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Effect of binder type and application rate on asphalt layer bonding evaluated by LCB test

Efecto del ligante y dosificación en la adherencia de capas asfálticas evaluadas en ensayo LCB

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ABSTRACT: Bonding between asphalt layers is a crucial factor affecting the durability and mechanical response of flexible pavements. The effect of tack coat application on this bonding has been extensively studied, with several factors influencing the degree of bonding achieved. These include the type of tack coat, application rate, temperature, and moisture, among others. This study evaluated the effect of binder type and application rate on the interface shear strength of bituminous layers made of asphalt concrete type MDC-19, using the*Laboratorio de Caminos de Barcelona* (LCB) shear test. Two types of asphalt emulsions, CRL-1 and CRL-1hm (conventional and modified with polymers, respectively), were used as tack coats at five residual application rates. The results of the study showed that the CRL-1hm tack coat developed a higher shear strength than the CRL-1 tack coat. Additionally, there was a variation in strength with an increase in application rate, leading to the determination of an optimum rate. These findings demonstrate the importance of binder type and application rate in achieving optimal bonding between asphalt layers, with potential benefits for the longevity and performance of pavements. Overall, this research provides valuable insights for pavement engineers seeking to optimize the bonding between asphalt layers. The study highlights the potential of modified emulsions, such as CRL-1hm, and the importance of carefully considering the application rate to achieve the desired bonding performance.

RESUMEN: La adherencia entre las capas de pavimentos asfálticos es crucial para su durabilidad y respuesta mecánica. La aplicación del riego de liga ha sido investigada para mejorar esta adherencia, encontrando diversos factores que influyen en el grado de adherencia logrado, como el tipo de riego, la tasa de aplicación, la temperatura y la humedad, entre otros. En este estudio se evaluó el efecto del tipo de ligante y la tasa de aplicación en la resistencia al corte de la interfase de capas bituminosas fabricadas en concreto asfáltico tipo MDC-19, utilizando el ensayo del *Laboratorio de Caminos de Barcelona* (LCB). Se utilizaron dos tipos de emulsiones asfálticas, CRL-1 (convencional) y CRL-1hm (modificada con polímeros), como riegos de liga en cinco tasas de aplicación. Los resultados mostraron que el riego CRL-1hm desarrolló una mayor resistencia al corte que el riego CRL-1. Además, hubo una variación en la resistencia con el aumento de la tasa de aplicación, lo que llevó a la determinación de una tasa óptima. Estos hallazgos demuestran la importancia del tipo de ligante y la tasa de aplicación para lograr una unión monolítica entre capas asfálticas, con posibles beneficios para la durabilidad del pavimento. Este estudio proporciona información valiosa para los ingenieros de pavimentos y destaca el potencial de las emulsiones modificadas, como la CRL-1hm, y la importancia de considerar cuidadosamente la tasa de aplicación para lograr la adherencia deseada.

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1. Introduction

Given that the analysis of road and airfield pavements extensively employs the layered elastic theory [1], the adhesion of asphalt layers is an important property that flexible pavements must achieve. According to ASTM, adhesion refers to "the state in which two surfaces are held together by interphase forces" [2]. In this case study, the surfaces consist of asphalt mixtures or asphalt concrete. Additionally, ASTM defines tack coat as the application of bituminous material to a non-absorptive surface to establish a comprehensive bond between old and new surfacing [3]. Similarly, the Federal Highway Administration (FHWA) defines a tack coat as the "sprayed application of asphalt binder upon an existing asphalt or Portland cement concrete pavement surface prior to an overlay, or between layers of new asphalt concrete" [4]. In flexible pavements, the tack coat is responsible for ensuring that two bituminous layers behave mechanically as one. This condition must exist; otherwise, the magnitude and location of critical stresses and strains will be different [5], and the design will not accurately predict the structure's performance, minimizing its life cycle [6, 7]. In the analysis of asphalt pavements, perfectly bonded layers at their interfaces are typically assumed, as stated in [8] and seen in [9], which utilized a finite element model.

For this reason, ensuring a high degree of adhesion between layers during construction is essential. It is also important to consider the adhesion at the interface between the asphalt layer and Portland cement concrete pavement, as found in [10], when constructing white-topping pavements. The application of seal coats between pavement layers plays an equally relevant role in the semi-permanent treatment used for pothole repair, as reported in [11].

Bituminous materials such as asphalt emulsions are commonly used to achieve proper adhesion between asphalt layers in flexible pavements. These emulsions consist of microscopic particles of asphalt dispersed in water and are referred to as tack coats. Therefore, it is crucial to study asphalt emulsions and their behavior as tack coats to understand the factors that influence the adherence of bituminous layers in pavement structures. The adhesion in asphalt pavements can also be analyzed on a different scale when considering the asphalt-aggregate system, where poor adhesiveness leads to the detachment of asphalt cement from the aggregates, causing cracking and moisture-related damage [12].

An experimental project was developed using a quantitative methodology to measure the bonding parameter of bituminous layers in different conditions. Test specimens were prepared by bonding two layers of asphalt mix commonly used in the region of Nariño in Colombia using emulsions, following the guidelines of the Spanish standard NLT 382/08. Bonding was evaluated using the LCB shear test developed in the Laboratorio de Caminos de Barcelona, which has been used by various researchers in Colombia [13–15] as well as in Argentina [16–18]. This test was used to determine the stress required to separate the bituminous layers.

The shear strength of the bonding surface of asphalt layers was initially determined using the LCB test. Five different dosages and two types of asphalt emulsions were used to manufacture the test specimens, which were subsequently subjected to the shear test to obtain the primary results for processing and analysis.

Finally, the effect of the application rate and type of binder on the bonding of asphalt layers was evaluated, and optimal application rates of asphalt emulsions were proposed. These rates allow for the highest efficiency in tack coats, resulting in the maximum value of shear strength and ensuring the proper adhesion of asphalt layers in pavement structures.

2. Concepts

2.1 Factors that affect the adhesion between bituminous layers

Binder dosage

The application rate or binder dosage is the amount of residual bitumen, measured either gravimetrically or volumetrically, that needs to be applied per unit area of the layer to be bonded. Residual bitumen refers to the bitumen that remains on the layer surface after the water has separated from the asphaltic phase and evaporated. The application of a tack coat may vary depending on the surface condition of the layer to be bonded, whether it is a new, old, or milled layer. In each condition, the binder dosage needs to be adjusted to ensure the layers are bonded together, creating a monolithic structure [19].

In Colombia, the General Highway Construction Specifications require an application rate of 200 to 300 g/m2 of residual binder [20]. This range of applications is suitable for normal conditions, but no quantitative or qualitative parameter is specified to determine the definitive value to be used.

For new layers, lower application rates are recommended. Intermediate values are suitable for existing pavements with relatively smooth surfaces, and those close to the upper limit are recommended for aged or cracked asphalt pavements and PCC pavements. Pavements that have been milled require an even greater amount of binder due to their greater specific surface area [19].

Type of bituminous binder

Various studies have concluded that the type of material used as a tack coat is one of the main factors influencing the ability to bond pavement layers, as different tack coats lead to varying shear strengths [5, 21, 22]. Within the group of asphalt emulsions, it can also be stated that there is a variation in interface shear strength depending on their electrical affinity; cationic emulsions generally exhibit higher strengths and fatigue life than other types of emulsions [23].

Polymer-modified asphalt emulsions display distinct behaviors compared to conventional emulsions, as modified emulsions can create a sealing effect in the lower layer, resulting in a higher bitumen content near the interface when applied in higher dosages. This reduces void content, which may lead to surface-related friction issues [19]. However, these modified emulsions increase resistance to top-down pavement cracking and reduce stress transmitted at the interface [23].

A study by Bae *et al.* found a correlation between interface shear strength and the rutting factor $\mathrm{G}^*/\sin\delta$, which is closely linked to the asphalt binder used in the tack coat. Therefore, laboratory design processes should incorporate this parameter to ensure the selection of the most suitable bituminous material as a tack coat in the field, along with an optimal application rate [23].

The applied tack coat has a greater influence on thin layers, as fatigue damage has been observed for most materials and tack dosages in thin pavement structures. Hence, ensuring a high degree of monolithic behavior in these layers is crucial. Conversely, in thicker structures, a satisfactory performance has been found regardless of the degree of adhesion achieved by the type and dosage of the tack coat [24].

2.2 General practices in tack coats

A survey was conducted by the National Cooperative Highway Research Program (NCHRP) between August 2005 and January 2006, in which a majority of the State Departments of Transportation from the United States, the Federal Highway Administration (FHWA), the Asphalt Institute, field engineers, contractors, and selected road agencies from Canada, Europe, and South Africa participated. The objective of the survey was to identify the general practices related to tack coats worldwide, including the types of materials used as tack coats, application rates, and other related factors [19]. The survey revealed that all consulted agencies reported using asphalt emulsions as tack coats, while asphalt cement and cutback asphalts were used in smaller proportions, as shown in Figure 1.

While Colombia and other Latin American countries did not participate in the NCHRP survey, it is well-known that the only approved tack coat material specified in Colombia is cationic asphalt emulsion [20]. This finding aligns with the results from a previous global survey conducted by the International Bitumen Emulsion Federation (IBEF) in 1999, which involved countries such as France, Italy, Japan, Netherlands, Spain, the United Kingdom, and the United States. The IBEF survey found that cationic emulsions were the most commonly used tack coat material [25]. However, the NCHRP survey revealed a discovery that stands in contrast to the emulsion break specification stipulated in Colombian regulations. This specification designates CRR as the required emulsion for tack coats due to its categorization as a cationic rapid-setting emulsion. The finding was that the most commonly employed emulsion types are those with slow-setting (SS) [19].

Among some of the advantages offered by slow-break emulsions compared to rapid-break ones, which could partially account for their higher usage, is the ability of the former to be diluted. This allows the distribution equipment to function at regular speeds when applying lower application rates. This is achieved by loading a larger volume of the emulsion. Furthermore, diluted emulsions can be more easily applied at room temperature, resulting in a more uniform application [26].

2.3 Pavement distresses associated with tack coat

The durability of asphalt pavements is known to be impacted by the tack coat bond. An effective interlayer bonding system prevents the different pavement layers from functioning independently of one another and causes the pavement structure to have non-uniform stress and strain profiles. Inadequate bonding between the pavement layers can cause a number of pavement failures, including slippage cracking, debonding, and early fatigue cracking, all of which shorten the fatigue life of the pavement [27].

Although incorrect type or application of tack coat can lead to distresses in flexible pavements, only a few have been identified, such as slippage failure (Figure 2), which manifests as cracks in a semi-circular form with curvatures in the direction of vehicle braking or acceleration, typically where heavy vehicles accelerate, brake or turn, and delamination (Figure 3), which refers to detachment of the upper asphalt layer without affecting

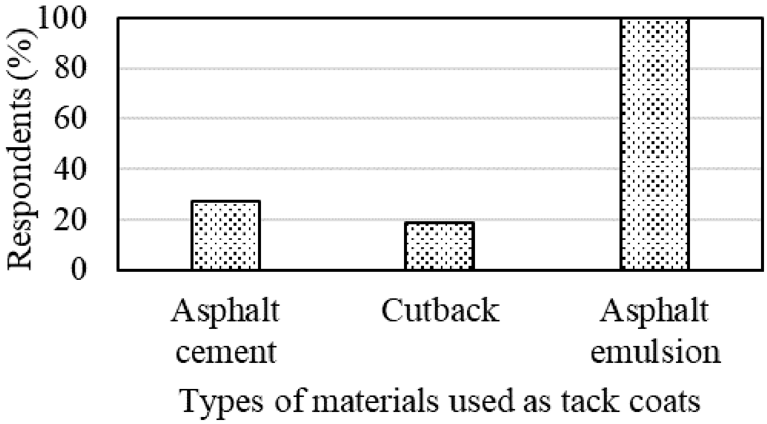

Figure 1 Tack coat material types [9].

Figure 2 Slippage.

Figure 3 Delamination.

the underlying layers [28]. These were also the most frequently reported distresses related to the improper use of tack coat in the NCHRP survey, with 89 % of respondents reporting slippage and 87 % reporting delamination. Other distresses reported included fatigue cracking, top-down cracking, and rutting, among others [19].

Although the monolithic behavior of pavement structure is clearly crucial, it appears that testing the performance of materials used in pavement layers to achieve this condition is not a priority for various highway and transportation agencies worldwide. This is evident from another finding

Table 1 Mineral aggregate characterization

Property	INV test	Result
Abrasion L.A. (%)		
500 rev.	E-218	22
100 rev.		4
Soundness, magnesium sulfate (%)	E-220	Coarse: 4 Fine: 7
Plasticity index	E-125 y E-126	NP
Crushed particles (%)		
One face	E-227	87
Two faces		80
Fine aggregate angularity (%)	E-239	48.2

in the NCHRP survey, which reveals that an overwhelming majority of respondents, 92 %, do not conduct any bonding verification tests between pavement layers [19].

3. Materials and methods

3.1 Materials

The materials employed in the research are associated with the hot mix asphalt layers and the bituminous binder used as a tack coat between them. Asphalt cement, mineral aggregate, as well as conventional and modified asphalt emulsion were collected and processed to create the necessary test specimens for the study. The mineral aggregate for the mix was derived from four types of crushed material obtained from a river, and its properties are detailed in Table 1.

The asphalt cement chosen for the research was type 60/70 from the Barrancabermeja refinery of Ecopetrol. It

Table 2 Asphalt cement characterization

Property	INV test	Result
Penetration, 25°C (0.1 mm)	E-706	64
Softening point (°C)	E-712	49.4
Penetration index	E-724	-7
Absolute viscosity, 60°C (P)	E-716	2 420
Ductility (cm)	E-702	140
Trichloroethylene solubility (%)	E-713	99.9
Mass loss (RTFOT) (%)	E-720	0.33

had a mixing temperature of 149 ± 1°C and a laboratory compaction temperature of 139 ± 1°C. The properties of asphalt cement are presented in Table 2.

The type of asphalt mixture that comprised the two bonded layers was a dense hot mix MDC-19 type, with proportions obtained from the Marshall design provided by the company Panavías Ingeniería y Construcciones S.A. located in Pasto, Nariño. The proportion of asphalt cement added was 5.4 % of the total mass of the mix, which also had the gradation of stone material shown in Figure 4.

For tack coat, two types of asphalt emulsions were utilized, namely, a CRL-1 cationic slow-setting emulsion and a CRL-1hm cationic slow-setting emulsion modified with polymers, both supplied by the company Humberto Quintero O y Cía. SCA. The characterization results for both emulsions are reported in Table 3.

3.2 Preparation of asphalt concrete specimens

The cylindrical asphalt concrete specimens were prepared with a diameter of 101.6 mm and a height of 110 mm. The specimens consisted of two layers of mix with thicknesses of 50 and 60 mm, respectively, which were bonded together by a bituminous tack coat. The first layer, with a thickness of 60 mm, was compacted in a Marshall mold using the standard impact hammer of the method. The specific compaction energy was established in accordance with the Spanish standard NLT 382/08 "Evaluation of Bonding Between Pavement Layers, by Shear Test," and was equal to 34928 $\mathrm{lb} \cdot \mathrm{ft}/\mathrm{ft}^3$. The first layer was compacted with an amount of 60 blows per face. After cooling, the asphalt emulsion was applied in the chosen dosage and left in an oven at a temperature between 20 and 25°C for 24 hours to ensure complete evaporation of the water present in the dispersion.

The LCB shear test was conducted on specimens manufactured from the same asphalt mix, two types of tack coat, and five application rates. The application rates were chosen based on the requirement present in the Colombian specification INV Art. 421-13, which establishes a residual binder dosage in the range of 200 to 300 g/m^2. Two additional superior values of 400 and 500 g/m^2, and an additional value below the specified range of 100 g/m^2 were also chosen. This range of binder applications allowed for the assessment of its effect on the bonding of asphalt layers and the determination of an optimum dosage.

The application of the emulsion as a tack coat in each specimen was determined based on its diameter of 101.6 mm and the residual asphalt content of the tacks, which was 60 % for the CRL-1 emulsion and 61 % for the CRL-1hm emulsion. The emulsion rates applied to achieve the desired residual asphalt dosage are shown in Table 4.

For the second layer, the simple compressive strength of the asphalt mixture specimen mold was used. The cylindrical shape of the mold, with a diameter and height of 177.8 mm (7 in), allowed for the formation of the first layer of the specimen with the residual asphalt of the emulsion. The second bituminous mix layer of 50 mm was then compacted on top of the first layer with a specific compaction energy equal to that established in the NLT 382/08 standard. Since it was only possible to compact from one side, the second layer was developed with an amount of 100 blows. After cooling, the bilayer set of asphalt mix bonded with emulsion was obtained to be used as the test specimen for the bonding study (Figure 5).

3.3 LCB bonding test

The LCB shear test, also known as Device B, as described in the Spanish standard NLT 382/08 "Evaluation of bonding between pavement layers, by shear test," is used to evaluate bonding between pavement layers. The device consists of a cylindrical clamp that can be removed in two halves, with an internal diameter of 101.6 mm (4 in) and a height of 177.8 mm (7 in) [29]. The clamp also has a plate and screws mounting to hold the test specimen firmly. The test specimen is a cylindrical sample made from two bonded layers of bituminous mix, placed inside the clamp. The metal base with supports located 188 mm apart is another component of the equipment.

Since temperature plays a crucial role in the adhesion between the bonding surface and the asphalt mix, the test specimens were conditioned in a thermostatic chamber regulated at 20°C (68°F) for 3 hours before conducting the test [24].

To ensure accurate results, the second layer of the specimen was kept outside the clamp, holding up on one of the supports, while the interface of the layers was

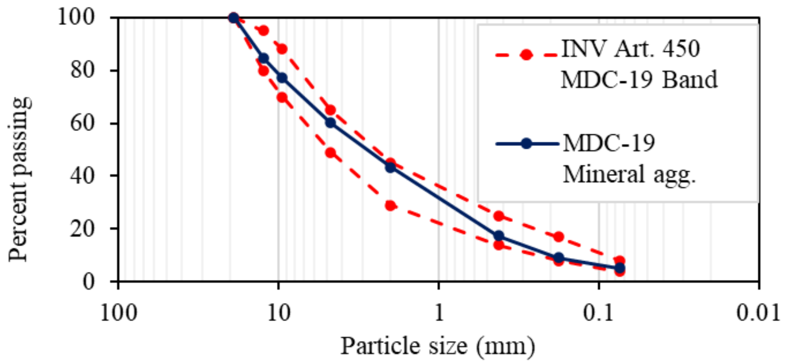

Figure 4 Asphalt mix mineral aggregate gradation

Table 3 Asphalt emulsions characterization

Property	INV test	Result CRL-1	Result CRL-1hm
Saybolt Furol Viscosity, 25°C (s)	E-763	27.67	27.80
Residual asphalt content (%)	E-762	60.13	61.11
Distillation residue tests			
Penetration (0.1 mm)	E-706	64.7	68.9
Softening point (°C)	E-712	N/A	63.1
Ductility (cm)	E-702	>100	>100

Table 4 Relationship between residual asphalt and emulsion to be applied

Residual asphalt (g/m^2)	100	200	300	400	500
CRL-1 Emulsion (g)	1.3	2.7	4.0	5.3	6.7
CRL-1hm Emulsion (g)	1.3	2.6	3.9	5.3	6.6

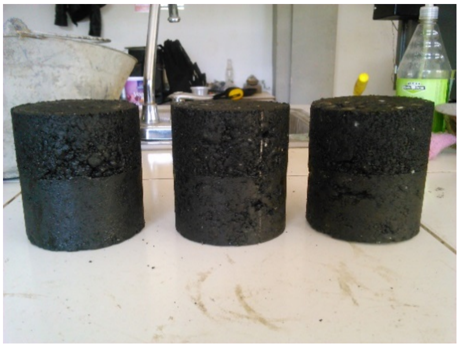

Figure 5 Specimens manufactured

located 5 mm from the edge of the clamp and 5 mm from the edge of the support. This arrangement ensures that the bending moment in this area is of a very small magnitude, and there is only shear force [30]. The test specimen and metal clamp assembly were then placed horizontally on the base (Figure 6). The load application was continued at a point on the clamp that is equidistant from each of the base supports [29].

A digital compression press was used for load application, with the piston moving vertically downwards on the clamp at a constant speed of 1.27 mm/min (0.05 in/min), corresponding to the CBR test speed. This speed is low enough to better appreciate the effects of bonding. The maximum failure load was used to characterize the adhesion developed by the bonding surface and to determine the shear strength.

The interface shear strength (ISS) was calculated as half of the maximum load exerted by the press piston on the device during the test (P), divided by the cross-sectional area of the specimen (S) (Figure 7). Therefore, the interface shear strength was calculated using the following Equation:

$$ISS = (P/2)/S \tag{1}$$

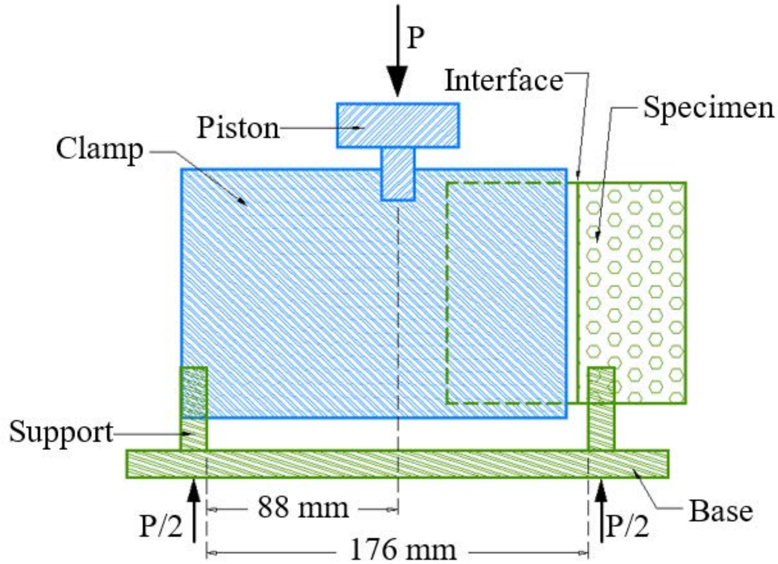

Figure 6 Components of LCB test device

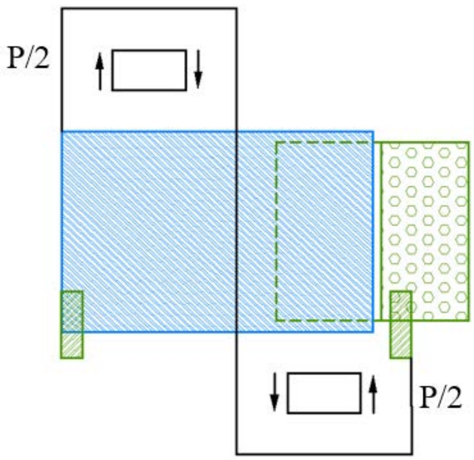

Figure 7 Forces diagram acting on the specimen in the LCB test

Table 5 Interface shear strength with CRL-1 asphalt emulsion

Application rate (g/m^2)	100	200	300	400	500
	0.19	0.30	0.39	0.38	0.30
ISS (MPa)	0.24	0.33	0.36	0.41	0.35
	0.21	0.36	0.43	0.39	0.29
Mean	0.21	0.33	0.40	0.39	0.31
S.D.	0.02	0.03	0.04	0.02	0.03
COV (%)	9.8	8.6	9.0	4.7	10.4

4. Results

For each test condition defined by the residual binder dosage and the type of tack coat, three specimens were fabricated. The results for the interface shear strength, along with the standard deviation and coefficient of variation, are presented in Tables 5 and 6 for conventional and modified asphalt emulsions, respectively.

In Figure 8, the individual results for shear strength are depicted for each group of results based on the type of tack coat, along with a third-degree polynomial regression curve obtained for each group. For both groups of specimens analyzed according to the type of tack, a dosage exists that yields the maximum strength value. This dosage can be considered optimal as it guarantees a closer

Table 6 Interface shear strength with CRL-1hm asphalt emulsion

Application rate (g/m^2	100	200	300	400	500
	0.41	0.53	0.51	0.43	0.38
ISS (MPa)	0.49	0.61	0.60	0.47	0.43
	0.43	0.62	0.61	0.39	0.36
Mean	0.45	0.59	0.57	0.43	0.39
S.D.	0.04	0.05	0.05	0.04	0.04
COV (%)	10.0	7.9	9.2	9.1	9.6

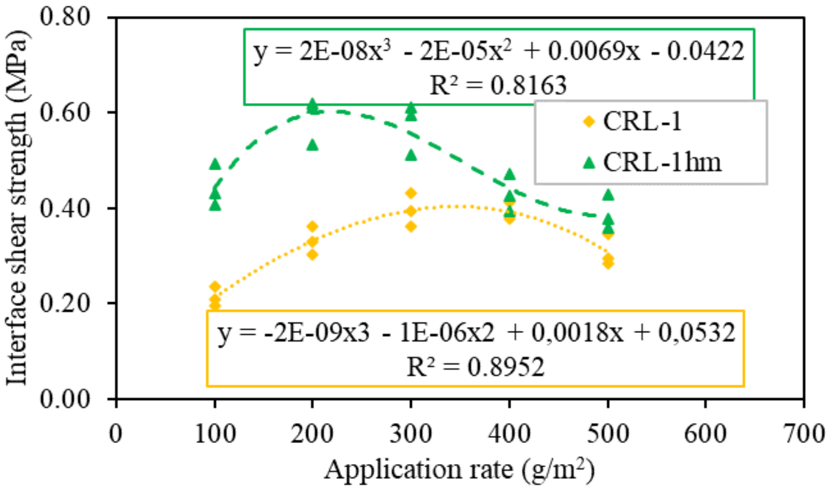

Figure 8 Shear strength according to application rate and type of tack coat together with regression curve

Table 7 Interface shear strength with CRL-1hm asphalt emulsion

Type of emulsion	Optimum application rate of residual binder (g/m^2)	Interface shear strength (MPa)
CRL-1	350	0.40
CRL-1hm	220	0.60

approximation to the monolithic behavior required for asphalt layers. The optimum application rates calculated using the third-degree polynomial regression curves from Figure 8 are shown in Table 7.

5. Conclusions

The results of the present study showed that the type of tack coat significantly impacts the interface shear strength of asphalt layers. Specifically, the modified asphalt emulsion CRL-1hm demonstrated superior strength compared to the conventional asphalt emulsion CRL-1. It was also observed that the effect of the type of tack coat is more pronounced for dosages lower than 300 g/m^2, and that an increase in application rate reduces the effect of the type of asphalt binder on shear strength.

Additionally, the residual application rate of the tack coat was found to have an important effect on the shear strength developed by the bonded interface of the asphalt layers. Optimum rates of 350 and 220 g/m^2 were identified for tacks CRL-1 and CRL-1hm, respectively.

Notably, the shear strength estimated for the optimum dosage of tack coat type CRL-1hm was found to be 50 % higher than the corresponding strength for tack coat type CRL-1. This highlights the significant advantages that could be achieved through the use of modified asphalt emulsion, specifically CRL-1hm, to achieve the desired monolithic behavior in asphalt layers.

6. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

7. Acknowledgments

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8. Author contributions

The authors Gerardo Dorado and Laura Rosero developed the experimental design and conducted laboratory tests with asphalt materials to obtain the results of asphalt layer adhesion, and the author Gerardo Dorado wrote the article. Author Magda Martínez performed the statistical analysis of the results.

9. Data availability statement

The data that support the findings of this study are available from the corresponding author, [G-A Dorado-Jurado], upon reasonable request.

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