Modern Applied Science; Vol. 7, No. 10; 2013
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Interface Roughness Parameters and Shear Strength

Antonio D'Andrea[1], Cristina Tozzo[1], Alberto Boschetto[2] & Luana Bottini[2]

[1] DICEA, Sapienza University of Rome, Italy

[2] DIMA, Sapienza University of Rome, Italy

Correspondence: Cristina Tozzo, DICEA, Sapienza University of Rome, Via Eudossiana 18, Rome 00184, Italy. Tel: 39-6-4458-5124. E-mail: cristina.tozzo@gmail.com

Received: May 23, 2013 Accepted: August 20, 2013 Online Published: September 11, 2013

doi:10.5539/mas.v7n10p1 URL: http://dx.doi.org/10.5539/mas.v7n10p1

Abstract

The interlayer bond strength between binder and wearing course and several possible treatments of enhancing the contact surface roughness and the interlocking are investigated. For this purpose, conventional methods, such as shear tests, but also laser image acquisition of the binder upper surface have been used. The mechanical outcomes of a shear test device and the binder surface roughness parameters, have been compared looking for a relation between the shear performance and the surface characteristics. The comparison between the roughness average and the root mean square of the profile heights with the maximum shear stress shows the achievement of the same strength level for treatments with similar roughness parameters, as proved by the statistical analysis. Furthermore, the comparison between the roughness parameter kurtosis and the maximum height of the profile with the slope of the response curve before the peak and residual shear stress, demonstrates a better locking for more high peaks.

Keywords: interface, roughness, shear strength, asphalt pavement, laser images

1. Introduction

Texture is a feature that plays an important role in most physical phenomena. In the field of road pavement, surface texture influences tire-road interactions, such as noise, wet friction, rolling resistance and tire wear (Loprencipe & Cantisani, 2013). Significant factors are shape, grading and size of the aggregates. Several measurement methods are employed: Sand patch, British pendulum test, Outflow meter and electro-optic methods. A large effort of research has been devoted to those aspects.

Texture seems to be important also for interfaces between layers forming the structure of a road pavement, with a direct influence on the bond resistance to the shear stresses caused either by the vertical loading applied by rolling wheels and in occasion of braking, accelerating and turning maneuvers.

Therefore, focusing on the possible use of the most recent texture detection methods for the better comprehension of interface behavior seems to be of interest at the present time. In this paper, a novel application of the non-contact methodologies is proposed with the aim to evaluate the macrotexture of the upper binder surface in order to find a correlation between the roughness characteristics and the interface shear performance. The interface represents the contact plane between this investigated binder surface and the upper wearing coarse layer built on its top.

For this purpose a 3D laser scanning has been employed: it is an emerging technology that allows the acquisition of a great quantity of point clouds in few minutes. The application ranges from design, industrial quality control, surveying to scanning of buildings. The aim of this study is to apply this technique in order to acquire the contact surface shape and achieve roughness parameters.

2. Background

The importance of the interface between pavement layers and the negative influence of the lack of bond on the performance of the infrastructure, have been understood since the first 1970ies. The first achievement of most researches is the design and the development of new testing methodologies, able to characterize in situ or in lab the shear strength performance of the interface. Different devices and testing procedures have been presented, divided in several types: Torque Test; Tensile Test (Pull-off Test); Pure Direct Shear Test and Direct Shear Test with Normal Stress Applied, but the lack of standards on these procedures allows the diffusion of ever new prototypes, typically used to better investigate the different factors affecting shear interface strength. The comparison between the proposed devices has shown that the shear test is a good and effective method for testing the interlayer bond of asphalt pavements (Raab et al., 2009).

The pure direct shear test represents the most common equipment working through the application of a shear displacement and the record of the shear strength. The first one, known as Leutner Shear Test (Leutner, 1979), applies a constant shear displacement until the achievement of the failure of the investigated contact plane between the layers. In the following researches, comparable devices have been developed, such as the LPDS (Layer Parallel Direct Shear Test) used by Raab et al. (2004) and the shear test used by Molenaar et al. (1986).

Different working scheme belongs to the pure direct shear test known as LCB (Laboratorio de Camino de Barcelona) and presented by Miro et al. (2005) where a particular system of two supports holds the specimen and the shear load is applied at a constant deformation rate. The short distance between the two supports leads to the elimination of the bending moment.

To investigate the effect of the normal stress on the interface shear strength, direct shear test with normal load has been used by other researchers. From the first device of this type considered in the road pavement research of Uzan et al. (1978), direct shear boxes with the addition of a normal load have been developed as the ASTRA (Ancona Shear Testing Research and Analysis) (Canestrari et al., 2005) apparatus and the device presented by Chen et al. (2010). Recently, the Sapienza University of Rome designed and developed the SHSTM (Sapienza Horizontal Shear Test Machine), a machine able to perform tests on double-layer asphalt specimens 100 mm diameter and 120 mm high, 60 mm for each layer. The working scheme derives from the Miro device (Miro et al., 2005) but includes some modification in the support configuration in order to allow the application of a compression load during the test eliminating some specimen rotational problems that could develop in the previous scheme if a normal load is added. D'Andrea and Tozzo (2012) verified the statistic reliability of the device and investigated the relationship between several failure mechanisms and different state of imposed stress.

The experimental results obtained by the researchers have highlighted a strong dependence between layers interlocking and macrotexture of the binder surface, granulometric size distribution and compaction conditions. Several factors concerning the surface, such as cleanness, dryness, roughness and age have been considered in the experimental plan to define the interaction between different surface characteristics of the underlying layer and the adhesion properties (Raab et al., 2009; Tashman et al., 2006). This result is also confirmed by Santagata et al. (2008) that showed an increasing interlayer shear resistance for higher macro-texture.

Sholar et al. (2004) found that coarse graded HMA mixes had higher shear strength compared to fine graded mixes and observed significant resistance improvement for milled surface. Furthermore, for milled sections, they noticed that using tack coat the increasing of the shear strength at the interface was not effective. The finding of a correlation between the interface shear strength and the surface features was confirmed by D'Andrea and Tozzo (2013) testing the interface shear strength of double layer asphalt specimens where the surface of the binder was treated in different ways to improve the roughness. West et al. (2005) also proved higher bond strengths for fine-graded mixtures than for the coarse-graded ones, considering the results of laboratory fabricated specimens and field experiments. The significant interactions of the mix type with other variables e.g. tack coat application rate, materials used, and testing temperature, was also evaluated with contradictory trends in some cases.

In the present paper an analysis based on visual methods is proposed with the aim to investigate the effect of roughness features of the binder upper surface on the interlayer shear strength when on the binder is built the wearing coarse and the double-layer system is tested.

With the introduction of emerging 3D laser imaging technology, the potential of high resolution 3D surface for the pavement analysis has been investigated by Wang et al. (2012). In this study, pavement texture and distress survey have been explored with a high-speed 3D imaging sensor system in order to model the pavement characteristics. They found a quantitative and useful correlation between the outcomes of the texture indicators and the different surface textures.

The use of laser inertial road profiler macrotexture measuring device has been also considered by several researchers (Flintsch et al., 2003; McGhee et al., 2003; McGhee et al., 2004), looking to possible applications as detecting and measuring methods for segregation and non-uniformities in HMA. Various parameters were computed to characterize the different surface texture, e.g. measure of contrast, correlation energy and homogeneity.

Furthermore, for quality assurance purposes, high speed laser profilers have been identified as promising tool for surface texture measurements in the state of Virginia. In the recent years, in the Virginia Smart Road has been tested a method for the final inspection process of asphalt pavements based on the automatic capture and analysis of newly constructed roads (de León Izeppi et al., 2007). From the captured images, various parameters for the characterization of the visual texture and a road profile with the non-uniformities location have been developed. They also implemented imaging techniques in several highway applications such as pavement crack detection, aggregate shape properties and characterization, pavement distress surveys.

3. Objective

In this study, different interfaces between asphalt and wearing course of asphalt pavement are investigated: different sizes of limestone chip coat, toothed compactor roller footprint, oily and smoothing surface and also no treatment. The purpose is to find a correlation between the interface strength and the parameters obtained through the surface characterization of the binder surface, acquired with a laser scanner. As study parameters, the maximum shear stress, the corresponding displacement and the slope of the response curve before the peak are selected. The surface data analysis is performed according to ISO standard 4287 and 13565, typically used for mechanical part characterization. The Roughness Average (Ra), the Root Mean Square Roughness (Rq), the Maximum Height of the Profile (Rt) and the roughness parameters skewness (Rsk) and kurtosis (Rku) are evaluated.

4. Specimen Preparation

Double-layer specimens including binder and wearing course have been prepared with bitumen PEN 60-70 and two different aggregate mixtures, according to the Italian standards. A Marshall Compactor has been used to prepare the samples in cylindrical molds, 130 mm high and 100 mm interior diameter, applying the compaction blows only to the upper surfaces.

According to previous research (D'andrea & Tozzo, 2012), seventy-five blows have been assigned for both the layers because this level of compaction ensures the achievement of the density commonly required in Italian public work specifications as the 98% of the average bulk density (EN 12697) of the same mixture compacted in standard Marshall conditions (75 blows on upper and bottom side of a 63 mm high specimen). The mixtures characteristics are summarized in Table 1.

The upper binder surface has been treated in different ways:

- Chipping: immediately after the binder compaction, limestone chip coat has been placed and inserted into the hot surface with the application of three compaction blows; two different chip coat sizes have been tested, using 5-10 mm and 10-20 mm limestone granules;

- Smoothing: after cooling the binder specimens at room temperature, the upper surface has been rounded by tape grinding, usually referred as "sanding";

- De-bitumening: after cooling the binder specimens at room temperature, the interface has been left for 24 hours in a trichloroethylene bath, 1 mm depth to keep the surface clean by the bitumen;

- Toothed compactor roller: on hot binder surface, three screws have been beaten by three compaction blows to simulate the passage of a toothed wheel;

Laser scanner acquisitions have been carried out on all the treated binder surfaces. Moreover, a no treatment specimen has been acquired as term of comparison.

After the wearing course preparation, the samples, 120 mm high, have been left to cool at room temperature for more than 24 hours before performing the shear test.

Table 1. Mixture characteristics

		Wearing course	***Binder course***
Mix design	*Bitumen [%]*	6.5	4.5
	Aggregates	3% Filler	3% Filler
		40%-0/4 Limestone	47%-0/4 Limestone
		22%-3/5 Basalt	20%-6/12 Limestone
		35%-5/10 Basalt	30%-10/20 Limestone

	40 mm	-	-
	31.5 mm	-	-
	20 mm	-	98
	16 mm	-	93
	14 mm	-	87
	12.5 mm	-	84
	10 mm	-	76
% Passing	8 mm	90	64
	6.3 mm	74	55
	4 mm	50	47
	2 mm	30	33
	1 mm	19	21
	0.5 mm	13	14
	0.25 mm	10	10
	0.125 mm	8	8
	0.063 mm	7	7
Bituminous mixture	*Density [kg/m^3]*	2330	2365
	Air Void Content [%]	6	4.7
	*Compaction blows**	75	75

*Only on the upper surface of each layer.

5. Experimental investigation

5.1 Shear Testing Machine

The device used to test double layer asphalt specimens is the SHSTM (Sapienza Horizontal Shear Test Machine). In the working scheme, the specimen is held horizontally in two collars, as shown in Figure 1, in order to remove the dead load of the specimen and the upper part of the device on the shear strength. Only one collar is supported by a link; the other is free to move vertically due to a low friction guide placed on the back side of the specimen. The interface must be placed with an edge of 5 mm from both sides of the collars. The loading machine works at a displacement rate of 1.27 mm/min and the contrast is applied on the unrestricted half specimen; a piston connected with a pneumatic compressor provides the horizontal load. The normal pressure is fixed at 0.2 MPa during the tests. The data acquisition system records the shear load, converted in shear stress (τ) considering the cross sectional area at the beginning of the test, and the interface displacements are measured by an LVDT. A typical response curve is shown in Figure 2.

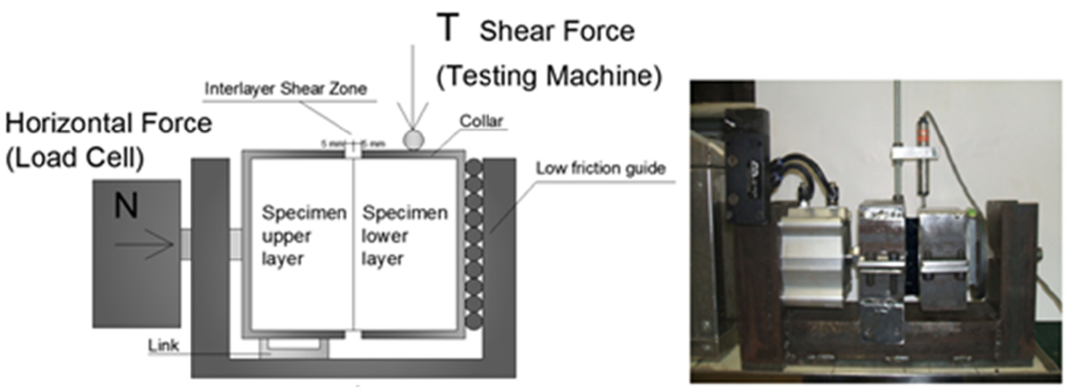


Figure 1. SHSTM working scheme

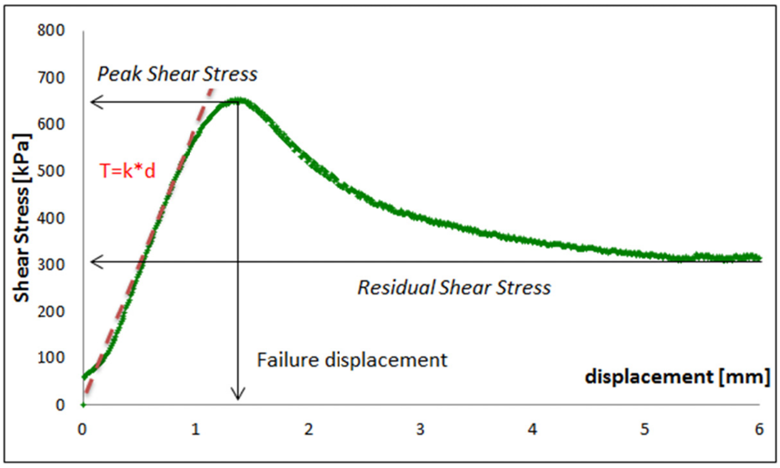


Figure 2. SHSTM typical response curve

5.2 Laser Scanner

A NextEngine 3D laser scanner has been used to acquire absolute x-y-z coordinates of produced surfaces. It works on the principle of triangulation: the laser is swept across the object, which is focused through the lens of a CCD camera. The manufacturer declares a precision of 0.1 mm, quite enough to characterize the asphalt surface considering the granules sizes. The amount of points has been more than 150000, useful for a good statistical analysis. The 3D data acquisition has been performed in ScanStudioHD. The time needed for the operation is only 1 minute. The processing and analysis phases have been carried out in Geomagic 2012 environment. 3D data have been exported in STL format and analyzed in Wolfram Mathematica 8.04. From the STL files have been extracted the vertex data, filtered by means of a regression plane in order to eliminate positioning errors. Different roughness parameters have been calculated according to ISO standard 4287 and 13565 as reported also in Boschetto et al. (2011); they are typically used for mechanical part characterization in which the profile values are taken around the regression plane. These parameters are: the arithmetic average of the absolute height of the profile (Ra): the maximum height of the profile evaluated as the difference between the highest peak and the lowest valley (Rt); the Root Mean Square of the profile heights (Rq); the Skewness, which describes the asymmetry of the probability distribution of the profile heights (Rsk); the Kurtosis, which evaluates the sharpness of the probability distribution of the profile heights (Rku). Typical graphical results are shown in Figure 3.

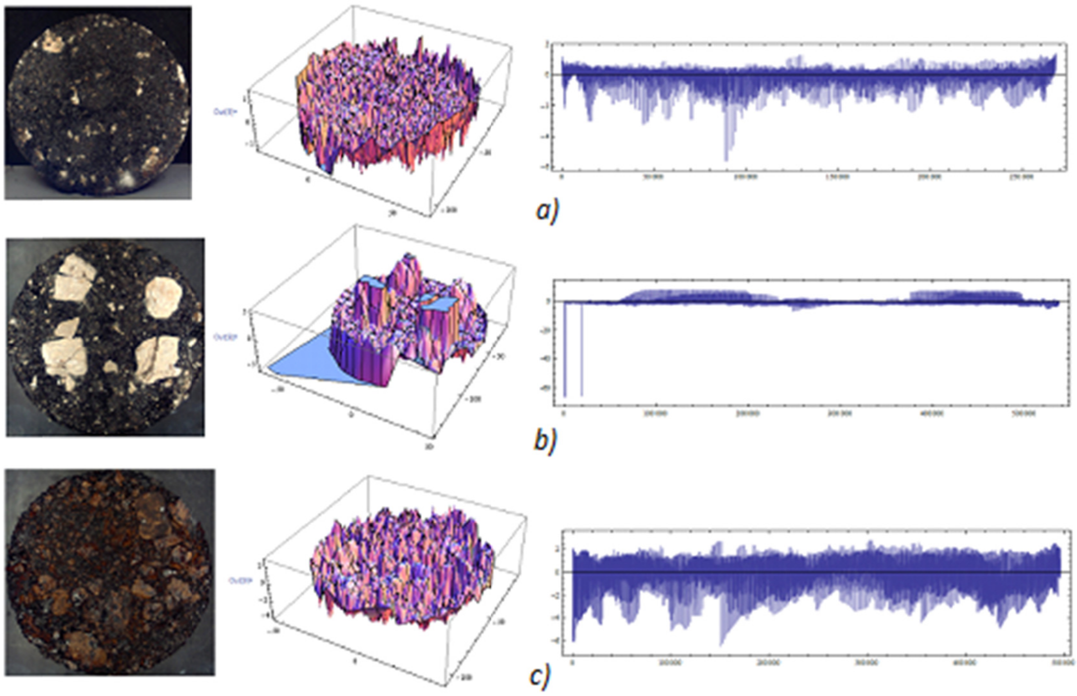


Figure 3. Graphical results for the investigated treatments: a) No treatment; b) Chipping 5/10; c) De-bitumening

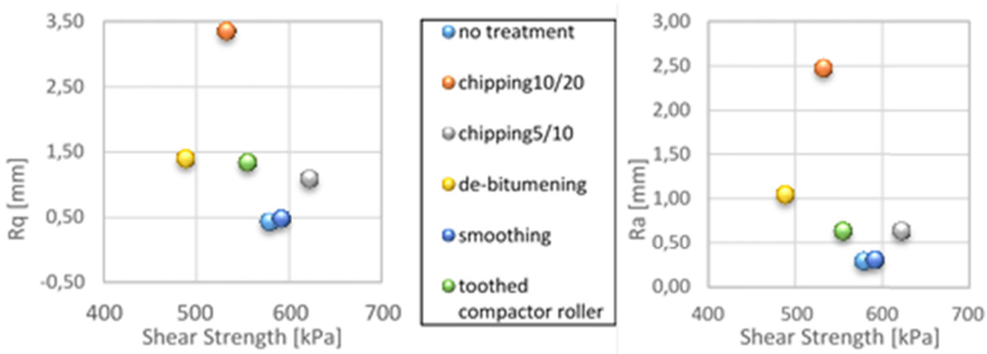
6. Results

The outcomes of mechanical tests, performed at a controlled temperature of 20 °C, are shown in Table 2 in terms of maximum shear stress (Tmax), corresponding displacement (d), slope of the response curve before the peak (k) and residual shear stress (Tres).

Table 2. Summary of the results

	T max [kPa]	***d*** [mm]	***k*** [KN/mm3]	***T res*** [kPa]	***Ra*** [mm]	***Rq*** [mm]	***Rt*** [mm]	***Rsk*** [mm]	***Rku*** [mm]
NO TREAMENT	578.60	2.96	0.30	331.66	0.29	0.43	8.86	-3.01	34.01
CHIPPING 10/20	532.31	2.48	0.28	393.59	2.48	3.36	58.57	0.85	18.38
CHIPPING 5/10	622.36	1.98	0.34	345.55	0.63	1.09	68.74	-15.56	1047.68
DE-BITUMENING	488.56	2.22	0.29	424.85	1.04	1.40	60.26	-8.04	337.19
SMOOTHING	591.37	1.98	0.35	322.38	0.30	0.48	18.06	-10.84	866.73
TOOTHED ROLLER	554.81	2.17	0.29	398.38	0.63	1.34	48.55	-14.40	601.87

Fifteen replications have been performed for each investigated treatment and the mean values have been considered. Also, the roughness parameters are presented. As shown in Figure 4, all the treatments, except for smoothing, record an increased root mean square (Rq) if compared with “no treatment”. The average roughness (Ra) presents the same behavior.



a) b)

Figure 4. Shear strength VS Rq (a); Shear Strength VS Ra (b)

These trends can be investigated by the Analysis of Variance (ANOVA): this method is widely used to determine whether the factors of a process are significantly related to the response. The main output of the ANOVA study is arranged in a table including the list of the sources of variation, the degrees of freedom (DF), the total sum of squares (SS), the mean squares (MS), the F-statistics and the p-values. The p-value determines the appropriateness of rejecting the null hypothesis that there are no differences due to the considered factor's levels, assuming a maximum acceptable level of risk α. A commonly used α value is 0.05. If the p-value is lower than 0.05, then the factor is significant (Montgomery et al., 1994). In Table 3 the ANOVA analysis for Ra versus all treatments is reported. A very low p-value (0.000) proves that there are differences among the mean values of the Ra treatments outcomes.

Table 3. Analysis of variance for Ra

Source	DF	SS	MS	F	p
Treatment	5	51.003	10.200	165.32	0.000
Error	84	5.183	0.062		
Total	89	56.185			

As this analysis is multivariate, it does not permit to discriminate between the factor's levels. In order to determine specifically which means are different, a pairwise comparison test has been performed and reported in Tab. 4. This test applies the ANOVA for each combination of levels two by two. The obtained p-values assess that in two cases the treatments cannot be considered different.

Table 4. Pairwise comparison p-values of differences between factor level means

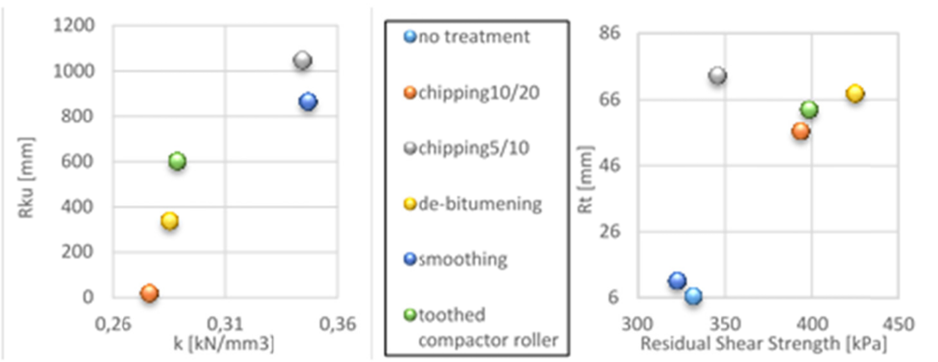
	no treatment	chipping 10/20	chipping 5/10	de-bitumening	smoothing	toothed roller	
p-value							no treatment
	0.000						chipping 10/20
	0.000	0.000					chipping 5/10
	0.000	0.000	1.39E-05				de-bitumening
	0.329	0.000	0.000	0.000			smoothing
	2.87E-05	0.000	0.523	0.003	4.60E-05		toothed roller

The results prove that "smoothing" and "no treatment" are similar: in this case the p-value is 0,329. Consequently no evidence exists that the treatments are different in roughness. This is due to limited profile modifications that lead also to the same shear strength outcomes. This result is confirmed by the ANOVA reported in Table 5: the p-value 0.572 implies that there is no evidence for judging that the shear strength does not vary upon these two treatments. Same results are achieved comparing in roughness “toothed compactor roller” and “chipping 5/10” (the p-value reported in Table 4 is 0.523). In this case “chipping 5/10” records also the higher shear strength due to the inclusion of limestone aggregates which assures a better interlocking between layers during the shear test. On the other hand, “toothed Compactor roller” doesn’t achieve the same shear performance.

Table 5. Analysis of Variance for the shear strength with two levels: “chipping 5/10” and “toothed compactor roller”

Source	DF	SS	MS	F	p
Treatment	1	1100	1100	0.33	0.572
Error	25	83736	3349		
Total	26	84836			

“Chipping 10/20” and “de-bitumening” provide significant effects on Ra value with a p-value equal to 4.72×10^{-12}; in this case, the achieved higher roughness values don’t lead to higher strength. In fact, the chipping with a larger aggregate size doesn’t record the same shear performance because the limestone aggregates are too big to became part of the binder layer and are totally incorporated in the wearing course, getting worse the joint. Probably the increasing in Ra for the treatment “de-bitumening” can be attributed to the mastic removal after the trichloroethylene bath. So, Ra and Rq are higher than “no treatment” but the shear strength is too low probably because on the contact surface there is less bitumen or trichloroethylene residuals that could inhibit good adhesion at the interface of asphalt layers. Furthermore, in Figure 5a, is illustrated the slope of the response curve before the peak (k) as function of the roughness parameter Rku, only for the treated interfaces.



a) b)

Figure 5. Rt VS residual shear stress (a); Rku VS k (b)

A high value of Rku, i.e. an amplitude density distribution characterized by a marked peakedness, is typically related to a surface with isolated spikes. This implies a very high k value because the spikes allow the achievement of the maximum shear stress for very low corresponding displacements. Also Rt can be an indicator used to correlate the shear stress performance of specimens. In Figure 5b Rt is correlated with the residual strength showing the same better locking for more high peaks.

6. Conclusions

Different interfaces between asphalt and wearing course of asphalt pavement are investigated with the aim to find a correlation between the interface strength of double layer asphalt specimens, tested on a shear test device with normal load, and the parameters obtained through the laser scanner characterization of the binder surface. By means statistical approach, all the treatments, except for smoothing, record an increased average roughness if compared with “no treatment”. The Ra outcomes are compared with the shear performance showing that the same strength level is achieved by the treatments with similar roughness parameters. “Chipping 5/10”, which records the higher shear strength, and “toothed compactor roller” are an exception because the same Ra value corresponds to two different interlocking mechanism between the layers, as confirmed by two different strength levels. Also, the roughness parameter kurtosis and the maximum height of the profile are presented in relation with the slope of the shear response curve before the peak and the residual shear strength, respectively. The plots show the achievement of stronger resistance parameters for higher texture peaks, probably due to a better locking between the superposed layers.

References

Bae, A., Mohammad, L. N., Elseifi, M. A., Button, J., & Patel, N. (2010). Effects of Temperature on Interface Shear Strength of Emulsified Tack Coats and Its Relationship to Rheological Properties. *Transportation Research Record: Journal of the Transportation Research Board*, 102-109.

Boschetto, A., Giordano, V., & Veniali, F. (2011). Modelling micro geometrical profiles in fused deposition process. *The International Journal of Advanced Manufacturing Technology, 61*(9-12), 945-956. http://dx.doi.org/10.1007/s00170-011-3744-1

Canestrari, F., Ferrotti, G., Partl, M. N., & Santagata, E. (2005). Advanced Testing and Characterization of Interlayer Shear Resistance. *Transportation Research Record: Journal of the Transportation Research Board*, 69-78.

Chen, J., & Huang, C. (2010). Effect of Surface Characteristics on Bonding Properties of Bituminous Tack Coat. *Transportation Research Record: Journal of the Transportation Research Board*, 142-149.

D'Andrea, A., & Tozzo, C. (2012). Interlayer Shear Failure Evolution with Different Test Equipments. *Procedia-Social and Behavioral Sciences, 53*, 556-567. http://dx.doi.org/10.1016/j.sbspro.2012.09.906

D'Andrea, A., & Tozzo, C. (2013). Investigation Of Possible Improvements Strength In Asphalt Pavements. *TRB 92nd Annual Meeting Compendium of Papers, Report Numbers 13-3020*

de León Izeppi, E. D., Flintsch, G. W., & Lynn Abbott, A. (2007). Measuring the Uniformity of Hot Mix Asphalt Pavements with Digital Image Technology. *Transportation Research Board Annual Meeting 2007*.

Flintsch, G. W., de León, E., McGhee, K. K., & Al-Qadi, I. L. (2003). Pavement Surface Macrotexture: Measurement and Application. *In Transportation Research Record: Journal of the Transportation Research Board*, 168-177.

Leutner, R. (1979). Untersuchung des Schichtverbundes beim bituminösen Oberbau. *Bitumen, 3*, 84-91.

Loprencipe, G., & Cantisani, G. (2013). Unified Analysis of Road Pavement Profiles for Evaluation of Surface Characteristics. *Modern Applied Science, 7*(8), 1-14. http://dx.doi.org/10.5539/mas.v7n8p1

McGhee, K. K., Flintsch, G. W., & de León, E. (2003). *Using High-Speed Texture Measurement to Improve the Uniformity of Hot-Mix Asphalt.* p. 23. Technical Report VTRC 03-R12, Virginia Transportation Research Council and Federal Highway Administration, May 2003.

McGhee, K. K., Flintsch, G. W., & de León, E. (2004). Detecting and Measuring Hot-Mix Asphalt Segregation using High-Speed Texture Measurement. *Paper 04-3827 in Transportation Research Board 83rd Annual Meeting. CD-ROM. Transportation Research Board of the National Academies*. Washington, DC., 2004.

Miró, R., Martínez, A., & Pérez, F. (2005). Evaluation of The Effect Of Heat-Adhesive Emulsions For Tack Coats With Shear Test From The Road Research Laboratory Of Barcelona. *2006 Annual Meeting of the Transportation Research Board.*

Mohammad, L. N., Raqib, M. A., & Huang, B. (2002). Influence of Asphalt Tack Coat Materials on Interface Shear Strength. *In Transportation Research Record: Journal of the Transportation Research Board, No. 1789*. TRB, National Research Council, Washington, D.C., pp. 56-65.

Molenaar, A. A. A., & Heerkens, J. C. P. (1986). Effect of stress absorbing membrane interlayers. *Association of Asphalt Paving Technologists Proc. Tech. Sessions, 55*, 453-481.

Montgomery, D. C., & Runger, G. C. (1994). *Applied Statistics and Probability for Engineers*. John Wiley & Sons, Inc..

Raab, C., & Partl, M. N. (2004). Interlayer shear performance: experience with different pavement structures. *In: Proceedings of the 3rd Eurasphalt & Eurobitume Congress,* May 2004, vol.1, pp. 535-545. Vienna.

Raab, C., Partl, M. N., & Abd El Halim, A. O. (2009). Evaluation of Interlayer Shear Bond Devices for Asphalt Pavements. *Baltic Journal of Road and Bridge Engineering, 4*(4), 186-195.

Santagata, F. A., Partl, M. N., Ferrotti, G., Canestrari, F., & Flisch, A. (2008). Layer characteristics affecting interlayer shear resistance in flexible pavements. *Journal Association of Asphalt Paving Technologists, 77*, 221-256.

Sholar, G., Page, G., Musselman, J., Upshaw, P., & Moseley, H. (2004). Preliminary Investigation of a Test Method to Evaluate Bond Strength of Bituminous Tack Coats. *Association of Asphalt Paving Technologists, 73*, 771-801.

Tashman, L., Nam, K., & Papagiannakis, T. (2006). Evaluation of the influence of tack coat construction factors on the bond strength between pavement layers. *Report of Washington Center for Asphalt Technology*, WCAT, Final Report #06-002.

Uzan, J., Livneh, M., & Eshed, Y. (1978). Investigation of Adhesion Properties between Asphaltic Concrete layers. Asphalt Paving Technology. *Proceedings of the Association of Asphalt Paving Technologists, Technical Sessions, 47*, Lake Buena Vista, FL. pp. 495-521.

Wang, K. C. P., & Li, L. (2012). Pavement Surface Texture Modeling Using 1mm 3D Laser Images. *Transportation Systems Workshop 2012*, 5-8 March 2012, Renaissance Austin Hotel, Austin, TX.

West, R., Zhang, J., & Moore, J. (2005). Evaluation of bond strength between pavement layers. *Report of National Center for Asphalt Technology, NCAT*.