANOVA) has been conducted for each measure made with regard to physical and mechanical properties. The response variables of each ANOVA test were, namely:

- air void content (using 24 observations, with 4 specimens for each mixture, including the reference baseline PA mixture);

- particle loss (using 24 observations, with 4 specimens for each mixture);
- stiffness (using 8 observations, with 2 specimens for each mixture);
- indirect tensile strength (ITS) in dry conditions (using 18 observations, 3 specimens for each mixture);
- indirect tensile strength (ITS) in wet conditions (using 18 observations, 3 specimens for each mixture);
- ITS ratio (using 18 observations, with 3 specimens for each mixture).

Factors considered in the ANOVA test were:

- "RAP", that is, presence of RAP (0 = not present, 1 = 10% RAP, 2 = 20% RAP, 3 = 30% RAP);
- "WAX", that is, presence of wax additive (0 = not present, 1 = present);
- "T", that is, compaction temperature (0 = 145 °C, 1 = 125 °C).

In this way, it is possible to assess the contribution of each factor to the differences in the properties of the mixes, accounting for the main effects of the other considered factors.

Due to the unbalanced design, Type-II ANOVA was conducted. Statistically significant differences (at the 5% significance level) between mean values (response variables) of different groups may indicate which factors have the most significant influence on the variation in physical and mechanical properties. Post-hoc tests (Tukey adjusted) were applied in case of statistically significant differences associated with the RAP factor (since it is the only factor with more than two levels). Statistical analyses were run in R environment.

It should be noted that the permeability index (Equation 1) was not used as a response variable for ANOVA tests, since only one measure for each mixture was possible. Moreover, it is clearly related to the porosity, as discussed below. Outlier values were discharged from the dataset before the analysis, excluding one observation in particle loss measures from Cantabro tests and one ITS measure in dry conditions (and then one measure of ITS ratio). The ITS ratio was obtained for each of the 18 observations by applying Equation 4, considering the average ITS measure in dry conditions and the ITS measure in wet conditions for each of the three specimens made with the mixtures investigated. Moreover, due to the limited number of samples, interaction terms were not considered in the ANOVA model specifications.

Given the research questions of this study, results from the analyses were used to consider the influence of different factors on the RAP-WMA PA characteristics and mechanical properties. Life cycle assessments (see, e.g., Oner & Sengoz, 2015; Riekstins et al., 2020) are outside the scope of this study, while they may be useful in the future, once the properties of different WMA-RAP PAs will be consolidated based on research outcomes.

2. Results

The results obtained are presented and discussed below.

2.1. Physical characteristics

Results concerning physical characteristics are graphically depicted in Figure 2, while ANOVA results are summarized in Table 3.

Table 3. Results from the ANOVA tests for physical characteristics

Response variable: Air Void (AV) content					
	Mean difference (AV)	***df***	***Sum of squares***	***F statistic***	***p-value****
RAP	(see post-hoc below)	3	13.02	10.00	**<0.001**
WAX (yes VS no)	2.25**	1	10.13	23.34	**<0.001**
T (125 °C VS 145 °C)	–1.50**	1	4.50	10.38	**0.005**
Residuals		18	7.81		

Tukey post-hoc test (*p*-values* and statistically significant mean differences in AV reported in the parenthesis)

	RAP = 0%	**RAP = 10%**	**RAP = 20%**	**RAP = 30%**
RAP = 0%	–	–	–	–
RAP = 10%	0.716	–	–	–
RAP = 20%	**0.005 (–1.85)****	0.099	–	–
RAP = 30%	**0.008 (–2.43)****	**0.008 (–1.15)****	0.614	–

**p-values in bold indicate statistical significance (5% significance level).*
***Tukey-adjusted mean differences.*

2.1.1. Air void content

Mix #4 (R20_T145), which is a RAP PA not supplemented with wax and compacted at 145 °C, has the lowest value of the air void average, while Mix #5 (W_R20_T145) shows the highest value. If an environmental concern is considered and the temperature is lowered (down to 125 °C), the highest voids are achieved with a low RAP content (Mix #1, 10% RAP). Hence, with respect to the baseline PA mixture,

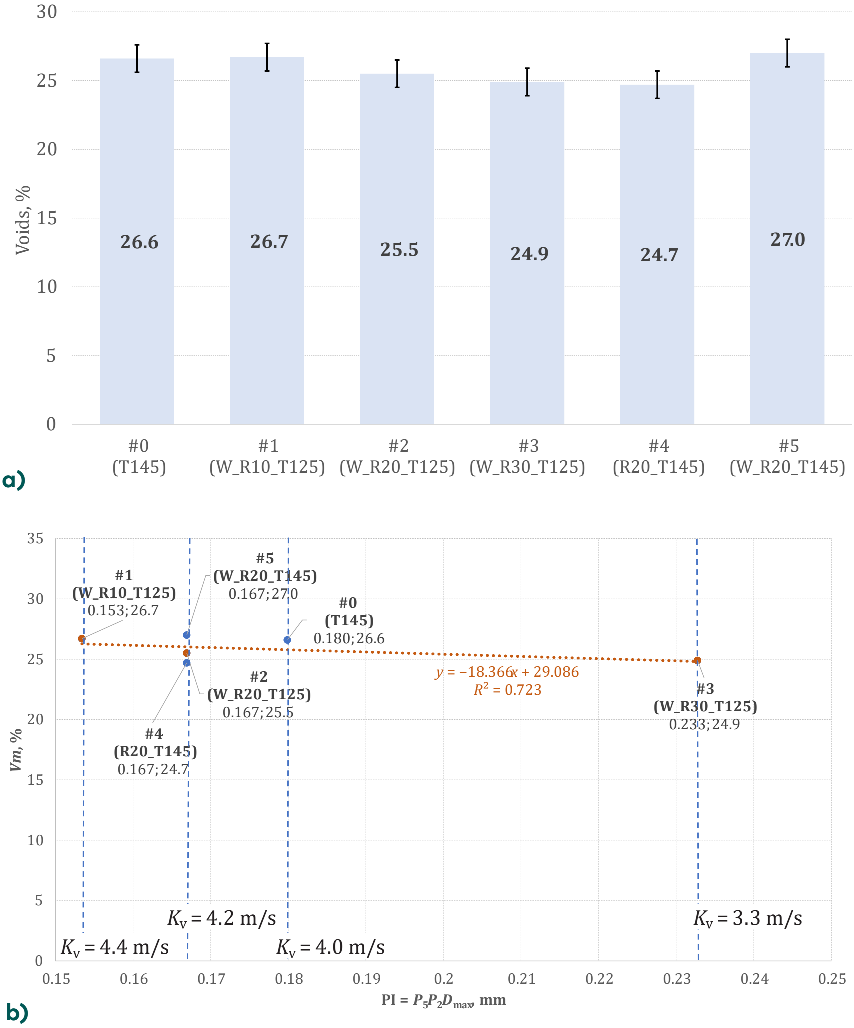


Figure 2. Results in terms of physical characteristics: a) air void content, b) relation between air void content and permeability index PI (values of the vertical permeability deduced from Equation 2 are reported along dashed lines for each PI value)

the WMA-RAP PA mixture is related to a general decrease in voids and density, except in the case of using a 145 °C compaction temperature. In particular, the use of at least 20% RAP (Mixes #2, W_R20_T125 and #3, W_R30_T125) leads to a statistically significant different average air content with respect to the baseline PA mixture.

Concerning the RAP amount in WMA-RAP PAs, the increasing RAP percentage is related to a decrease in the air void content. In fact, there is a decrement of 7% in average air voids between Mix #1 (W_R10_T125) and Mix #3 (W_R30_T125) found to be statistically significant as well.

From the comparison between Mix #4 (R20_T145, without wax additive) and Mix #5 (W_R20_T145, with wax additive), it is possible to notice a great increase (around 9%) in air void. In fact, the presence of wax additive itself is associated with a statistically significant increase in the mean air void content.

Increasing the compaction temperature from Mix #2 (W_R20_T125) with wax additive to Mix #5 (W_R20_T145), the air void content increases by about 6%. In fact, the temperature factor was identified to produce statistically significant differences.

2.1.2. Permeability

In general, as the air void content increases, the permeability also increases (the index $P_2 \cdot P_5 \cdot D_{\max}$ decreases).

With respect to the baseline PA mixture, all other mixes show an increased permeability (lower $P_2 \cdot P_5 \cdot D_{\max}$ index), except for the WMA-RAP with 30% RAP (mix #3, W_R30_T125). The highest permeability is shown for mix #1 (W_R10_T125).

A linear porosity-permeability trend can be noticed for mixes #1 (W_R10_T125), #2 (W_R20_T125) and #3 (W_R30_T125). So, increasing the RAP amount (considering the same compaction temperature and the same wax additive quantity), the air void content decreases while $P_2 \cdot P_5 \cdot D_{\max}$ increases. Hence, by increasing the RAP amount in WMA-RAP PAs, the permeability should evidently decrease.

Whereas, by looking at differences between Mixes #2 (W_R20_T125), #4 (R20_T145), 5 (W_R20_T145), it is possible to note that for the same amount of RAP (20%), different compaction temperatures or the use of the wax additive does not influence permeability.

It is however important to note that once converted into the vertical permeability values through Equation 2 (see Figure 2), the differences in permeability are very limited (i.e., in the order of 0.1 mm/s). The most significant difference is for WMA-RAP PAs produced with high RAP content (30%) compared to lower contents, which is in the order of 1 mm/s, thus still practically having weak significance for the drainage purposes.

Table 4. Results from the ANOVA tests for asphalt mechanical properties

Response variable: Stiffness, S

	Mean difference, S	*df*	*Sum of squares*	*F statistic*	*p-value**
RAP	(more than 1 group)	3	698271	2.137	0.197
WAX (yes VS no)	–831**	1	690561	6.339	**0.045**
T (125 °C VS 145 °C)	270**	1	73170	0.672	0.444
Residuals		6	653639		

Response variables: Indirect Tensile Strength in dry conditions (ITSd) and Indirect Tensile Strength in wet conditions (ITSw)

	Mean difference (ITSd)	*df*	*Sum of squares*	*F statistic*	*p-value**
RAP	(see post-hoc below)	3	0.0514	7.10	**0.006**
WAX (yes VS no)	–0.05**	1	0.0043	1.77	0.210
T (125 °C VS 145 °C)	–0.05**	1	0.0043	1.77	0.210
Residuals		11	0.0265		

	Mean difference (ITSw)	*df*	*Sum of squares*	*F statistic*	*p-value**
RAP	(see post-hoc below)	3	0.0114	9.46	**0.002**
WAX (yes VS no)	0.04**	1	0.0028	7.04	**0.021**
T (125 °C VS 145 °C)	–0.07**	1	0.0081	20.17	**<0.001**
Residuals		12	0.0048		

Tukey post-hoc test (*p*-values* and statistically significant mean differences in ITSd reported in the parenthesis)

	RAP = 0%	**RAP = 10%**	**RAP = 20%**	**RAP = 30%**
RAP = 0%	–	–	–	–
RAP = 10%	0.552	–	–	–
RAP = 20%	0.078	0.839	–	–
RAP = 30%	**0.010 (0.24)****	**0.018 (0.16)****	0.064	–

Tukey post-hoc test (*p*-values* and statistically significant mean differences in ITSw reported in the parenthesis)

	RAP = 0%	**RAP = 10%**	**RAP = 20%**	**RAP = 30%**
RAP = 0%	–	–	–	–
RAP = 10%	0.498	–	–	–
RAP = 20%	0.120	0.976	–	–
RAP = 30%	**0.004 (0.10)****	**0.005 (0.07)****	**0.010 (0.06)****	–

Response variable: Indirect Tensile Strength Ratio (ITSR)

	Mean difference (ITSR)	*df*	*Sum of squares*	*F statistic*	*p-value**
RAP	(see post-hoc below)	3	204.86	3.84	0.039
WAX (yes VS no)	15.80**	1	376.04	21.12	<0.001
T (125 °C VS 145 °C)	–5.37**	1	43.20	2.43	0.145
Residuals		12	213.64		

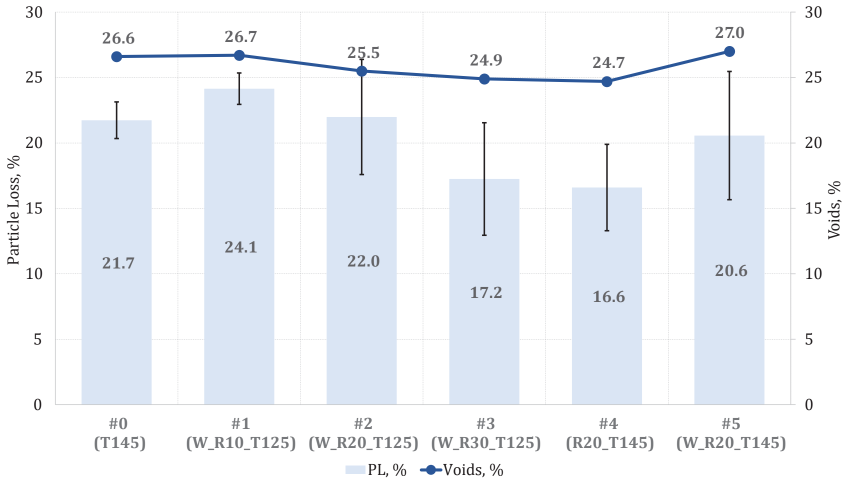
Tukey post-hoc test (*p*-values* and statistically significant mean differences in ITSR reported in the parenthesis)

	RAP = 0%	**RAP = 10%**	**RAP = 20%**	**RAP = 30%**
RAP = 0%	–	–	–	–
RAP = 10%	0.870	–	–	–
RAP = 20%	0.300	0.865	–	–
RAP = 30%	0.078	0.072	0.245	–

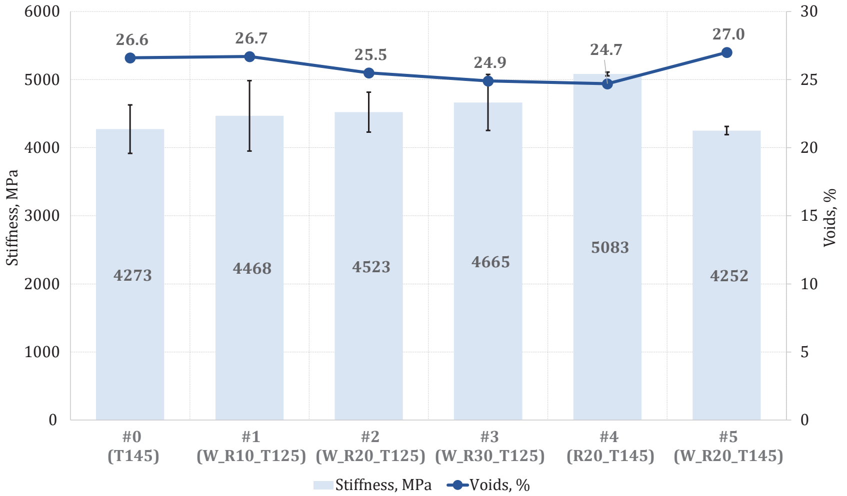
**p*-values in bold indicate statistical significance (5% significance level).
**Tukey-adjusted mean differences.

2.2. Mechanical properties

Results concerning mechanical properties (particle loss, stiffness, and tensile strength) are graphically depicted in Figure 3, while ANOVA results are summarized in Table 4.

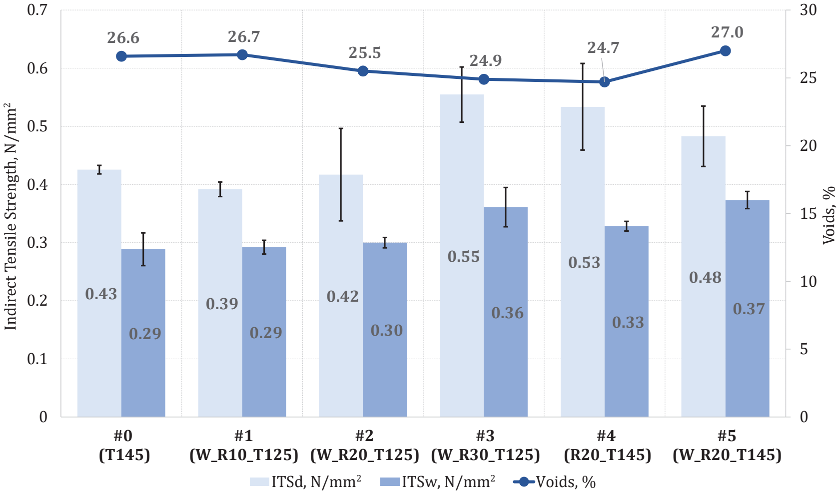


a) particle loss

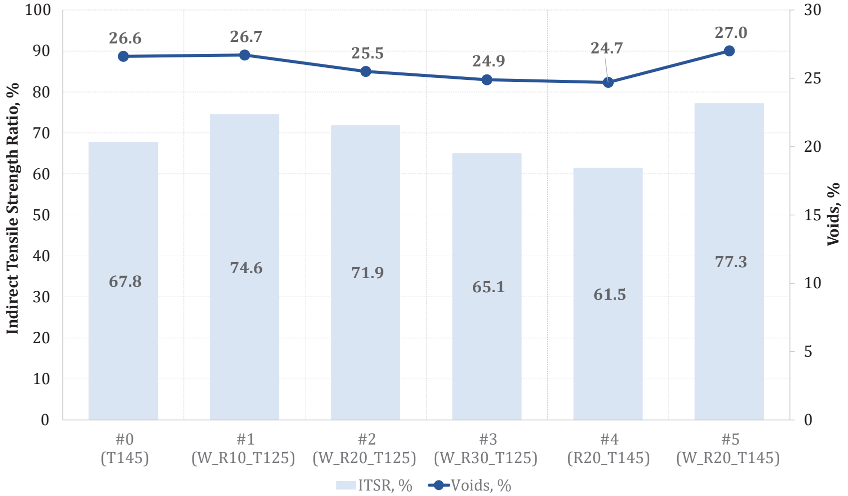


b) stiffness

Figure 3. Results in terms of mechanical properties of the asphalt:
a) particle loss, b) stiffness, c) indirect tensile strength, d) indirect tensile strength ratio



c) indirect tensile strength



d) indirect tensile strength ratio

Figure 3. (continuation) Results in terms of mechanical properties of the asphalt: a) particle loss, b) stiffness, c) indirect tensile strength, d) indirect tensile strength ratio

2.2.1. Particle loss

The results show that particle loss is strictly related to the air void content: as the PL index increases, the voids generally increase as well. A significantly increased cohesiveness (decreased particle loss) can be noted for high RAP content (30%) WMA-RAP mixtures (Mix #3) and for RAP mixtures (without wax) compacted at 145 °C (Mix #4). A decreased cohesiveness (increased particle loss) can be observed for low RAP content (10%) WMA-RAP mixtures (Mix #1) instead.

Considering WMA-RAP PA mixes from #1 to #3 compacted at 125 °C, it can be determined that the mixture with higher amount of RAP exhibits better resistance to particle loss: the PL index decreases of 40% in Mix #3 (W_R30_T125) compared to Mix #1 (W_R10_T125). Differences due to the RAP factor were found to be statistically significant (i.e., the higher the RAP content, the lower the PL). However, pairwise comparisons adjusted for multiple comparisons reveal no statistically significant differences between different RAP contents (also with respect to the reference PA Mix #0).

The wax factor was not found to have a statistically significant influence on particle loss. However, adding the wax additive to a RAP PA results in a slight increase in the void content and a less cohesive mixture. This emerges from the comparison between Mix #4 (R20_T145) and #5 (W_R20_T145).

The compaction temperature factor was not found to have a statistically significant influence on particle loss either. In fact, only a slight decrease in PL (–7%) can be noted between Mix #2 (W_R20_T125) and #5 (W_R20_T145), which differ from each other in the compaction temperature only.

2.2.2. Stiffness

It can be immediately noticed that stiffness seems to be strictly correlated to the void content as well: the greater the void content, the lower the stiffness. All mixtures different from the reference standard PA mix show higher stiffness values, except for Mix #5 (W_R20_T145), which is a WMA-RAP with wax compacted at 145 °C. The better result in terms of stiffness is achieved by Mix #4 (R20_T145) and Mix #3 (W_R30_T125), considering only WMA mixes.

Comparing WMA-RAP PA mixes with different RAP percentages, the higher the RAP percentage (from Mix #1, W_R10_T125 to Mix #3, W_R30_T125), the higher the stiffness becomes (up to 4% more for Mix #3), even if the differences due to RAP were not highlighted as statistically significant (also with respect to the reference PA mix).

The presence of wax additive lowers the stiffness of the mixtures by about 20% (other conditions being equal, considering the comparison between Mixes #4, R20_T145 and #5, W_R20_T145). Differences due to the presence of wax (the higher the wax content, the lower the stiffness) are indeed highlighted as statistically significant. WMA-RAP PA mixes from #1 to #3 have slightly higher stiffness than the reference PA mix even if wax is added, but this effect is due to the presence of RAP.

The increased compaction temperature (145°C) is related to a decrease in stiffness (−6% if mix #5, W_R20_T145 is directly compared to mix #2, W_R20_T125). However, differences due to the temperature factor are not statistically significant.

2.2.3. Indirect tensile strength

It can be generally noted that the higher the RAP percentage and the compaction temperature, the higher the ITS value. Moreover, there is a weak relationship between air void content and ITS.

In particular, with respect to the reference PA mixture, the presence of RAP significantly affects the ITS (both the dry and the wet measures). In detail, a 30% of RAP (Mix #3, W_R30_T125) is needed to achieve statistically significant differences (in both cases). Moreover, between WMA-RAP Mixes #1 and #3, ITS is increased by 41% (in dry conditions) and by 23% (in wet conditions).

The presence of the wax additive statistically significantly affects the ITS in wet conditions. In fact, in dry conditions, the ITS even decreases by about 5%, while it increases by 12% in wet conditions (comparison between RAP Mixes #4 and #5, at 145 °C compaction temperature, without and with wax additive).

The presence of the compaction temperature significantly affects the ITS only in wet conditions as well. This is clear while comparing Mixes #2 (W_R20_T125) and #5 (W_R20_T145): the ITS increases by 14% in dry conditions, but by 23% in wet conditions.

2.2.4. Moisture susceptibility

From a moisture resistance perspective (related to the ITSR content), the best performance was achieved by Mix #5 (W_R20_T145). Among WMA PAs, the best performance was shown by Mix #1 (with a low RAP content: 10%).

Analysis results are straightforward. In fact, since the RAP content influences both the dry and wet ITS, the pairwise differences in ITSR between mixes with different RAP content are not statistically significant. Hence, while the moisture resistance related to ITSR slightly decreases between Mixes #1 and #3 with different RAP contents, the moisture resistance is comparable, on average, to the performance of reference Mix #0.

On the other hand, wax and compaction temperature statistically significantly affected only the ITS in wet conditions. This is reflected in the influence of wax on ITSR (which is not valid for temperature either). The presence of wax clearly leads to an increase in the ITSR (as is evident by looking at the comparison between Mixes #4 and #5) and then to an increase in moisture resistance.

3. Discussion

As demonstrated by Table 5 below, in general, some RAP PA mixes (in bold or underlined) systematically show better mechanical properties than the reference PA. Moreover, some RAP PA mixes show both an increased porosity (*Vm*) and permeability (measured through the PI index).

In detail, adding wax and using high compaction temperatures result in significantly increased porosity, other conditions being equal (see Table 5). The result concerning temperatures is surprising if compared with the results for ordinary asphalt mixes (see, e.g., Gao et al., 2014) and wax-treated porous asphalt mixes (see, e.g., Ranieri et al., 2017, Chen & Wang, 2013), which reveal opposite trends. In this case, other conditions being equal, a significant increase in porosity can be observed comparing WMA RAP PAs compacted at high temperature (145 °C) to the one compacted at 125 °C. Hence, porosity differences due to temperature in WMA-RAP-PAs are worth further investigation. On the other hand, high RAP contents (20–30%) result in a significantly decreased porosity (Table 4), which is coherent with the results from Goh & You (2012) and Frigio et al. (2013). In fact, among WMA-RAP PAs, the highest porosity is related to low RAP content (Mix#1, W_R10_T125). Moreover, the highest permeability is reached for the same low RAP WMA RAP PA (Mix#1), followed by all the 20% RAP mixes. It should be noted, however that, as already previously stated, even if statistically significant, the difference in permeability is practically slightly relevant (in the order of 0.1–1 mm/s).

As far as mechanical properties are concerned, clearly, there are advantages and disadvantages in considering different factors alone. In general, from Table 5 it is evident that:

- adding wax leads to a significant decrease in stiffness and an increase in moisture resistance;
- high RAP contents (30%) are pronouncedly related to an increase in the indirect tensile strength (both in dry and wet conditions);
- cohesiveness (and then durability) is not significantly affected by RAP, wax, or compaction temperature.

Table 5. Summary and comparison of results from the test program

Results from the test program*

Mix	**Characteristics**		**Mechanical properties**				
	Vm, %	**PI, mm**	**PL, %** [as PL decreases, cohesiveness increases]	**S, MPa**	**ITSd, MPa** [as ITS increases, cracking resistance increases]	**ITSw, MPa**	**ITSR, %** [as ITSR increases, moisture resistance increases]
0	26.6	0.180	21.7	4273	0.43	0.29	67.8
#1: W_R10_T125	26.7	**0.153**	24.1	4468	0.39	0.29	74.6
#2: W_R20_T125	25.5	0.167	22.0	4523	0.42	0.30	71.9
#3: W_R30_T125	24.9	0.233	17.2	4665	**0.55**	0.36	65.1
#4: R20_T145	24.7	0.167	**16.6**	**5083**	0.53	0.33	61.5
#5: W_R20_T145	27.0	0.167	20.6	4252	0.48	**0.37**	**77.3**

Influence of different factors highlighted from statistical tests**

(+ = characteristics/mechanical properties significantly increase,
– = characteristics/mechanical properties significantly decrease)

Factor	**Characteristics**	**Mechanical properties**				
	Vm, %	**PL, %** [as PL decreases, cohesiveness increases]	**S, MPa**	**ITSd, MPa** [as ITS increases, cracking resistance increases]	**ITSw, MPa**	**ITSR, %** [as ITSR increases, moisture resistance increases]
RAP 30 vs 0	–			+	+	
RAP 20 vs 0	–					
RAP 10 vs 0						
RAP 30 vs 20				+		
RAP 30 vs 10	–			+	+	
RAP 20 vs 10						
wax vs no wax	+		–	+		+
T 125 vs T 145	–			–		

*The best values among the six tested mixes (including the reference mix) according to each measure are reported in bold, while the second-best values are underlined.

**Statistical tests were not run on the PI index since only one measure for each mix was available.

However, the indications provided in Table 5 can be combined to obtain the following remarks:

- with regard to stiffness, a good trade-off between environmental and performance-related aspects is reached by the WMA high RAP content (30%) mix (Mix #3: W_R30_T125), for which the second-best stiffness was recorded;
- with regard to moisture resistance, the WMA low RAP content (10%) mix (Mix #1: W_R10_T125) is a good trade-off between the environmental and performance-related aspects, for which the second-best moisture resistance was recorded, which, however, may be lower than the minimum required by some road construction standards.

In summary, high RAP content (30%) WMA-RAP PAs (supplemented with wax, mixes from #1 to #3) show an excellent cracking resistance (see also Goh & You, 2012, in case of 15% RAP content), higher stiffness and cohesiveness compared to standard reference PAs, while they have lower porosity, permeability and moisture resistance (see also Guo et al. (2014) or Frigio & Canestrari (2018)). Low RAP content (10%) WMA-RAP PAs (supplemented with wax) show good permeability (related to very high porosity), higher moisture resistance, and relatively higher stiffness compared to standard reference PAs, while they have lower cohesiveness and indirect tensile strength.

The above-stated mechanical properties of WMA-RAP PAs are to a great extent attributable to the asphalt mixtures tested and the type/quantity of additive used (organic wax: Sasobit). In fact, performance may vary and even show opposite tendencies if the asphalt mixture composition and the type/amount of additives vary (see a comprehensive review reported in (Hettiarachchi et al., 2019; Cheraghian et al., 2020) which however mostly refers to dense-graded mixes, or (Sanchez-Alonso et al., 2011; Li et al., 2015). It was shown in the previous research related to WMA-RAP PAs that by varying the additive type, moisture resistance (Frigio & Canestrari, 2018; Frigio et al., 2017) and stiffness and fatigue behaviour (Frigio et al., 2016) can significantly vary.

As far as RAP PAs (Mix #4: R20_T145) are concerned, they show excellent cohesiveness (see also Frigio et al., 2014) and stiffness, higher permeability, and indirect tensile strength (see also Goh & You, 2012), while they have a lower porosity (Goh & You, 2012; Frigio et al., 2013) and moisture resistance. If wax is added (Mix #5: W_R20_T145), RAP PAs demonstrate improved moisture resistance, even at the worsened indirect tensile strength, stiffness and cohesiveness.

Conclusions

The effect of different RAP contents, presence of wax and different compaction temperatures was studied in detail with specific regard of the porous asphalt (PA) specimens. Characteristics and mechanical properties of the produced PAs were studied through a detailed test program. In particular, air void content, permeability, particle loss, stiffness modulus, indirect tensile strength (in dry and wet conditions), and indirect tensile strength ratio, were measured.

Statistical tests were conducted to assess the influence of each factor (RAP, wax, temperature), considering the variation of the other factors. The wax additive is significantly responsible for an increase in porosity (also while using high compaction temperatures), a decrease in stiffness, and an increase in moisture resistance measured through the ITS ratio. High RAP contents (30%) are significantly related to an increase in the indirect tensile strength. Cohesiveness measured through the particle loss seems to be not significantly affected by RAP, wax, or compaction temperature.

As far as advantages and disadvantages of different mixes are concerned:

- High RAP content (30%) WMA-RAP PAs show higher indirect tensile strength, stiffness, and cohesiveness compared to the reference PAs, while they have lower porosity, permeability, and moisture resistance;
- Low RAP content (10%) WMA-RAP PAs show higher porosity, permeability, moisture resistance, and stiffness compared to the reference PAs, while they have lower cohesiveness and indirect tensile strength;
- RAP PAs (20% RAP) show higher cohesiveness, stiffness, permeability, and indirect tensile strength than the reference PAs, while they demonstrate lower porosity and moisture resistance. If wax is added (WMA-RAP), moisture resistance is improved, while indirect tensile strength, stiffness, and cohesiveness get worse.

As far as the compaction temperature is concerned, lowering the compaction temperature in the WMA process (down to 125 °C) affects only the porosity, which decreases, and the ITS in dry conditions, which decreases either, while the ITSR is not statistically significantly affected. However, even if the porosity significantly decreases, especially considering the 30% RAP mixture, the corresponding computed permeability is still acceptable (i.e., about 3 mm/s). On the other hand, the cracking resistance could actually be unacceptable, especially considering the 10% RAP mixture.

Hence, the decision to use lower compaction temperatures in the case of WMA-RAP PAs, which results in saving energy and thus allows implementing the environmental agenda, could be adopted, even if it is subject to some important remarks. In fact, the appropriate amount of RAP in the mixture should be determined by considering all the requirements provided by specific country standards and, in particular, the strictest requirements. In other words, depending on the strictness of different regulatory requirements in terms of particle loss, stiffness, indirect tensile strength, moisture resistance, porosity, and permeability, different amounts of RAP may be acceptable. In particular, while all porosity, permeability, and stiffness values of WMA-RAP PAs (Mixes from #1 to #3) may be acceptable, one or more measures among particle loss, indirect tensile strength in dry conditions and the indirect tensile strength ratio could not meet specific standards/regulations. In detail, considering the extreme percentages, a 10% RAP content may lead to the development of acceptable moisture resistance, but unacceptable cohesiveness and/or cracking resistance; while a 30% RAP content may lead to a satisfying cracking resistance and cohesiveness, while unacceptable moisture resistance. The 20% RAP mixture clearly shows good performance in terms of cohesiveness, cracking, and moisture resistance, which constitutes a trade-off between the two extreme RAP percentages.

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Disclosure Statement

The authors have no competing financial, professional, or personal interests from other parties to declare.

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