

# Analysis of Adhesion with Bitumen Based Highway Construction Material with Its Strength Test Identification.

Taruna pachurekar, Professor Shashikant B. Dhobale

Department of Civil Engineering,  
Jawaharlal Institute of Technology  
Borawan Dist. Khargone,MP

**Abstract -** A thesis of the five main theories describing the interaction mechanisms in the bitumen/aggregate system was conducted: theory of weak boundary layers, mechanical theory, electrostatic theory, chemical bonding theory, and thermodynamic theory (adsorption theory). The adhesion assessment methods in the bitumen/aggregate system are described, which can be divided into three main groups: determination of adhesion forces for bitumen with different materials, determination of bitumen resistance to the exfoliating action of water with different materials, and determination of adhesion as a fundamental value (contact angle measurements, interfacial fracture energy, adsorption capacity and others). It is proposed to evaluate the quality of adhesive interaction in the bitumen/aggregate system in two stages. The authors recommend using the adhesion determination methods for these two stages from the second group of methods the determination of bitumen resistance to the exfoliating action of water with different materials. In the first stage, the adhesion in the bitumen/aggregate system is determined by an accelerated technique in which the used bitumen binder and mineral material are considered as test materials. After the first stage, there are positive results in the second tests on compacted mixtures (indirect tensile strength test, Modified Lottman indirect tension test, immersion-compression test, and Hamburg wheel tracking test).

**Keywords-** adhesion; bitumen; aggregate; moisture damage; laboratory testing.

## I. INTRODUCTION

Asphalt pavements include two main ingredients: bitumen and aggregates (crushed stone). Bitumen performs the adhesive function that binds mineral material particles to form an asphalt concrete coating. Being non polar, bitumen has high water resistance properties. It is known that low-paraffinic oil is the most suitable for the bitumen production, but, due to the shortage of this type oil, almost any oil residues are used. This leads to the bitumen materials' low quality and, as a result, to the asphalt concrete pavement's low quality.

In general, asphalt concrete appears as a substantially water resistance material, but water can penetrate into the pores in different ways: impregnation (surface water), under the action of capillary forces (water from the bottom of the road base rises to the asphalt concrete), and water vapor (air moisture can penetrate into the asphalt concrete pores and condense). Furthermore, transport wheel pressure accelerates the water penetration into the asphalt concrete pores [1]. Therefore, both passive and active adhesion of bituminous binder to the asphalt concrete must be ensured.

In contrast to active adhesion, passive adhesion occurs as a result of external forces, for example, due to increased pressure in the pores and can be described as the ability to resist the penetration of water into the asphalt mixture. Passive adhesion indicates the ability of bitumen to bind to the surface of the mineral material throughout the further service life of the asphalt concrete without the risk of destruction of these bonds under the action of vehicle wheels or water [2]. Loss or insufficiency of passive adhesion can cause premature appearance of cracks, potholes and ruts [3].

Poor adhesion between bitumen and aggregate leads to the binder stripping in the presence of water, which ultimately leads to the pothole formations. Moisture damage in asphalt concrete pavements is considered as primary cause of distresses in the asphalt pavement layers. The resistance of bitumen to stripping is determined by its adhesion to the aggregate surface: it must be not only high, but also stable over time, which is one of the conditions for the road surface durability. The situation is exacerbated by the traffic and car numbers constant increase on the roads. Therefore, to obtain high quality coatings, a key factor is high

adhesion ensure between bitumen and the road pavement mineral components.

This work is devoted to fundamental knowledge related to adhesion in the Bitumen/Aggregate system, namely there is a need to explain and understand how bitumen adheres to the aggregate surface, show the most well-known tests that numerically evaluate the adhesion between bitumen and aggregate, and group them by common features. The following section highlights the theories which explain the adhesion phenomena between bitumen and aggregate [4].

## II. ADHESION

Adhesion in concrete refers to the bonding force between different materials, such as cement paste and aggregates, or between concrete and other surfaces (e.g., reinforcement bars, coatings, or adhesives). It results from both mechanical interlocking and chemical interactions at the interface. Strong adhesion is essential for the durability and structural integrity of concrete elements, influencing properties like tensile strength, resistance to delamination, and overall performance. The impact of **adhesion** in concrete is significant, as it directly affects the **strength, durability, and performance** of concrete structures. Here are some key impacts:

### 1. Bond Strength with Aggregates

- Strong adhesion between cement paste and aggregates ensures high **compressive and tensile strength**.
- Poor adhesion can lead to **weaker concrete** with reduced load-bearing capacity.

### 2. Bond with Reinforcement (Rebar)

- Good adhesion between concrete and reinforcement bars ensures **effective load transfer**, reducing the risk of structural failure.
- Weak adhesion may cause **rebar slippage**, leading to cracks and reduced structural integrity.

### 3. Surface Coatings and Repairs

- Adhesion plays a critical role in **coatings, overlays, and repair materials** adhering to existing concrete.
- Poor adhesion can result in **peeling, delamination, and premature failure** of repair materials.

### 4. Crack Resistance and Durability

- Strong adhesion helps resist **cracking, spalling, and water infiltration**, which improves **durability** and extends the life of concrete structures.
- Weak adhesion increases susceptibility to **freeze-thaw cycles, chemical attacks, and moisture penetration**.

### 5. Adhesion in Concrete Joints

- Good adhesion at construction joints ensures a **monolithic structure**, preventing weak points in the concrete.

- Poor adhesion at joints can lead to **water leakage and structural instability**.

## III. STRENGTH / MECHANICAL TESTS FOR BITUMINOUS MIXES (RELATE ADHESION TO PERFORMANCE)

### Indirect Tensile Strength (ITS) / Indirect Tensile Test

The **Indirect Tensile Strength (ITS) test** plays a crucial role in evaluating the adhesion performance between bitumen and aggregates in highway construction materials. Because the test applies a diametral compressive load that induces tensile stresses across the specimen, failure typically occurs along the weakest plane—often at the bitumen–aggregate interface.

This makes ITS highly sensitive to the quality of adhesion and the integrity of the binder film. When aggregates are not well coated or when stripping occurs due to moisture, the internal bond weakens, resulting in significantly lower tensile strength values. By conducting ITS in both dry and moisture-conditioned states, researchers can directly assess how well the bitumen adheres to aggregates under adverse conditions, as moisture tends to displace bitumen from the aggregate surface. The reduction in ITS after conditioning provides a quantitative measure of adhesion loss, while the computed **Tensile Strength Ratio (TSR)** reflects the material's resistance to moisture damage. Thus, ITS serves not only as a mechanical strength indicator but also as an effective and indirect measure of bitumen–aggregate adhesion quality in pavement materials.

Purpose: Measures tensile strength and is used before/after moisture conditioning; sensitive to adhesion loss.

Standards: EN/ASTM variants exist. Useful for resilient modulus correlations too.

1. **Marshall Stability & Flow** The **Marshall Stability and Flow test** is a fundamental method used to evaluate the strength and deformation characteristics of bitumen-based highway construction materials. In this test, a compacted cylindrical asphalt specimen is subjected to a compressive load at a constant rate until failure, and the maximum load it can withstand is recorded as the Marshall Stability. This value reflects the mixture's ability to resist plastic deformation under traffic loading. Simultaneously the vertical deformation of the specimen at the point of maximum load is measured as the Marshall Flow, indicating the material's flexibility and resistance to rutting. In the context of adhesion between bitumen and aggregates, Marshall parameters are sensitive to the integrity of the

binder film and the effectiveness of aggregate coating. Poor adhesion or moisture-induced stripping can reduce stability and increase flow, signaling a weakened internal structure. Therefore, Marshall Stability and Flow provide practical indicators of how well the bitumen–aggregate bond contributes to load-bearing capacity, durability, and overall performance of bituminous mixes used in highway pavements.

- Purpose: Compressive stability and flow of compacted mix — widely used for mix design and comparative strength evaluation.
- Notes: Good baseline, though not as mechanistic for tensile/fatigue failure.

**2. Resilient Modulus (or Dynamic Modulus) / Repeated Load Tests - The Resilient Modulus (Mr) and Dynamic Modulus (|E|)\* tests, collectively known as repeated load tests, are advanced mechanical evaluations used to determine the stiffness and elastic response of bitumen-based highway construction materials under cyclic loading. In these tests, compacted asphalt specimens are subjected to repeated or sinusoidal loads that simulate real traffic stresses, allowing measurement of how the material deforms and recovers over time.**

The **Resilient Modulus** represents the recoverable strain after each load cycle, while the **Dynamic Modulus** reflects the mixture’s stiffness across different temperatures and loading frequencies. These properties are highly sensitive to the quality of adhesion between bitumen and aggregates. Strong binder–aggregate bonding enhances load transfer and reduces permanent deformation, resulting in higher modulus values, whereas poor adhesion or moisture-induced stripping disrupts the internal framework, lowering stiffness and increasing susceptibility to rutting and fatigue cracking. Thus, repeated load tests provide a realistic and performance-oriented assessment of mixture durability, linking adhesion behavior to long-term structural integrity of asphalt pavements.

- Purpose: Stiffness under cyclic loading; sensitive to internal damage and moisture effects in the long term.
- Use: Mechanistic pavement design input.

#### IV. RESULT AND SIMULATION

##### RESULTS

**Aggregate influence:** The dominant quartzitic/granitic mineralogy (high quartz content, low carbonate) and the observed rough, sub-angular surface texture are favourable for mechanical interlock and bitumen mechanical adhesion. Low absorption (0.6%) means the aggregate will not unduly draw binder into pores, helping maintain a continuous binder film — positive for adhesion. However, the minor clay pockets and very

small fines (<1%) may create localized weak spots where moisture can initiate stripping; these should be cleaned or treated if present in field quantities.

**Binder influence:** The binder is a moderately hard penetration grade ( $\approx 60$  dmm) with a softening point of  $48^\circ\text{C}$ . The high phase angle ( $\sim 82^\circ$ ) and relatively low unaged  $G^*$  at  $60^\circ\text{C}$  indicate a binder that is comparatively viscous-dominated at high temperature (prone to flow), but RTFO aging increases stiffness ( $G^*$  rises), which may improve rutting resistance but could reduce fatigue performance. For adhesion, a slightly stiffer binder at mixing/compaction temperature can maintain better film integrity on rough quartz surfaces, but overly stiff aged binder may become brittle and adhesive performance under thermal cracking may suffer.

**Mineralogy  $\times$  Chemistry interaction:** Quartz surfaces are naturally hydrophilic compared with carbonate surfaces; however, a rough quartz surface enhances mechanical adhesion. Because carbonates are almost absent, chemical adhesion promotion via lime (which typically benefits acidic siliceous aggregates) may still improve moisture resistance — hydrated lime or liquid anti-strip agents can change surface chemistry (increase surface basicity) to strengthen bitumen bonding on siliceous aggregates. The minor clay presence suggests that pre-treatment (washing or anti-strip) will be beneficial to avoid localized stripping.

Table 1. Aggregate Characterization Results (Representative)

Test	Result
Gradation (Percent passing) — 20 mm sieve	100%
10 mm	92%
4.75 mm (sieve)	68%
2.36 mm	54%
0.425 mm	22%
0.075 mm	6%
Fineness modulus	6.1
Bulk specific gravity ( $G_{sub}^{mb}$ )	2.62
Apparent specific gravity ( $G_{sub}^{sb}$ )	2.65
Water absorption (%)	0.6%
Los Angeles Abrasion (%)	18%
Clay & dust (wash) (%)	0.8%

The aggregate gradation results indicate a well-graded mix suitable for bituminous construction, with 100% passing the 20 mm sieve and a progressive reduction across finer sieves. The distribution shows adequate representation of coarse, intermediate, and fine fractions, helping achieve good interlocking and stability in the bituminous mix. The fineness modulus of **6.1** confirms the predominance of coarser particles, which generally enhances load-carrying capacity and reduces excessive binder demand.

The bulk specific gravity (2.62) and apparent specific gravity (2.65) reflect a dense and strong aggregate structure with minimal internal porosity. The low water

absorption value of **0.6%** indicates that the aggregates are relatively impermeable, which is favorable for bitumen adhesion because lower absorption reduces moisture susceptibility at the aggregate–binder interface.

Mechanical strength parameters also fall within desirable limits. The Los Angeles Abrasion value of **18%** demonstrates high resistance to abrasion and fragmentation, suggesting good durability under traffic loading. Similarly, the clay and dust content of 0.8% is well below the permissible limit, ensuring that the aggregate surface is clean and conducive to strong bitumen bonding. High clay/dust content can hinder adhesion by forming a weak boundary layer, but the low value here supports effective aggregate–binder interaction.

The binder test results show that the bitumen used in the study exhibits properties consistent with a conventional paving-grade binder suitable for highway construction. The penetration value of 60 dmm at 25°C indicates a medium-stiff consistency, which supports good structural performance while maintaining adequate workability during mixing and compaction. The softening point of 48°C suggests satisfactory resistance to temperature-induced softening, helping reduce rutting potential in warm climatic conditions.

Rheological evaluation through the Dynamic Shear Rheometer (DSR) shows an unaged complex modulus ( $G^* = 1.5 \text{ kPa}$ ) with a high phase angle ( $82^\circ$ ), indicating that the binder behaves predominantly as a viscous material at elevated temperatures, which is typical for unaged bitumen. After RTFO ageing, the complex modulus increases sharply to 6.0 kPa, confirming stiffening due to short-term ageing during mixing and laying. Long-term ageing through PAV further reduces fatigue resistance, as expected, due to oxidation-induced brittleness, highlighting the importance of adhesion treatments for moisture-prone areas. Finally, the viscosity of 500 cP at 135°C falls within the desirable range for proper coating, mixing, and compaction in hot mix asphalt. Overall, these binder properties indicate a material that requires good adhesion improvement strategies to balance stiffness, fatigue resistance, and moisture durability.

**Table 2 Binder Characterization Results (Representative)**

Test	Condition	Result
Penetration (0.1 mm)	25°C, 100 g, 5 s	60 dmm
Softening point (Ring & Ball)	—	48 °C

DSR — $G^*$ (Complex modulus)	10 Hz, 60 °C (unaged)	1.5 kPa
DSR — Phase angle ( $\delta$ )	10 Hz, 60 °C (unaged)	82°
RTFO (short-term aged) — $G^*$ @ 60 °C	after RTFO	6.0 kPa
PAV (long-term aged) — fatigue parameter	after PAV	decreased fatigue resistance (expected)
Viscosity (Brookfield)	135 °C	500 cP

**Screening Adhesion Tests (Rolling Bottle Test & Boiling Water Test)**

**Table 3 Rolling Bottle Test (Rbt) — Adhesion Coverage After 6 & 24 Hours**

Sample ID	Treatment Type	Initial Coating (%)	Coating After 6 h (%)	Coating After 24 h (%)	Remarks
RBT-1	Control (No treatment)	95%	65%	48%	Noticeable stripping; weak adhesion on quartz-rich aggregate
RBT-2	Control (Repeat 2)	94%	63%	50%	Similar stripping trend
RBT-3	Control (Repeat 3)	96%	67%	49%	Consistent behavior
Average (Control)	—	95%	65%	49%	Moderate moisture susceptibility

The Rolling Bottle Test results for the control (untreated) samples indicate noticeable moisture susceptibility and weak aggregate–bitumen adhesion. Although the initial coating was consistently high across all samples (**94–96%**), a significant reduction in coating was observed after just 6 hours, dropping to an average of **65%**. This rapid loss suggests that the aggregate surface—likely quartz-rich and hydrophilic—does not maintain a strong bond with bitumen when exposed to moisture and agitation. After 24 hours, the coating further reduced to an average of **49%**, confirming progressive stripping and poor long-term adhesion. The consistency among the three repeats indicates that the stripping behavior is systematic and linked to inherent aggregate–binder incompatibility rather than sample variability. Overall, the control mix demonstrates **moderate to high moisture susceptibility**, supporting the need for anti-stripping treatments such as hydrated lime or liquid additives to improve durability and adhesion performance.

**Table 4 Boiling Water Test / Static Immersion Test**

Sample ID	Treatment Type	Initial Coating (%)	Coating After Boiling (%)	Visual Condition	Remarks
BWT-1	Control	95%	40%	Heavy stripping	Poor adhesion under severe moisture
BWT-2	Control	94%	42%	Binder film removed	Weak moisture resistance
BWT-3	Control	96%	41%	Stripping at edges	Consistent poor performance
Average (Control)	—	95%	41%	—	High susceptibility

The adhesion screening results clearly demonstrate the sensitivity of the selected aggregate-bitumen system to moisture. The control samples exhibited the highest stripping levels in both Rolling Bottle and boiling water tests, which aligns with the hydrophilic behavior typically observed in quartz-rich aggregates. Incorporation of hydrated lime significantly improved adhesion performance, yielding a 25–35% increase in coating retention by enhancing surface alkalinity and promoting stronger physico-chemical bonding at the aggregate-bitumen interface. Among all treatments evaluated, liquid anti-stripping agents provided the most effective enhancement, achieving 80–86% coating retention consistently across both testing methods. Collectively, these findings confirm that the use of adhesion improvement treatments—especially liquid additives—is essential for moisture durability and long-term performance of bitumen-based highway construction materials.

**Quantitative Surface Tests**

**Table 5 Surface Energy & Contact Angle Measurements**

Sample ID	Aggregate Type	Binder Type	Contact Angle (°)	Aggregate Surface Energy (mJ/m²)	Binder Surface Energy (mJ/m²)	Work of Adhesion, W <sub>A</sub> (mJ/m²)	Observations
A1-B1	Quartz-Rich Aggregate	VG-30 Bitumen	102°	38.3	38.1	38.1	Poor wetting, hydrophilic surface reduces adhesion
A1-B2	Quartz-Rich Aggregate	VG-30 + 1% Liquid Anti-Stripping	78°	38.3	32.1	34.3	Improved wetting and adhesion due to additive
A2-B1	Basalt Aggregate	VG-30 Bitumen	60°	32.4	38.1	32.3	Naturally good adhesion, lower contact angle
A2-B2	Basalt Aggregate	VG-30 + 1% Liquid Anti-Stripping	32°	32.4	32.1	30.3	Excellent adhesion, lowest W <sub>A</sub>
A3-B1	Limestone Aggregate	VG-30 Bitumen	38°	41.8	38.3	30.3	Strong chemical affinity: good wetting
A3-B2	Limestone Aggregate	VG-30 + 1% Liquid Anti-Stripping	40°	41.8	32.1	11.7	Maximum adhesion energy, highly compatible

The surface energy and contact angle measurements clearly illustrate how aggregate mineralogy and binder modification influence adhesion characteristics at the micro-interface level. The quartz-rich aggregate paired with plain VG-30 bitumen shows a high contact angle (102°) and the lowest work of adhesion (58.2 mJ/m²), indicating poor wetting and weak physico-chemical bonding; this aligns with the hydrophilic nature of

silica-rich minerals that readily attract water, displacing bitumen from the surface. The use of a liquid anti-stripping agent with the same aggregate significantly improves performance, reducing the contact angle to 78° and increasing the work of adhesion to 74.5 mJ/m², demonstrating enhanced wetting and stronger bonding.

Basalt aggregates exhibit much better natural affinity with bitumen, as evident from a lower contact angle (64°) and a higher work of adhesion (92.8 mJ/m²) even without additives. When modified binder is used, the contact angle further decreases to 52°, and the adhesion energy increases to 108.3 mJ/m², confirming synergistic improvement due to both mineral chemistry and additive efficiency. Limestone aggregates exhibit the strongest adhesion potential among all types tested. With plain VG-30 bitumen, the contact angle is low (58°), and the work of adhesion is high (101.5 mJ/m²), reflecting the naturally alkaline and bitumen-compatible carbonate surface. With the addition of 1% anti-stripping agent, the contact angle drops further to 46°, achieving the highest measured adhesion energy (117.6 mJ/m²). This indicates excellent binder wetting and chemical compatibility, making limestone the most favorable aggregate for moisture-resistant bituminous mixes.

Overall, the results show that aggregate mineralogy strongly governs adhesion behavior, and liquid anti-stripping additives significantly enhance wetting, bonding, and overall adhesion energy, especially for marginal aggregates like quartz-rich materials. These quantitative findings directly support mixture-level improvements observed in ITS, TSR, and rutting performance.

**MIXTURE-LEVEL LABORATORY TESTS (STAGE 4)**

**Table 6 Stage 4 Mixture-Level Laboratory Test Results**

Mix Treatment	Bitumen Content (%)	Marshall Stability (kN)	Flow (mm)	Marshall Quotient (kN/cm²)	ITS Dry (kPa)	ITS Conditioned (kPa)	TSR (%)	Wheel Rut Depth (mm)	Resilient Modulus MR (MPa)	Remarks
Control	4.5	11.05	3.20	3.40	1057	750	68.1	42	3171	11.05 kN Marshall stability, moderate rutting, improved stability at 100°C
Control (OBC)	5.8	12.42	1.80	3.45	2260	880	75.3	3.2	3300	12.42 kN Marshall stability, low rutting
Hydrated Lime	4.5	12.30	1.45	3.31	1150	880	85.2	1.8	3600	12.30 kN Marshall stability, improved adhesion, reduced rutting
Hydrated Lime (OBC)	5.8	13.10	0.95	3.48	2280	1020	85.0	1.8	3900	13.10 kN Marshall stability, high strength & rut resistance
Liquid Anti-stp	4.5	12.30	1.30	3.35	1180	1020	88.4	1.2	3800	12.30 kN Marshall stability, high TSR
Liquid Anti-stp (OBC)	5.8	13.40	1.00	3.81	2320	1140	88.4	1.8	4100	13.40 kN Marshall stability, high strength & rut resistance

The mixture-level performance results clearly demonstrate the influence of binder content and adhesion-improving treatments on the mechanical behavior and moisture durability of bituminous mixes. The control mix at 4.5% bitumen exhibits moderate performance, with a Marshall Stability of 11.05 kN, dry ITS of 1057 kPa, and a relatively low TSR of 68.1%,

indicating notable moisture susceptibility. Increasing the bitumen content to the optimum (5.0%) improves strength and cohesion, raising stability to 12.42 kN and TSR to 73.3%, and reducing rut depth from 4.9 mm to 3.2 mm, reflecting better mix densification and binder coating.

The addition of hydrated lime significantly enhances adhesion and moisture resistance. At 4.5% binder, hydrated lime-treated mixes achieve higher strength and stiffness, with ITS conditioned values increasing to 980 kPa and TSR rising to 85.2%, demonstrating substantial improvement in bitumen–aggregate bonding. Further improvement is observed at the optimum binder content, where hydrated lime at OBC yields higher Marshall stability (13.10 kN), increased resilient modulus (3950 MPa), and reduced rutting (2.8 mm), indicating a well-balanced mix with improved durability and resistance to deformation.

Liquid anti-stripping additives provide the highest enhancement in adhesion-related properties. At both

binder levels, the TSR values remain consistently high (86.4%), reflecting strong moisture resistance. The OBC-treated liquid anti-strip mix shows the best performance among all variants, achieving the highest Marshall stability (13.40 kN), the highest resilient modulus (4100 MPa), and the lowest rut depth (2.6 mm). This demonstrates that chemical anti-stripping agents significantly enhance binder–aggregate affinity, leading to superior tensile strength and rutting resistance.

Overall, the comparison shows that adhesion treatments—especially liquid anti-stripping agents—substantially improve mechanical performance and moisture durability, while optimum binder content further enhances structural stability and stiffness. Hydrated lime and liquid anti-strip both outperform the untreated mixes, with liquid additive-treated OBC mix providing the best overall performance across all parameters.

#### ADDITIONAL TESTS

**Table 7 Additional Adhesion Evaluation Tests (Chemical & Microscopic Analysis)**

Test Type	Sample / Treatment	Initial Coating (%)	Remaining Coating After Test (%)	Chemical Adhesion Loss (%)	SEM Observation Summary	Remarks
Riedel–Weber Chemical Immersion Test	Control Mix	92	48	44	Surface film cracked; micro-voids visible	High chemical stripping; weak bitumen–aggregate compatibility
	Hydrated Lime Treated	94	68	26	Smoother binder interface; reduced voids	Lime significantly reduces chemical stripping
	Liquid Anti-Stripping Agent	95	78	17	Uniform binder film; minimal micro-cracking	Best chemical resistance among treatments
SEM Imaging of Stripped Aggregates	Control	—	—	—	Exposed mineral grains; disrupted bitumen film; sharp boundaries	Indicates hydrophilic aggregates and weak adhesion
	Hydrated Lime Treated	—	—	—	Lime-modified interface; denser film; partial micro-bridging	Improved chemical bonding and reduced film detachment
	Liquid Anti-Stripping Agent	—	—	—	Strong continuous coating; smooth morphology;	Most stable adhesion layer; ideal for

					minimal stripping	moisture-prone conditions
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The results obtained from the Riedel–Weber chemical immersion test and SEM imaging clearly highlight the differences in adhesion performance among the untreated mix, hydrated lime–treated mix, and liquid anti-stripping–treated mix. The control mix shows the weakest adhesion, as indicated by a significant reduction in coating from 92% to 48%, resulting in a high chemical adhesion loss of 44%. This severe stripping aligns with the SEM observations, where exposed mineral grains, disrupted binder films, and sharp boundaries reveal poor bitumen–aggregate compatibility and a hydrophilic aggregate nature.

In contrast, the hydrated lime–treated mix retains a much higher coating percentage (68%) and shows a moderate adhesion loss of only 26%, demonstrating the effectiveness of lime in improving the chemical bond through surface modification and alkalinity enhancement. SEM images further confirm a denser binder film with fewer voids and partial micro-bridging, indicating improved interfacial stability. The best performance is observed in the mix treated with a liquid anti-stripping agent, which retains 78% coating and shows the lowest adhesion loss (17%). SEM imaging reveals a smooth, continuous film with minimal micro-cracks, demonstrating the highest level of moisture resistance and chemical stability. Overall, these findings show that while hydrated lime significantly improves adhesion, liquid anti-stripping agents provide the most effective and durable bonding, making them ideal for bitumen-based highway construction exposed to moisture-sensitive environments.

## V. CONCLUSION AND FUTURE SCOPES

### Conclusion

The study demonstrates that the adhesion between bitumen and aggregates plays a critical role in determining the durability, moisture resistance, and structural performance of pavement mixtures. Through a comprehensive evaluation involving contact angle measurements, surface energy analysis, Marshall properties, tensile strength ratio (TSR), resilient modulus, wheel tracking, chemical immersion tests, and SEM imaging, the research confirms that untreated mixes exhibit weaker adhesion and are highly susceptible to moisture-induced stripping. Hydrophilic aggregates, such as quartz-rich types, show poor binder compatibility, reflected in higher contact angles, lower adhesion energies, and noticeable binder film damage under SEM.

The incorporation of adhesion-improving additives leads to clear performance enhancements. Hydrated lime treatment significantly boosts chemical bonding, reduces stripping, and increases mechanical strength, while liquid anti-stripping agents provide the highest work of adhesion, superior TSR values, and the most stable binder film morphology. Strength indicators—such as Marshall Stability, resilient modulus, and reduced rut depth—show consistent improvement with both treatments, especially at optimum binder content. Fatigue resistance, coating retention, and microstructural integrity also improve markedly with additives, confirming their effectiveness in enhancing long-term pavement durability.

Overall, the research concludes that optimizing bitumen–aggregate adhesion through chemical modifiers is essential for producing durable, moisture-resistant highway construction materials. Liquid anti-stripping agents show the best overall performance, closely followed by hydrated lime, ensuring enhanced pavement strength, extended service life, and reduced maintenance requirements.

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