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Interlayer bonding properties of warm recycled asphalt pavements

Gilda Ferrotti [1], Lorenzo Paolo Ingrassia [1*], Francesco Canestrari [1]

[1] *Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy*

Abstract

The need for sustainable road infrastructures has led to great interest in Warm Mix Asphalt (WMA) technologies, which allow the production, lay-down and compaction of asphalt mixtures at reduced temperatures, about 40°C lower than traditional Hot Mix Asphalt (HMA). The use of WMA ensures lower emissions and is also beneficial in the recycling of Reclaimed Asphalt (RA) deriving from the milling of end-of-life pavements. One of the main concerns regarding WMA is the possible poor adhesion between the pavement layers that could be caused by the reduced working temperatures during the paving operations. However, almost no data are currently available in literature on this aspect, which thus could represent a deterrent to the wide application of WMA by road agencies. In this regard, this paper focuses on the investigation of the interlayer bonding properties of warm recycled asphalt pavements constructed along various Italian motorways and national roads using different WMA chemical additives. The Interlayer Shear Strength (ISS) was measured at different pavement interfaces (wearing-binder, binder-base) and time intervals by testing extracted cores with ASTRA and Leutner equipment. The results show that the interlayer bonding properties of WMA pavements are comparable to HMA pavements and are not affected by the WMA additive type. Moreover, ISS depends on the properties of the tack coat applied between the layers and increases over time due to aging effects, especially when the interface is below an open-graded friction course (OGFC). These findings further encourage the use of WMA as environmentally sustainable technologies for the construction and maintenance of asphalt pavements.

Keywords: Asphalt pavement; Warm Mix Asphalt (WMA); full-scale field trial; Interlayer Shear Strength (ISS); Reclaimed Asphalt (RA); sustainable road infrastructure.

1. Introduction

In recent years, the need for sustainable road infrastructures has led to great interest in Warm Mix Asphalt (WMA) technologies, which allow the production, lay-down and compaction of asphalt mixtures at reduced temperatures, about 40°C lower than traditional Hot Mix Asphalt (HMA). The use of WMA ensures lower emissions and fumes, reducing the environmental impact and the health risks for the workers. In addition, significant energy savings can be achieved as compared to HMA (Capitão et al., 2012; Cheraghian et al., 2020; Rubio et al., 2012; Thives and Ghisi, 2017).

* Corresponding author: Lorenzo Paolo Ingrassia (l.p.ingrassia@pm.univpm.it)

At the same time, the reduced working temperatures are also beneficial in the recycling of Reclaimed Asphalt (RA) deriving from the milling of end-of-life pavements. In fact, the lower binder aging deriving from the temperature reduction allows the use of higher RA amounts, in full agreement with the circular economy objectives (Guo et al., 2020; Hettiarachchi et al., 2019).

However, one of the main issues still open about WMA is the possible poor adhesion between the pavement layers that could be caused by the reduced working temperatures. In fact, during the paving operations, the lower temperature could imply only a partial softening of the bitumen of the underneath materials (i.e. tack coat and upper part of the underlying layer), thus negatively affecting the interlayer bonding properties. It is well known that a good interlayer bonding is necessary for the transfer of the shear stresses caused by the traffic loadings within the pavement. If bonding is not ensured, the pavement does not behave as a whole, leading to its premature failure (Uzan et al., 1978). Therefore, this uncertainty could represent a deterrent to the wide application of WMA by road agencies.

So far, only few studies have focused on the investigation of the Interlayer Shear Strength (ISS) of WMA pavements. Pasquini et al. (2015) studied double-layered specimens produced in the laboratory without any tack coat at the interface. They found that, at any temperature, the ISS values of WMA specimens (prepared with both plain and modified bitumen) were comparable with those of the corresponding HMA specimens. Stimilli et al. (2017a) tested the wearing-binder and binder-base interfaces of cores extracted from a full-scale field trial constructed along an Italian motorway. The field trial was composed of several sections constructed with different tack coats. Overall, the reduced lay-down temperatures of WMA did not show any detrimental effect on the interlayer bonding. It is evident that the data available in literature are very limited and do not allow to draw firm conclusions about the adhesion between the layers in WMA pavements.

Within this framework, this paper investigates the interlayer bonding properties of several warm recycled asphalt pavements constructed along various Italian motorways and national roads using different WMA chemical additives. Specifically, ISS was measured at different pavement interfaces (wearing-binder, binder-base) and time intervals by testing extracted cores with ASTRA (Ancona Shear Testing Research and Analysis) and Leutner equipment. The investigation allowed to assess also the effect of the tack coat properties and the mixture type as well as the influence of the production in different asphalt plants.

2. Experimental program

2.1 Field trials

The main information on the investigated field trials is summarized in Table 1 and described below. Moreover, a scheme of the cross-section of the field trials is provided in Figure 1.

Field trial 1 was constructed in April 2016 along the A1 Italian motorway. The project consisted in the milling and reconstruction of all the asphalt layers. Field trial 1 was composed of four consecutive sections, coded as HMA_1, WC1_1, WC2_1 and WC3_1, with equal length (200 m) and the same pavement structure: a 4 cm open-graded friction course (OGFC) containing 15% of RA, a 10 cm binder layer containing 25% of RA, and a 15 cm base layer containing 30% of RA, over the existing cold recycled subbase layer (25 cm). The virgin bitumen as well as the bitumen from RA were styrene-butadiene-styrene (SBS) polymer modified (3.8% of polymers by binder weight). At the tested OGFC-binder interface, a hot SBS bitumen (3.8% of polymers) with a dosage of 0.6 kg/m^2 was applied as tack coat. In each section (WC1_1, WC2_1 and WC3_1), the three asphalt mixtures (OGFC, binder and base) were produced with the same WMA chemical additive. All the additives employed were commercial products. Specifically, the additive C1 was composed of ammine substances acting as surfactants and adhesion enhancers, the additive C2 was composed of alkylates and fatty acids acting as viscous regulators, the additive C3 was composed of surfactants. Their dosages were chosen within the range recommended by the producers. The production and compaction temperatures were respectively 170°C and 160°C for the HMA mixtures, whereas 130°C and 120°C were selected for the WMA mixtures. Additional information on the field trial, the materials used and the properties of the mixtures can be found in previous publications (Ingrassia et al., 2021; Stimilli et al., 2017b).

Field trial 2 was constructed in October 2015 along the A14 Italian motorway. The OGFC (4 cm) and the binder layer (8 cm) were milled and reconstructed over the existing base layer. Field trial 2 was composed of three sections, coded as HMA_2, WC1_2 and WC2_2. Each section was divided into two sub-sections to study different interlayer configurations. In one sub-section, at both the OGFC-binder and the binder-base interfaces, a cationic emulsion with a dosage of 0.3 kg/m^2 of residual bitumen was applied as tack coat. In the other sub-section, hot applied SBS bitumen (0.5 kg/m^2) was used at the OGFC-binder interface, whereas no tack coat was applied at the binder-base interface. The WMA additives (C1 and C2), the mix design of the OGFC and the binder mixtures as well as the working temperatures adopted for HMA and WMA were the same as those considered for field trial 1. More details about field trial 2, the materials used and the properties of the mixtures can be found in Stimilli et al. (2017a).

Field trial 3 was constructed in July 2020 along SS16, an Italian road of national interest. The dense-graded wearing layer (4 cm) and the binder layer (5 cm) were milled and reconstructed over the existing base layer (20 cm). Field trial 3 consisted of two consecutive sections, coded as HMA_3 and WMA_3, each one with a length of about 100 m. The wearing mixture and the binder mixture of the reference HMA_3 section were produced with a SBS polymer modified bitumen and contained 15% and 20% of RA, respectively. The use of WMA technology allowed the optimization of the mix design, thus increasing the RA content up to 25% in the wearing layer and 30% in the binder layer. In the WMA_3 section, the wearing and binder mixtures were produced with the additive C1, dosed according to the producer recommendations. The production and compaction temperatures were respectively 170°C and 160°C for the HMA mixtures, whereas 130°C and 120°C were selected for the WMA mixtures. No tack coat was applied at the wearing-binder interface.

Table 1: Main information on the field trials.

Field trial	*Location*	*Construction*	*Sections*	*Constructed layers*
1	Motorway A1	April 2016	HMA_1, WC1_1, WC2_1, WC3_1	OGFC (15% RA), binder (25% RA), base (30% RA)
2	Motorway A14	October 2015	HMA_2, WC1_2, WC2_2	OGFC (15% RA), binder (25% RA)
3	National road SS16	July 2020	HMA_3, WMA_3	Wearing (15% or 25% RA), binder (20% or 30% RA)

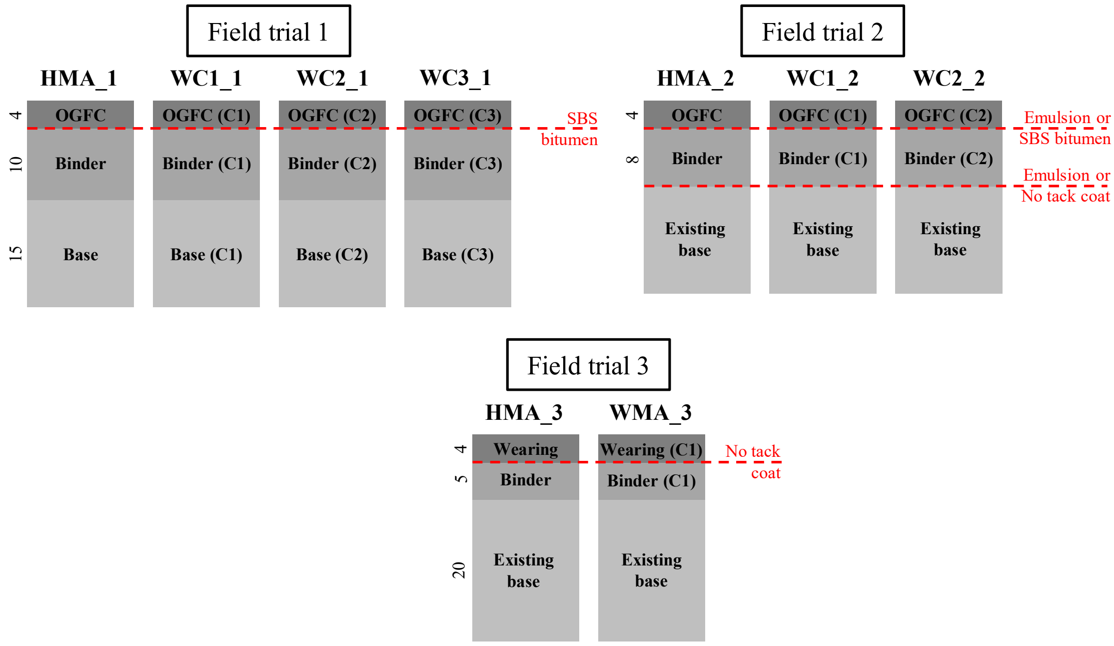

Figure 1: Scheme of the cross-section of the field trials (thicknesses in cm).

2.2 Testing program and procedures

The interlayer bonding properties were assessed through ASTRA and Leutner tests carried out on 100 mm diameter cores taken from the field trials, according to the testing program summarized in Table 2.

The ASTRA tests were performed considering a horizontal displacement rate of 2.5 mm/min and a normal stress of 0.2 MPa, whereas the Leutner tests were performed considering a vertical displacement rate of 50.8 mm/min, without any normal load (EN 12697-48, 2021). In both cases, the testing temperature was 20°C. Both tests (ASTRA and Leutner) allowed the calculation of the Interlayer Shear Strength (ISS) as the ratio between the maximum shear force and the interlayer contact area.

The testing program allowed to evaluate the effect on ISS of several variables, such as WMA technology, WMA additive, age, tack coat properties, mixture type and asphalt plant production. Specifically, the effect of age was assessed for field trial 1 by performing the shear tests immediately after the construction in 2016 and after three and half years of in-service life in 2019. Moreover, the mixtures used for the construction of field trial 1 and field trial 2 were produced in two different asphalt plants but considering the same mix design, production process and materials, thus allowing to assess the influence of the production in different plants.

Table 2: Testing program.

Field trial	*Equipment*	*Interface*	*Specimens*
1 (2016)	ASTRA	OGFC-binder	5
1 (2019)	Leutner	OGFC-binder	5 (3 for HMA_1)
2	ASTRA	OGFC-binder	3
		Binder-base	3
3	Leutner	Wearing-binder	5 (4 for WMA_3)

3. Results and analysis

3.1 Interlayer shear strength

Figure 2 shows the average ISS values obtained. The error bars represent the standard deviation. It should be noted that the graphs in Figure 2 present different scales on the y-axes to emphasize the differences between the results obtained from ASTRA and Leutner tests. In fact, the different testing conditions in terms of displacement rate always lead to higher ISS values in the case of Leutner tests. These results are discussed in detail in the following sections, which focus on the analysis of several variables, including the effects of WMA technology, WMA additive, age, tack coat properties, mixture type, and the influence of the production in different asphalt plants.

Specifically, to assess whether the observed differences were significant or not from a statistical point of view, one-factor analysis of variance (ANOVA) was performed, where possible. A confidence level of 95% was considered, meaning that the difference was statistically significant only if the calculated p-value was lower than 0.05. The outcomes of the ANOVA analysis are presented in the sections below.

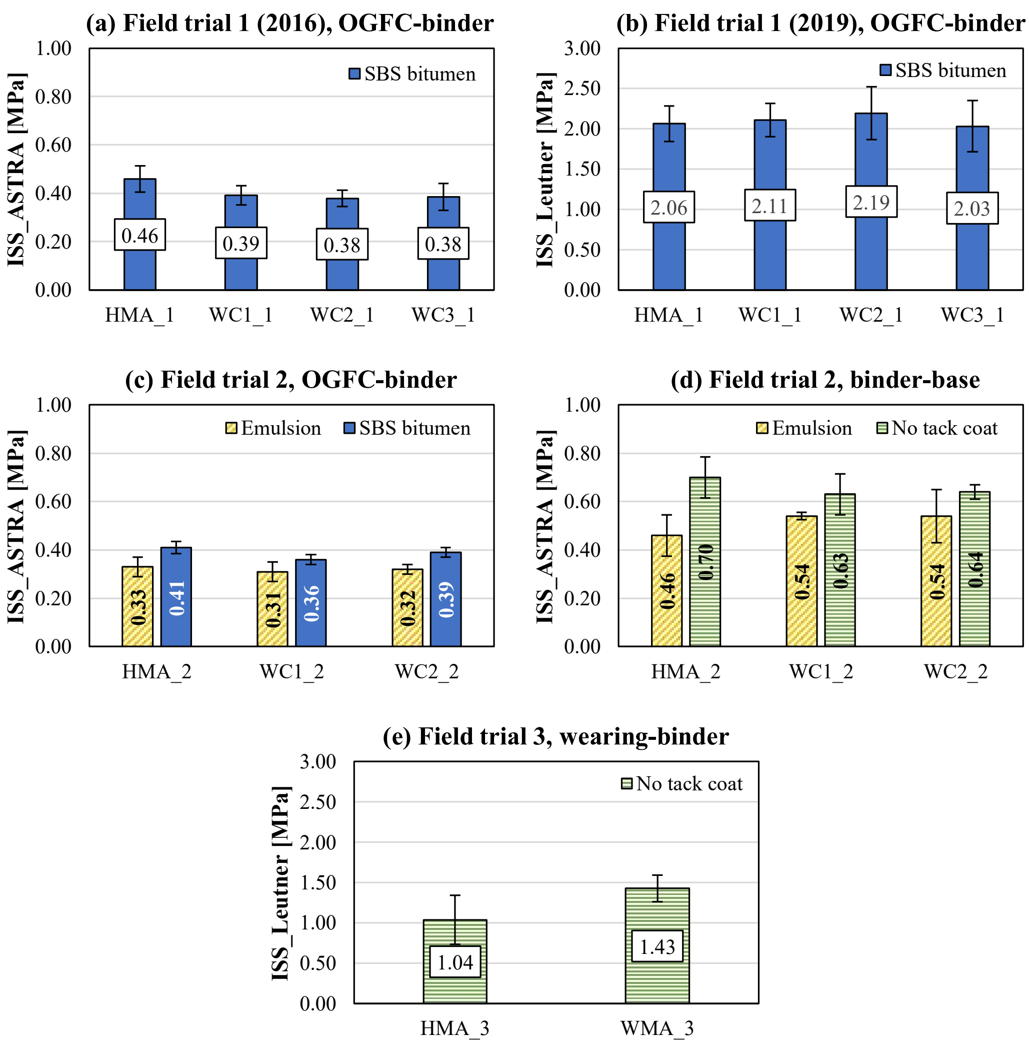

Figure 2: ISS values.

3.2 Effect of WMA technology

The results of the ANOVA analysis concerning the effect of the WMA technology for field trials 1 and 2 are summarized respectively in Tables 3 and 4. In most cases, the ISS values obtained for the reference HMA section and the corresponding WMA sections were similar, and thus the differences were not statistically significant (p-value much higher than 0.05).

However, for field trial 1 in 2016 conditions, the difference between HMA_1 and WC2_1 was statistically significant, and the p-values for the pairs HMA_1-WC1_1 and HMA_1-WC3_1 were close to 0.05 (Table 3). Specifically, Figure 2(a) shows that the ISS values of the three WMA sections (WC1_1, WC2_1, WC3_1) were almost the same (0.38÷0.39 MPa), whereas the ISS value of the HMA_1 section was higher (0.46 MPa). An analogous situation was observed for the pair HMA_2-WC1_2 of field trial 2 in the case of the OGFC-binder interface with SBS bitumen, for which the p-value was close to 0.05 (Table 4) and the ISS value of the HMA_2 section was higher than that of the WC1_2 section (0.41 MPa vs 0.36 MPa, see Figure 2(c)).

It should be noted that, in some cases, the interlayer bonding properties of WMA sections were even better than those of the corresponding HMA section, such as for the binder-base interface of field trial 2 with the emulsion in Figure 2(d) (even though the differences were not significant from a statical point of view). This is true also for field trial 3, for which the ANOVA analysis was not performed due to the differences in the mix design of the HMA and WMA mixtures. In this case, the average ISS value observed for the WMA_3 section (1.43 MPa) was considerably higher than that of the HMA_3 section (1.04 MPa), as can be seen from Figure 2(e).

Overall, these findings indicate that the reduced lay-down temperatures of WMA mixtures do not penalize the interlayer bonding properties of the pavement, which remain comparable to those of HMA pavements.

Table 3: Effect of WMA technology: field trial 1, OGFC-binder interface.

	2016		*2019*	
Sections	*p-value*	*Significance*	*p-value*	*Significance*
HMA_1 vs WC1_1	0.056	NO	0.782	NO
HMA_1 vs WC2_1	0.024	YES	0.573	NO
HMA_1 vs WC3_1	0.066	NO	0.880	NO

Table 4: Effect of WMA technology: field trial 2.

	OGFC-binder interface				*Base-binder interface*			
	Emulsion		*SBS bitumen*		*Emulsion*		*No tack coat*	
Sections	*p-value*	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*
HMA_2 vs WC1_2	0.574	NO	0.054	NO	0.184	NO	0.370	NO
HMA_2 vs WC2_2	0.718	NO	0.340	NO	0.375	NO	0.313	NO

3.3 Effect of WMA additive

The results of the ANOVA analysis about the effect of the WMA additive for field trials 1 and 2 are reported in Tables 5 and 6, respectively. All the p-values were much higher than 0.05, meaning that the differences between WMA sections constructed with different WMA additives were never statistically significant. In fact, from Figures 2(a), (b), (c) and (d), it can be observed that the ISS values obtained for the WMA sections were very similar in all cases.

It can be concluded that the interlayer bonding properties of the pavement are not affected by the WMA chemical additive type.

Table 5: Effect of WMA additive: field trial 1, OGFC-binder interface.

	2016		*2019*	
Sections	*p-value*	*Significance*	*p-value*	*Significance*
WC1_1 vs WC2_1	0.609	NO	0.640	NO
WC1_1 vs WC3_1	0.831	NO	0.658	NO
WC2_1 vs WC3_1	0.850	NO	0.450	NO

Table 6: Effect of WMA additive: field trial 2.

	OGFC-binder interface				*Base-binder interface*			
	Emulsion		*SBS bitumen*		*Emulsion*		*No tack coat*	
Sections	*p-value*	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*
WC1_2 vs WC2_2	0.718	NO	0.140	NO	1.000	NO	0.857	NO

3.4 Effect of age

For field trial 1, the field cores were subjected to ASTRA tests in 2016 (Figure 2(a)) and to Leutner tests in 2019 (Figure 2(b)), which does not allow a direct comparison between the ISS values obtained.

Considering the analytical correlation for converting ASTRA results to equivalent Leutner results available in literature (Canestrari et al., 2013), the 2016 ISS values would slightly increase to 0.56 MPa for the HMA section and 0.42÷0.44 MPa for the WMA sections. Instead, in 2019, all sections exhibited ISS values higher than 2 MPa, as shown in Figure 2(b), suggesting that ISS increased by about four times in three and a half years. Such increase in the ISS can be ascribed to the aging of the bitumen in the tack coat (Raab et al., 2015), which enhanced the cohesion within the tack coat. The magnitude of the ISS increase is probably due to the presence of an OGFC characterized by an air void content of about 20%, which greatly exposed the tack coat to oxygen, water and ultraviolet radiation.

3.5 Effect of tack coat properties

Table 7 summarizes the results of the ANOVA analysis concerning the effect of the tack coat properties, which was examined for field trial 2. For the OGFC-binder interface, Figure 2(c) shows that, for all sections, the ISS value in the presence of SBS bitumen tack coat was always higher than in the case of emulsion tack coat. For the HMA_2 and WC2_2 sections, the differences were also statistically significant, as denoted by p-values lower than 0.05. These results are justified by the better affinity between the SBS bitumen tack coat and the asphalt mixtures, in which both the virgin bitumen and the bitumen from RA were SBS polymer modified. As for the binder-base interface, Figure 2(d) shows that the ISS value without any tack coat was always higher than in the presence of an emulsion tack coat for all sections, even though the difference was statistically significant only for the HMA_2 section. In this case, the emulsion had a lubricating effect, which probably penalized the contribution given by the friction between the aggregates of the asphalt layers (Stimilli et al., 2017a).

In summary, these findings clearly demonstrate that the interlayer bonding depends on the properties of the tack coat applied between the layers, and thus the most appropriate tack coat should be selected case by case.

Table 7: Effect of tack coat properties: field trial 2.

		HMA_2		*WC1_2*		*WC2_2*	
Interface	*Tack coats*	*p-value*	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*
OGFC-binder	Emulsion vs SBS bitumen	0.042	YES	0.125	NO	0.013	YES
Binder-base	Emulsion vs No tack coat	0.026	YES	0.145	NO	0.203	NO

3.6 Effect of mixture type

The effect of the mixture type can be assessed by comparing the ISS values obtained at the interface between the wearing and binder layers after the pavement construction for field trial 1 (Figure 2(a)), field trial 2 (Figure 2(c)) and field trial 3 (Figure 2(e)). Even converting the ASTRA results into the corresponding Leutner values (Canestrari et al., 2013), all ISS values in Figures 2(a) and (c) would remain lower than 0.55 MPa in the presence of an OGFC, whereas ISS was in the range 1.0÷1.5 MPa in the case of a dense-graded wearing layer (field trial 3, Figure 2(e)), regardless of the technology adopted. At the same time, for field trial 2, considering the OGFC-binder and binder-base interfaces with the same emulsion tack coat (Figures 2(c) and (d) respectively), the ISS values of the lower interlayer were about 33% higher than those of the upper interlayer.

These findings are probably due to the fact that the OGFC is characterized by a discontinuous gradation and a high air void content (20%), which led to limited contact points with the aggregates of the underneath layer (Stimilli et al., 2017a). In light of these outcomes, the ISS requirements in the technical specifications should be differentiated depending on the gradation of the mixtures involved (an aspect that is neglected in most cases).

3.7 Influence of asphalt plant production

The ISS results obtained for field trial 1 in 2016 and field trial 2 in the case of the OGFC-binder interface with SBS bitumen (Figures 2(a) and (c) respectively) were compared to assess the influence of the production in different asphalt plants.

The results of the related ANOVA analysis, shown in Table 8, indicate that the ISS values observed in the two cases were basically the same, especially for the WMA sections. This finding suggests that the interlayer bonding of WMA pavements does not depend on the asphalt plant, as long as the proper production procedure is followed.

Table 8: Influence of asphalt plant production: field trial 1 (2016) vs field trial 2, OGFC-binder interface with SBS bitumen.

HMA_1 vs HMA_2		*WC1_1 vs WC1_2*		*WC2_1 vs WC2_2*	
p-value	*Significance*	*p-value*	*Significance*	*p-value*	*Significance*
0.138	NO	0.190	NO	0.592	NO

4. Conclusions

This paper investigated the interlayer bonding properties of several warm recycled asphalt pavements constructed along various Italian motorways and national roads using different WMA chemical additives. Specifically, the Interlayer Shear Strength (ISS) was measured at different pavement interfaces (wearing-binder, binder-base) and time intervals by testing extracted cores with ASTRA and Leutner equipment. The investigation allowed to assess also the effect of the tack coat properties and the mixture type as well as the influence of the production in different asphalt plants. One-factor analysis of variance (ANOVA) was performed on the ISS results to assess whether the observed differences were statistically significant or not.

Based on the results and analyses provided, the following conclusions can be drawn:

- The reduced lay-down temperatures of WMA mixtures do not penalize the interlayer bonding properties of the pavement, which remain comparable to HMA pavements.
- The interlayer bonding properties of the pavement do not depend on the WMA chemical additive type.
- The interlayer bonding strongly depends on the properties of the tack coat applied between the layers, and thus the most appropriate tack coat should be selected case by case.
- ISS increases over time due to the aging of the bitumen in the tack coat, especially when the interface is below an open-graded friction course.
- In the presence of an open-graded mixture, the ISS values are always lower than in the case of dense-graded mixtures.
- The interlayer bonding of WMA pavements does not depend on the asphalt plant, as long as the proper production procedure is followed.

These findings further encourage the use of WMA as environmentally sustainable technologies for the construction and maintenance of asphalt pavements.

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