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# Comparative Analysis of Adhesive Behavior of Rapid-Setting and Slow-Setting Asphalt Emulsions in Tack Coats Evaluated by LCB Test

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***Abstract***

*Interlayer bonding in asphalt pavements is a key factor governing the durability, structural performance, and mechanical response of flexible pavements under traffic loading. Inadequate monolithic action between bituminous layers leads to premature distresses such as slippage, delamination, and fatigue cracking, severely compromising pavement service life. This study presents a comprehensive comparative analysis of the bonding performance of cationic asphalt emulsions of rapid setting (CRR-60 and CRR-65) and slow setting (conventional CRL-1 and polymer-modified CRL-1hm), used as tack coats between dense-graded hot-mix asphalt layers (MDC-19) representative of Colombian specifications. The experimental program was based on the Laboratorio de Caminos de Barcelona (LCB) shear test, standardized in the Spanish specification NLT-382/08, which quantifies the interface shear strength developed at the bonding surface between asphalt layers joined by a tack coat. Five residual binder application rates were evaluated for slow-setting emulsions and four for rapid-setting emulsions (100, 200, 300, 400, and 500 g/m²), with the aim of identifying the optimal dosages that maximize interface strength. In addition, the influence of binder viscosity and the effect of surface dust contamination on bonding performance were assessed. Experimental results revealed marked differences between emulsions as a function of their setting rate. The polymer-modified slow-setting emulsion (CRL-1hm) achieved the highest interface shear strength (0.60 MPa) at a substantially lower optimum application rate (220 g/m²), satisfying European requirements for layers beneath wearing courses. By contrast, rapid-setting emulsions (CRR-60 and CRR-65) required higher application rates (440–445 g/m²) to reach maximum strengths of 0.345 and 0.418 MPa, respectively, values that lie outside the range prescribed by current Colombian specifications (200–300 g/m². Viscosity, governed by residual asphalt content, had a positive effect on bonding, with strength increases of 16–21% between emulsions with different residual contents. Surface dust contamination significantly reduced shear strength, with decreases of 56% for CRR-60 and 29% for CRR-65 at a contamination level of 123.46 g/m², highlighting the critical importance of proper surface cleaning prior to tack coat application. These findings provide essential technical criteria for the selection and dosage of asphalt emulsions for tack coats, with clear implications for improving pavement durability and in-service performance.*

**Keywords:** *Asphalt emulsion, tack coat, shear strength, application rate, interlayer bonding, LCB test, rapid setting, slow setting, NLT-382/08, flexible pavement*

## Introduction

The development of road infrastructure in Colombia and Latin America demands the modernization and expansion of the capacity of road networks, where asphalt pavements represent the most widely used alternative due to their characteristics, advantages, and versatility (Jahanbakhsh et al., 2016). The construction of pavement structures with considerable thicknesses requires installation in multiple layers to achieve the required dimensions and the

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appropriate degree of compaction (Xu & Huang, 2012).

The adhesion generated at the interface of the asphalt layers is of high importance, since it directly influences the performance and durability of the pavement structure (Vargas Saa, 2008). King and May (2003) demonstrated through simulation of pavement structures that the decrease in the adhesion state from total adhesion (without slipping) to a level of 90% (partial slippage), significantly increased the values of tension and deformation, reducing the final useful life by approximately 50%.

In the analysis of asphalt pavements, it is generally assumed that the layers are perfectly adhered at their interfaces (Bacha et al., 2023; Rodríguez-Calderón & Pallares-Muñoz, 2015). However, this ideal condition is not always achieved in practice, resulting in premature deteriorations such as layer slippage, fatigue cracking, and delamination (Transportation Research Board [TRB], 2012).

Bond irrigation is the procedure responsible for ensuring that the structure functions as a single system, through a thin and uniform application of asphalt material, usually an emulsion diluted in water, on the existing surface of the pavement prior to the placement of a new asphalt layer (Asphalt Institute, 2008). The selection of an optimal emulsion and its application rate is critical for the proper development of bond strength between pavement layers.

Asphalt emulsions are classified according to their breakage speed into: fast breakage (RS/CRR), medium breakage (MS) and slow breakage (SS/CRL). This classification determines the time it takes for the emulsion to cure and the amount of mixing that can be done before the emulsion ruptures. In the United States, slow-breaking emulsions diluted with water are the most commonly used as binder irrigations, while in Europe, undiluted fast-breaking cationic emulsions predominate (Asphalt Emulsion Manufacturers Association, 2023).

The present study aims to compare the adhesive performance of fast-curing emulsions (CRR-60, CRR-65) versus slow-curing emulsions (CRL-1, CRL-1hm), determining optimal application rates and evaluating factors affecting the shear strength of the interface.

## Theoretical Framework

### Adhesion between asphalt pavement layers

The analysis of flexible pavements using multilayer elastic theory assumes that the layers are perfectly adhered at their interfaces, behaving like a monolithic structure (Huang, 2004). However, this ideal condition requires the application of a bond irrigation that guarantees the effective transfer of stresses between layers (TRB, 2012)

King and May (2003) demonstrated that reducing the adhesion status from full adhesion (100%) to a level of 90% significantly increases stresses and deformations in the structure, reducing the useful life by approximately 50%:

$$\frac{N_{f,parcial}}{N_{f,total}} \approx 0.50$$

Poor adhesion generates premature deterioration such as layer slippage, delamination, and fatigue cracking, compromising the structural performance of the pavement (Wang et al., 2017; Wruck et al., 2022).

### Shear Stress Resistance of the Interface

The shear stress resistance of the interface (ISS or REC) is the fundamental parameter to characterize the adhesion between asphalt layers (AASHTO, 2018). The LCB test according to the Spanish standard NLT-382/08 determines this property by means of the equation (Center for Studies and Experimentation of Public Works, 2008):

$$REC = \frac{P/2}{S}$$

Where:

- $REC$ = Shear Strength (MPa)
- $P$ = Maximum breaking load (N)
- $S$ = Cross-sectional area (mm²)

For cylindrical specimens of mm diameter:$D = 101.6$

$$S = \frac{\pi(101.6)^2}{4} = 8107.32 \text{ mm}^2 \ (3)$$

The Spanish specification Order FOM/2523/2014 establishes minimum requirements of 0.6 MPa under the wearing layer and 0.4 MPa in lower layers.

### Asphalt emulsions and breakage speed

Asphalt emulsions are colloidal dispersions of asphalt particles in water, stabilized by cationic or anionic emulsifying agents (Asphalt Institute, 2008). They are classified according to their breaking speed into three categories (EEA, 2023):

| Classification | Nomenclature | Breakage time |
|---|---|---|
| Quick breakage | RS/CRR | < 5 minutes |
| Medium break | MS/CRM | 5-60 minutes |
| Slow Break | SS/CRL | > 60 minutes |

Rapid Break Emulsions (CRRs) break immediately upon contact with the aggregate, allowing for rapid placement of top coats. Slow-breaking emulsions (CRLs) offer longer working time and can be diluted to facilitate uniform application at room temperature ((TRB, 2012; Tashman et al., 2006).

### Factors Affecting Adherence

### Binder application rate

The optimal rate of application can be determined by third-degree polynomial regression (TRB, 2012):$R_{opt}$

$$REC(R) = a_0 + a_1R + a_2R^2 + a_3R^3$$

Deriving and equating to a candle:

$$\frac{dREC}{dR} = a_1 + 2a_2R + 3a_3R^2 = 0$$

In Colombia, the INVIAS specifications (2022) establish rates between 200-300 g/m² of residual binder. Recent studies with fast-curing emulsions evaluated rates between 200-500 g/m², while for slow-curing emulsions rates from 100 to 500 g/m² were evaluated (Dorado-Jurado et al., 2024)

### Type of binder

The type of emulsion significantly influences the adhesion strength (Ali et al., 2023; Ghabchi &

Dharmarathna, 2020). Polymer-modified emulsions develop higher shear strength due to their sealing effect and higher effective bitumen content near the interface (Wang et al., 2017). Bae et al. (cited in Wang et al., 2017) correlated resistance with the rheological factor:

$$ISS = k_1 \cdot \left(\frac{G^*}{\sin\,\delta}\right)^{k_2}$$

Where is the complex modulus and phase angle of the binder.$G^*\delta$

### Incidence of dust

The presence of dust as a surface contaminant reduces the adhesion resistance, empirically modeled as:

$$REC_{polvo} = REC_0 \cdot (1 - \beta \cdot P_d)$$

Where is the coefficient of reduction per dust (m²/g) and the surface density of dust (g/m²).$\beta P_d$

## MATERIALS AND METHODS

### Study Area

The investigations were carried out in the municipality of San Juan de Pasto, capital of the department of Nariño, Colombia, located in the southwest of the country near the border with Ecuador. The laboratory tests were carried out in specialized facilities in the region, using materials produced in local asphalt plants and bituminous binders marketed in the country.

### Materials

### Stone aggregate and asphalt mix

A hot dense asphalt mixture type MDC-19 was used with a proportion of asphalt cement of 5.4% with respect to the total mass. The asphalt cement type 60/70 from the Barrancabermeja refinery had a mixing temperature of 149 ± 1°C and a laboratory compaction temperature of 139 ± 1°C. Table 1 presents the characterization of asphalt cement.

**Table 1.** Characterization of asphalt cement

| Ownership | INV Assay | Result |
|---|---|---|
| Penetration, 25°C (0.1 mm) | E-706-13 | 64 |
| Softening point (°C) | E-712-13 | 49,4 |
| Penetration Rate | E-724-13 | -7 |
| Absolute viscosity, 60°C (P) | E-716-13 | 2.420 |
| Ductility (cm) | E-702-13 | 140 |
| Trichloroethylene solubility (%) | E-713-13 | 99,9 |
| RTFOT Mass Loss (%) | E-720-13 | 0,329 |

*Source:* Adapted from Dorado-Jurado et al. (2024)

## Asphalt emulsions

Four types of cationic asphalt emulsions were evaluated: two fast-curing (CRR-60 and CRR-65) and two slow-curing (conventional CRL-1 and polymer-modified CRL-1hm). Table 2 presents the comparative characterization of the emulsions.

**Table 2.** Characterization of the evaluated asphalt emulsions

| Ownership | CRR-60 | CRR-65 | CRL-1 | CRL-1hm |
|---|---|---|---|---|
| Breaking speed | Fast | Fast | Ribbon | Ribbon |
| Residual asphalt content (%) | 60.76 | 66.90 | 60,13 | 61,11 |
| Saybolt Furol Viscosity 25°C(s) | 22.0 |  | 27,67 | 27,80 |
| Saybolt Furol Viscosity 55°C(s) |  | 110 |  |  |
| Residual penetration (0.1 mm) | 60 | 60.1 | 64,7 | 68,9 |
| Residual Softening Point (°C) | N/A | N/A | N/A | 63,1 |
| Residue ductility (cm) | 98 | >100 | >100 | >100 |

*Source:* Adapted from Obando Ante (2023) and Dorado-Jurado et al. (2024)

## Specimen preparation

The cylindrical specimens were prepared with a diameter of 101.6 mm and a total height of 110 mm, consisting of two layers of mixture with thicknesses of 50 and 60 mm respectively, joined by league irrigation. The first layer corresponded to 60 mm, compacted in a Marshall mold using the method's standard impact hammer, with specific compaction energy according to the NLT-382/08 standard.

For the studies with fast-curing emulsions (CRR-60 and CRR-65), a total of 76 specimens were produced, evaluating four application rates (200, 300, 400 and 500 g/m²) of residual binder, with 5 samples for each emulsion rate and type (40 specimens), plus an additional 36 specimens for dust incidence analysis. For the slow-curing emulsions (CRL-1 and CRL-1hm), three specimens were manufactured for each test condition with five application rates (100, 200, 300, 400 and 500 g/m²)

After compaction of the first layer and its cooling, the asphalt emulsion was applied in the selected dosage, leaving the specimens in the oven at a temperature between 20-25°C for 24 hours to ensure the complete evaporation of the water present in the dispersion.

## LCB Cut Test

The LCB shear test, also called Device B according to the Spanish standard NLT-382/08 "Evaluation of adhesion between pavement layers, by means of a shear test", was used to evaluate the adhesion between pavement layers (Center for Studies and Experimentation of Public Works, 2008).

The device consists of a cylindrical jaw that can be detached in two halves, with an internal diameter of 101.6 mm and a height of 177.8 mm, as well as a metal base with brackets 188 mm apart. The specimens were conditioned in a thermostatic chamber regulated at 20°C for 3 hours before the test.

The loading application was performed by digital compression press, with the piston moving vertically down over the jaw at a constant speed of 1.27 mm/min for slow-curing emulsions and 2.5 mm/min according to the NLT-382/08 standard for fast-curing emulsions. The shear stress resistance of the interface (REC) was calculated using the equation:

$$REC = \frac{P/2}{S} \ (1)$$

Where:

- REC = Shear Strength (MPa)
- P = Maximum breaking load (N)
- S = Cross-sectional area (mm²)

# RESULTS AND ANALYSIS

## Shear Resistance by Application Rate

The shear strength results for the four emulsions evaluated are presented in Table 3 and Figure 1.

**Table 3.** Shear Strength by Application Rate and Type of Emulsion

| Rate (g/m²) | CRR-60 REC (MPa) | CRR-65 REC (MPa) | CRL-1 ISS (MPa) | CRL-1hm ISS (MPa) |
|---|---|---|---|---|
| 100 | | | 0,21 | 0,45 |
| 200 | 0,183 | 0,212 | 0,33 | 0,59 |
| 300 | 0,215 | 0,263 | 0,40 | 0,57 |
| 400 | 0,325 | 0,399 | 0,39 | 0,43 |
| 500 | 0,298 | 0,350 | 0,31 | 0,39 |

*Source:* Authors' elaboration based on Obando Ante (2023) and Dorado-Jurado et al. (2024)

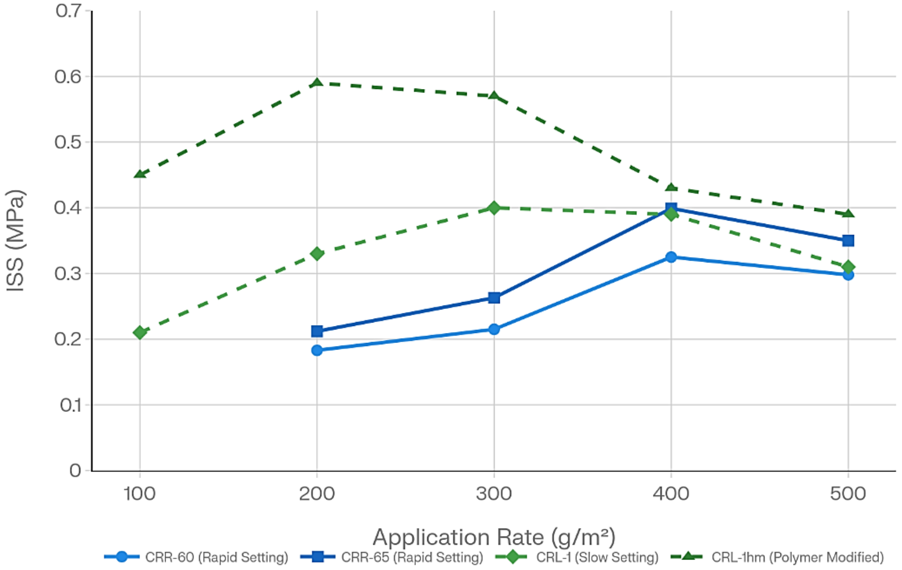

**Figure 1. Interface Shear Strength vs Application Rate**

When comparing shear strength between emulsions, the results show differentiated behaviors between fast-curing and slow-curing emulsions. CRR-60 and CRR-65 emulsions showed increasing resistances up to rates close to 400-450 g/m², decreasing subsequently. In contrast, the CRL-1hm emulsion reached its maximum strength (0.59-0.60 MPa) at lower rates (200-220 g/m²), showing a progressive decrease with increasing dosage.

## Determination of optimal application rates

By means of third-degree polynomial regression, the optimal application rates for each type of emulsion were determined, presented in Table 4 and Figures 2 and 3.

**Table 4.** Optimal application rates and maximum strength per emulsion type

| Emulsion Type | Breaking Speed | Optimum Rate (g/m²) | Maximum REC (MPa) |
|---|---|---|---|
| CRR-60 | Fast | 445 | 0,345 |
| CRR-65 | Fast | 440 | 0,418 |
| CRL-1 | Slow | 350 | 0,40 |
| CRL-1hm | Slow Modified | 220 | 0,60 |

*Source:* Own elaboration

Figure 2 shows substantial differences in the optimal application rates according to the emulsion breakage rate. The fast-curing emulsions (CRR-60 and CRR-65) presented practically equivalent optimal rates of 445 and 440 g/m² respectively, values that exceed the range established by the Colombian INVIAS specifications (200-300 g/m²) by 48-123%. In contrast, slow-curing emulsions showed significantly lower optimal rates: 350 g/m² for conventional CRL-1 and 220 g/m² for polymer-modified CRL-1hm.

The modified CRL-1hm emulsion required the lowest optimal rate (220 g/m²), representing a 50% reduction compared to CRR emulsions and placing it within the Colombian regulatory range. This behavior can be attributed to two factors: slow-curing emulsions, by allowing longer working time, facilitate a more uniform distribution of the binder on the surface, optimizing effective coverage with less material (Tashman et al., 2006); and the polymeric modification of CRL-1hm generates a sealing effect that increases the efficiency of the residual binder near the interface (Wang et al., 2017).

From a technical-economic perspective, the use of modified slow-curing emulsions could represent savings of up to 50% in binder consumption compared to fast-curing emulsions, maintaining or exceeding adhesive performance.

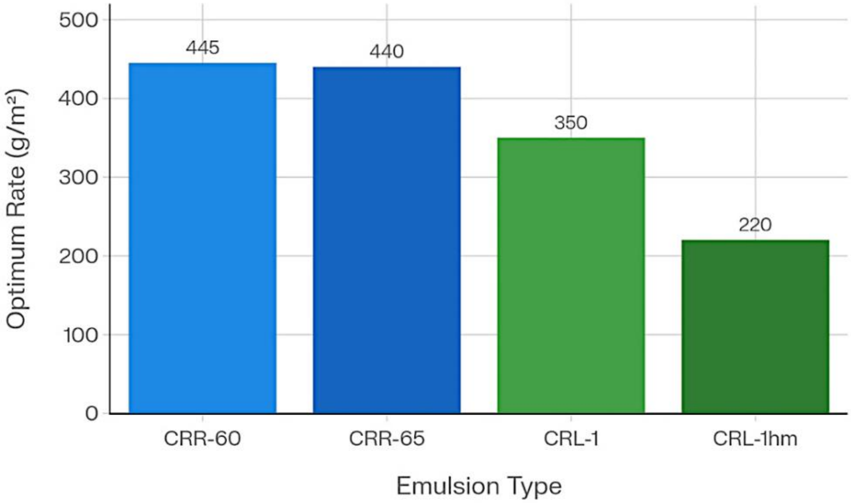

**Figure 2: Optimum Application Rate by Emulsion Type**

Figure 3 presents the maximum shear strength achieved by each type of emulsion, including the reference lines corresponding to the minimum requirements established in the Spanish specification Order FOM/2523/2014: 0.6 MPa for under-rolling layers and 0.4 MPa for lower layers.

The comparative analysis reveals a clear hierarchy of performance: CRL-1hm (0.60 MPa) > CRR-65 (0.418 MPa) > CRL-1 (0.40 MPa) > CRR-60 (0.345 MPa). The polymer-modified emulsion CRL-1hm was the only one to meet the regulatory requirement of 0.6 MPa for rolling layers, beating the best fast-curing emulsion (CRR-65) by 43% and its conventional counterpart (CRL-1) by 50%.

Regarding compliance with the 0.4 MPa requirement for lower layers, three of the four emulsions evaluated (CRL-1hm, CRR-65 and CRL-1) reached or exceeded this threshold, while the CRR-60 emulsion (0.345 MPa) was 14% below.

A relevant finding is that, within each category of breaking rate, emulsions with higher residual asphalt content (CRR-65 with 65% vs CRR-60 with 60%) or with polymeric modification (CRL-1hm vs CRL-1) developed superior strengths. This confirms the positive influence of viscosity and binder modification on adhesion between asphalt layers, consistent with the reported correlations between the rheological factor G*/without δ and the shear strength of the interface (Wang et al., 2017).

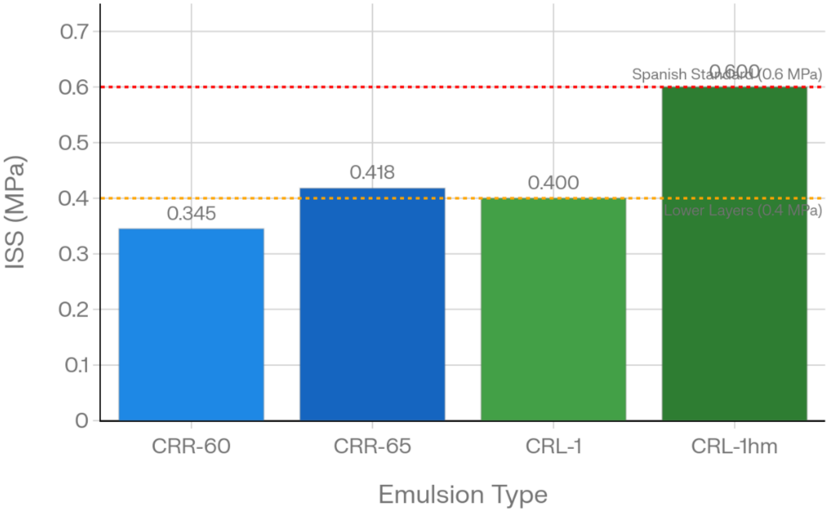

**Figure 3: Maximum Interface Shear Strength by Emulsion Type**

Comparative analysis reveals that the polymer-modified CRL-1hm emulsion developed 50% higher strength than conventional CRL-1 emulsion and 43% higher than fast-curing CRR-65. Additionally, slow-curing emulsions required significantly lower optimal rates (220-350 g/m²) compared to fast-curing emulsions (440-445 g/m²), representing a potential material savings of 21-50%.

### Effect of viscosity on adhesion

The results showed that the higher the viscosity, the higher the values of resistance to shear stress. In the specimens where the CRR-65 emulsion (65% residual asphalt) was used as bond irrigation, REC of 0.418 MPa was obtained, representing 16% more than for the CRR-60 emulsion (60% residual asphalt) with REC of 0.345 MPa.[1]

This behavior correlates with the G*/δ-free rutting factor, which is closely linked to the asphalt binder used in bond irrigation (Bae et al., cited in Wang et al., 2017). Emulsions with higher residual asphalt content and/or modified with polymers tend to develop higher adhesion strengths.

### Incidence of dust as a pollutant

The study of the incidence of dust was carried out exclusively with fast-curing emulsions, evaluating three conditions: absence of dust (0 g), presence of 0.5 g (61.73 g/m²) and presence of 1.0 g (123.46 g/m²). The results are presented in Table 5 and Figure 4.

**Table 5.** Impact of dust on shear resistance

| Powder (g/m²) | CRR-60 REC (MPa) | Reduction (%) | CRR-65 REC (MPa) | Reduction (%) |
|---|---|---|---|---|
| 0 | 0,349 | 0 | 0,406 | 0 |
| 61,73 | 0,286 | 18,0 | 0,363 | 10,6 |
| 123,46 | 0,153 | 56,2 | 0,290 | 28,6 |

*Source:* Adapted from Obando Ante (2023)

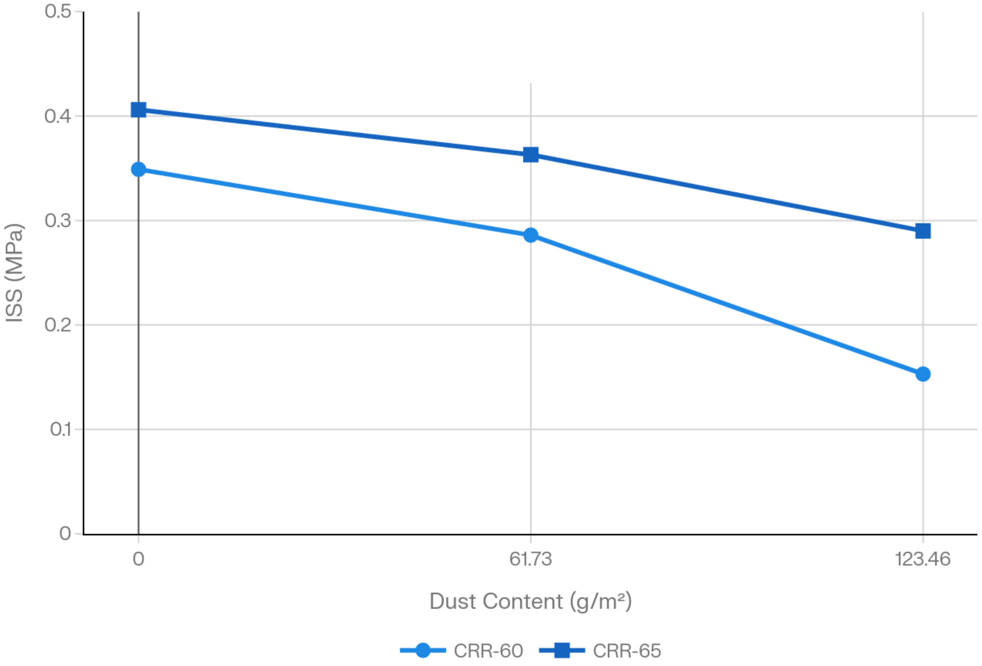

**Figure 4: Effect of Dust on Interface Shear Strength**

Regarding the effect of dust on shear strength, the results show a significant decrease in shear resistance with increasing dust content. The CRR-60 emulsion showed greater susceptibility to dust contamination, with a loss of 56.2% of strength under the maximum evaluated dust condition, compared to the 28.6% reduction for CRR-65. This suggests that emulsions with a higher content of residual asphalt have better behavior under surface contamination conditions.

### Comparison with international regulatory requirements

The Spanish specification complementary to NLT-382/08, Order FOM/2523/2014 + FOM/510/2018, in its article 531 of the PG-3, prescribes minimum requirements of 0.6 MPa under the wearing layer and 0.4 MPa in lower layers. The results obtained show that only the polymer-modified CRL-1hm emulsion reached the requirement of 0.6 MPa, while the conventional emulsions (CRR-60, CRR-65, CRL-1) presented values between 0.345-0.418 MPa, meeting only the requirement for lower layers.

## DISCUSSION

The observed differences between fast-curing and slow-curing emulsions can be attributed to multiple factors related to the mechanisms of binder breakage and distribution. Slow-curing emulsions (CRLs) allow for longer working time before phase separation, facilitating a more uniform distribution over the surface and optimizing effective coverage of the area to be bonded (Tashman et al., 2006). This phenomenon explains why CRL emulsions reached their maximum strengths at lower rates (220-350 g/m²) compared to CRR emulsions (440-445 g/m²). Additionally, slow-breaking emulsions can be diluted with water, allowing the distribution equipment to operate at regular speeds when low rates are applied, achieving more homogeneous applications at room temperature (TRB, 2012).

In contrast, fast-curing emulsions (CRRs) break down immediately upon contact with the aggregate, which, while allowing for rapid topcoat placement, can result in a less uniform distribution when applied at low rates. This behavior requires higher dosages to ensure effective surface coverage and compensate for potential distribution deficiencies inherent in the rapid coalescence process of asphalt particles (West et al., 2005). The results obtained in the present study are consistent with previous research reporting optimal rates between 250 and 500 g/m² for fast-breaking emulsions applied without dilution.

Regarding polymer-modified emulsions, the polymer-modified CRL-1hm emulsion demonstrated consistently superior performance over all conventional alternatives evaluated, reaching a shear strength of 0.60 MPa, 50% higher than its conventional counterpart CRL-1 (0.40 MPa) and 43% higher than the best fast-curing emulsion CRR-65 (0.418 MPa). This differentiated behavior can be explained by multiple mechanisms identified in the literature. According to Wang et al. (2017), polymer-modified emulsions generate a sealing effect on the bottom layer, increasing the concentration of effective bitumen near the binding interface. This phenomenon reduces the void content in the contact area and improves the transfer of stresses between layers.

Likewise, Bae et al. (cited in Wang et al., 2017) established a significant correlation between the shear strength of the interface and the binder's $G^*/\delta$ rutting factor, a rheological parameter that is inherently superior in polymer-modified asphalts due to their greater elasticity and lower thermal susceptibility. This factor would explain not only the higher absolute resistance achieved by CRL-1hm, but also its ability to develop optimal resistances at significantly lower application rates (220 g/m²), representing a significant technical-economic advantage. The polymers also increase resistance to top-down cracking and reduce the stresses transmitted at the interface under repeated traffic loads, suggesting additional benefits for the long-term durability of the pavement structure.

Regarding the critical incidence of dust as a contaminant, the experimental results showed that the presence of dust as a surface contaminant drastically reduces the shear resistance of the interface, with decreases of up to 56% for CRR-60 and 29% for CRR-65 under the maximum contamination condition evaluated (123.46 g/m²). This finding has fundamental practical implications for the construction of pavements, where frequently the surfaces to be adhered present particulate matter as a result of vehicle traffic, environmental conditions or adjacent construction activities. The difference in dust susceptibility between CRR-60 and CRR-65 suggests that emulsions with a higher residual asphalt content develop a more robust binder film, capable of partially penetrating through the contaminant particles and establishing effective contact with the underlying surface.

It is important to note that during the laboratory tests it was observed that high dust contents (above 123 g/m²) severely hinder the application of the bond irrigation, preventing adequate contact between the binder and the briquette surface, reaching resistance values close to zero. This condition, although unlikely in the field under adequate construction practices, shows the criticality of guaranteeing clean surfaces prior to the application of bond irrigation. The Colombian specifications INVIAS-2022 establish as a requirement the cleaning of the surface before the application of irrigation, however, they do not define quantitative parameters of acceptance or verification methods, which represents an opportunity for regulatory improvement based on the findings of this research.

Regarding the implications for Colombian regulations, the comparative analysis of the results with international regulatory requirements reveals important aspects for construction practice in Colombia. The INVIAS-2022 specifications establish application rates between 200-300 g/m² of residual binder; however, the results demonstrate that fast-curing emulsions (CRRs) require optimal rates of 440-445 g/m² to maximize adhesion strength, values that significantly exceed the current normative range. This discrepancy suggests the need to revise the specified rates or, alternatively, to consider the use of modified slow-curing emulsions (CRL-1hm), which achieve higher strengths with rates within the normative range (220 g/m²).

On the other hand, the Spanish specification Order FOM/2523/2014 establishes minimum shear strength requirements of 0.6 MPa under the wearing layer and 0.4 MPa in lower layers. Only the CRL-1hm emulsion met the requirement for rolling layers, while the other emulsions evaluated (CRR-60, CRR-65, CRL-1) only achieved values that would meet the requirement for lower layers. This finding is particularly relevant considering that current Colombian regulations do not establish minimum shear resistance values for league irrigation, limiting itself to specifying application rates without performance verification. The incorporation of minimum requirements for resistance to shear stress in the INVIAS specifications, following the European model, would contribute significantly to guaranteeing the monolithic behaviour of pavement structures and to optimising their useful life.

## CONCLUSIONS

The polymer-modified slow-curing emulsion (CRL-1hm) exhibited the highest resistance to interface shear stress (0.60 MPa), outperforming conventional CRL-1 emulsion by 50%, CRR-65 by 43%, and CRR-60 by 74%. This finding demonstrates the significant contribution of polymer modification to adhesive performance, beyond the effect of residual asphalt content.

Optimal application rates differed substantially depending on the emulsion breakdown rate. Fast-curing emulsions required rates of 440-445 g/m² to achieve maximum strength, while slow-curing emulsions achieved optimal performance at considerably lower rates: 350 g/m² for CRL-1 and 220 g/m² for CRL-1hm. The latter represents a potential 50% reduction in binder consumption, while simultaneously achieving superior adhesive performance.

The optimal rates determined for fast-curing emulsions exceed the range specified in the Colombian INVIAS-2022 regulation (200-300 g/m²) by 47-123%, suggesting that current specifications could result in suboptimal adhesion when CRR emulsions are employed. In contrast, modified slow-curing emulsions reach their maximum performance within the normative range.

Dust contamination critically reduces the shear resistance of the interface, with decreases of 56% for CRR-60 and 29% for CRR-65 under contamination levels of 123.46 g/m². Emulsions with higher residual asphalt content demonstrated greater resistance to dust interference, evidencing the importance of ensuring clean surfaces prior to the application of bond irrigation.

Only the modified emulsion CRL-1hm met the Spanish requirement of 0.6 MPa for rolling layers (Order FOM/2523/2014), while the other emulsions evaluated only met the threshold of 0.4 MPa for lower layers. This highlights the need to incorporate minimum shear strength requirements into Colombian specifications.

Viscosity, determined by residual asphalt content, positively influenced shear strength. Among the fast-curing emulsions, CRR-65 (65% residual) developed a resistance 21% higher than CRR-60 (60% residual), confirming that emulsions with a higher residual binder content generate better adhesion.

The LCB shear test proved to be a practical and reproducible method to evaluate the adhesion between layers, with coefficients of variation less than 10% in most of the conditions evaluated, validating its applicability for the quality control of league irrigation in pavement construction.

Future research should evaluate the incidence of dust in slow-curing emulsions, determine thermal susceptibility to elevated temperatures representative of tropical climates, and correlate laboratory results with field performance using experimental pavement sections.

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