

Investigating the Interfacial Adhesion of Steel Slag and Long-Term Aged Asphalt Binder and Its Impact on Asphalt Mixture Performance

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Research Article

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Posted Date: July 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10242733/v1>

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Additional Declarations: No competing interests reported.

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Abstract

The depletion of natural aggregates and the environmental challenges associated with industrial waste disposal have increased interest in sustainable alternatives for asphalt pavements. This study investigates the feasibility of using BOF steel slag as a partial replacement for sandstone aggregate in asphalt mixtures to improve sustainability without compromising pavement performance. Steel slag mixtures incorporating VG30, CRMB, and PMB binders were evaluated under both unaged and long-term aged conditions. A multiscale performance assessment was conducted using Surface Free Energy (SFE) analysis for adhesive characterization, Atomic Force Microscopy (AFM) for nanoscale adhesion and surface roughness evaluation through JKR and DMT models, Binder Bond Strength (BBS) testing for interfacial bonding, Hamburg Wheel Tracking for rutting resistance, IDEAL-CT for cracking resistance, resilient modulus testing for stiffness, and Tensile Strength Ratio (TSR) testing for moisture susceptibility. The results showed that steel slag exhibited higher adhesion energy than sandstone aggregates. Among the binders, PMB consistently demonstrated superior bonding and mechanical performance. Notably, the unaged PMB–steel slag mixture exhibited greater rutting, moisture, and cracking resistance, and a higher resilient modulus than other mixtures. These findings demonstrate that steel slag is a viable and sustainable aggregate alternative capable of delivering high-performance asphalt pavements.

Keywords: Steel slag, aging, asphalt mixture, Surface free energy, rutting, Craking

Introduction

In recent decades, India has made significant progress in highway infrastructure development. According to the latest statistics, by the end of 2023 the total length of highways in the country had reached approximately 63.45 lakh kilometers, including about 146,145 kilometers of expressways (MoRTH, 2024). India is currently undertaking large-scale highway development projects, including the construction of new highways and the expansion of existing road networks. The nation's pavement construction sector is projected to grow at an annual rate of nearly 8% over the next decade. Sustaining this level of growth requires a substantial supply of construction materials, particularly mineral aggregates, which constitute approximately 80% of the volume and about 95% of the weight of asphalt mixtures (Biswas & Sohel, 2025). While this rapid development has significantly contributed to economic growth and social progress, it has also created challenges related to resource utilization and environmental sustainability. Several regions of the country are currently facing a severe shortage of natural aggregates due to restrictions on open-cast mining imposed to mitigate environmental concerns such as deforestation and dust pollution. As a result, researchers are increasingly exploring alternative materials that can partially or fully replace natural aggregates in construction applications. One widely adopted strategy to enhance pavement sustainability is to reduce the consumption of natural stone aggregates by substituting them with alternative materials. Common alternative aggregates used in asphalt mixtures include recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), and steel slag. Steel slag is a solid waste generated during the steelmaking process, typically accounting for about 15% of total steel production (Indian Bureau of Mines, 2018). In India, approximately 12 million tonnes of steel slag are generated annually. It is projected that by 2030, steel slag production may increase to around 15–20 million tonnes per year (Indian Bureau of Mines, 2023). Steel slag is often dumped in areas surrounding steel plants, which can lead to environmental pollution due to the presence of toxic elements in the slag (Ragipani et al., 2020). Moreover, the utilization rate of steel slag in India remains significantly lower compared to that in other developing countries.

Cheng et al. (Cheng et al., 2019) investigated the cracking resistance of asphalt mixes with steel slag. They found that the inclusion of steel slag in place of conventional aggregates significantly improve the cracking resistance of asphalt mixes. Wang et al. (W. Wang et al., 2023) concluded that steel slag displayed better adhesion properties and higher moisture damage resistance than conventional diabase aggregate. Based on the experimental results reported by Panos and Andreas Loizos (Georgiou & Loizos, 2021), warm steel slag asphalt mixtures demonstrated equivalent or superior performance compared to hot mix asphalt (HMA) in terms of moisture susceptibility, stiffness, rutting resistance, fracture resistance, and surface macrotexture. Nugraha et al (Nugraha et al., 2021) concluded that the permanent deformation resistance of asphalt mixes improved with the inclusion of steel slag. Wang et al. (Z. Wang et al., 2025) concluded that the incorporation of steel slag along with carbon fiber can enhance the self-healing properties of asphalt mixes. Li et al. (Li et al., 2025) demonstrated that incorporating steel slag can significantly improve the heat transfer efficiency of asphalt mixtures; however, it may also lead to stronger vertical temperature gradients and localized hotspots, presenting both advantages and challenges for functional pavement design. Compared with the conventional asphalt mixture, the steel slag mixture exhibited a 22.2% increase in splitting tensile strength and a 28.1% increase in the cracking index, indicating improved resistance to cracking (Lei et al., 2025). Sun et al. (Sun et al., 2025) recommended to use 100% steel slag mixture for summer construction to accelerate traffic opening. Lan et al. (Lan et al., 2025) concluded that field tests and an economic analysis of asphalt mixtures containing 100% 9.5–16 mm steel slag coarse aggregate showed

satisfactory road performance. The study also reported a cost reduction of approximately 7.9%, indicating strong potential for practical application of steel slag in asphalt pavements. Mehdinazar et al. (Mehdinazar et al., 2025) investigated the influence of runoff water with varying pH on the fatigue performance of hot-mix asphalt. Their findings revealed that both acidic and alkaline environments significantly reduced the adhesion between asphalt binder and aggregates, thereby increasing the potential for fatigue cracking. However, their study demonstrated that the incorporation of zeolite additives improved binder–aggregate compatibility by modifying the acidic and basic components of surface free energy (SFE) and enhancing tensile strength, particularly in mixtures containing siliceous aggregates. Despite these positive outcomes, high porosity and expansion of steel slag caused by free lime have raised concerns about its consistency and reliability in asphalt mixtures (Pasetto et al., 2023). These characteristics often lead to weak asphalt binder and aggregate bonding, resulting in moisture-induced damage such as stripping and debonding, which can reduce pavement service life by up to 50%. Studies have reported that moisture exposure can decrease asphalt adhesion by more than 30%, particularly when hydration reactions involving calcium silicate phases are activated at elevated temperatures (Suryawanshi et al., 2025). Furthermore, the high porosity of steel slag facilitates greater moisture ingress, accelerating pavement deterioration under freeze–thaw cycles and repeated traffic loading. To address these challenges, researchers have investigated the use of anti-stripping agents, chemical treatments, and modifications in mix design.

Although previous studies support the use of BOF steel slag in asphalt mixtures, a significant research gap still exists under Indian conditions, particularly in evaluating the compatibility between BOF steel slag and long-term aged asphalt binders through a multi-scale framework. To date, no studies have evaluated the adhesion characteristics between BOF steel slag and long-term aged modified binders. Furthermore, no efforts have been made to systematically correlate micro-scale bonding mechanisms evaluated using surface free energy (SFE), atomic force microscopy (AFM), and binder bond strength (BBS) with macro-scale performance parameters, such as rutting resistance, resilient modulus, and fracture resistance, of asphalt mixtures. Along with that, the influence of BOF steel slag and binder type on these interactions remains largely unexplored. This study aims to address these critical knowledge gaps by comprehensively investigating the bonding behavior between steel slag and asphalt binders under controlled conditions. The research integrates both micro- and macro-scale testing to evaluate the adhesion between binders and sandstone/steel slag aggregates, thereby providing practical insights for the sustainable and high-performance utilization of steel slag in Indian asphalt pavements.

The objectives of this study are:

- To investigate the bonding behavior between BOF steel slag and various types of asphalt binders.
- To evaluate the impact of long-term aging of asphalt binder on adhesion properties
- To determine the interfacial bond strength and evaluate the potential bonding failure mechanisms between steel slag and asphalt binders using the Binder Bond Strength (BBS) test under pull-out tensile loading.
- To determine the impact of adhesion properties on the rutting resistance, resilient modulus and cracking resistance of asphalt mixtures.

The flowchart of this research work is displayed in Fig. 1.

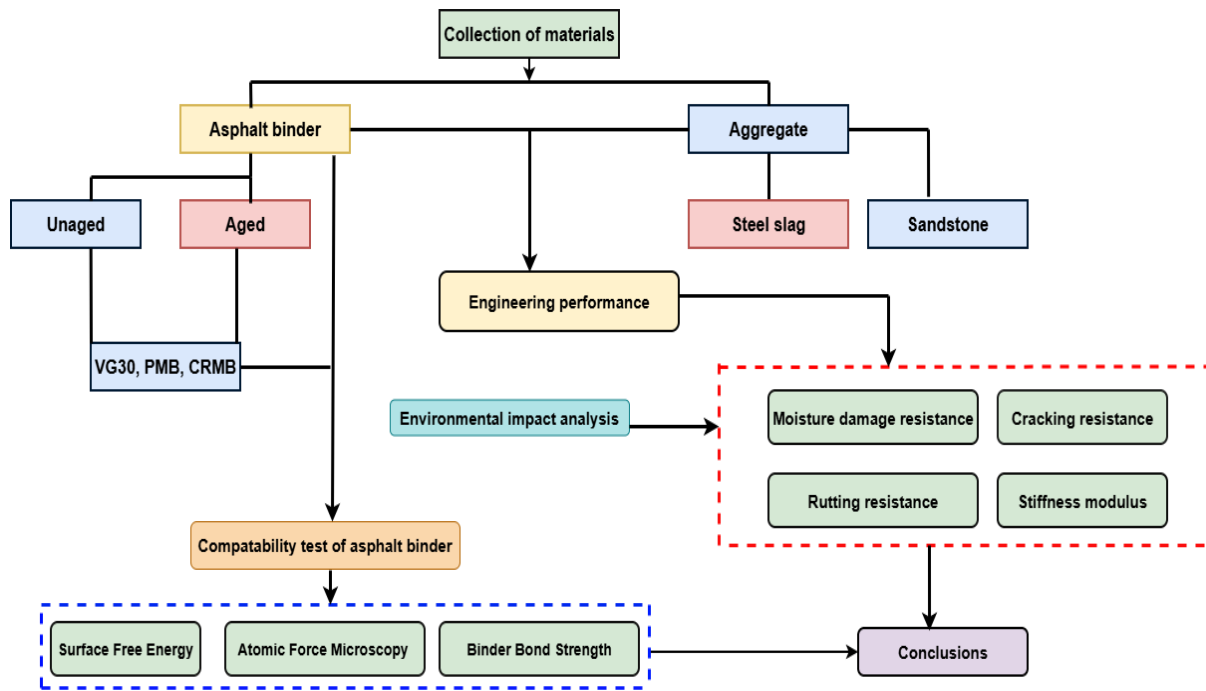


Fig. 1. Flowchart of this research

Materials

Asphalt binders

In this study VG30 is used as neat asphalt binder. Along with the base binder, two different types of modified binders were used in this study: CRMB (crumb rubber modified binder) and PMB (polymer modified binder). These binders are widely used in high-temperature and heavy-traffic regions due to their improved resistance to rutting and fatigue. Both binders were procured from Tiki Tar Industries, Gujarat. Prior to mix preparation, the binders were subjected to Rolling Thin Film Oven (RTFO) aging to simulate the short-term aging that occurs during asphalt production and paving. Subsequently, the RTFO-aged binders were further aged in a Pressure Aging Vessel (PAV) to prepare long-term aged binders (VG30L, CRMBL, and PMBL). The basic properties of asphalt binders is displayed in Table 1.

Table 1. Physical properties of asphalt binders

Properties	VG30		CRMB			PMB		
	Results	Limits	Results	Limits	(IS	Results	Limits	(IS
		(IS:73, 2013)		15462			15462	(2004),
				(2004), n.d.)			n.d.)	
Penetration at 25 °C	49	>45	41.4	<50		44.3	30-50	
Softening point (°C)	52	47	67.6	>60		71.3	>60	
Flash point	254	>220	274	>220		282	>220	
Viscosity at 150° C	-	-	5.13	3-9		6.85	3-9	
Viscosity at 60° C, poises	2185	2400-3600	-	-		-	-	
Separation difference (°C)	-	-	2.66	<4		1.32	<3	

Aggregates

In this study, BOF steel slag and conventional sandstone aggregate were used to fabricate the asphalt mixes. The BOF steel slag used in this study was untreated; however, its expansion remained within the acceptable limit. The chemical compositions of various aggregates were evaluated through XRD analysis and displayed in Fig.. The surface morphology was evaluated through SEM analysis and displayed in Fig. it was found that the surface texture of natural sandstone aggregates was even while the surface texture of steel slag was rough. The major chemical compounds found in natural aggregates is Quartz and Berlinite. The major chemical compounds found in steel slag are Larnite, Maghemite and Hematite. The physical properties of aggregates is displayed in Table 2.

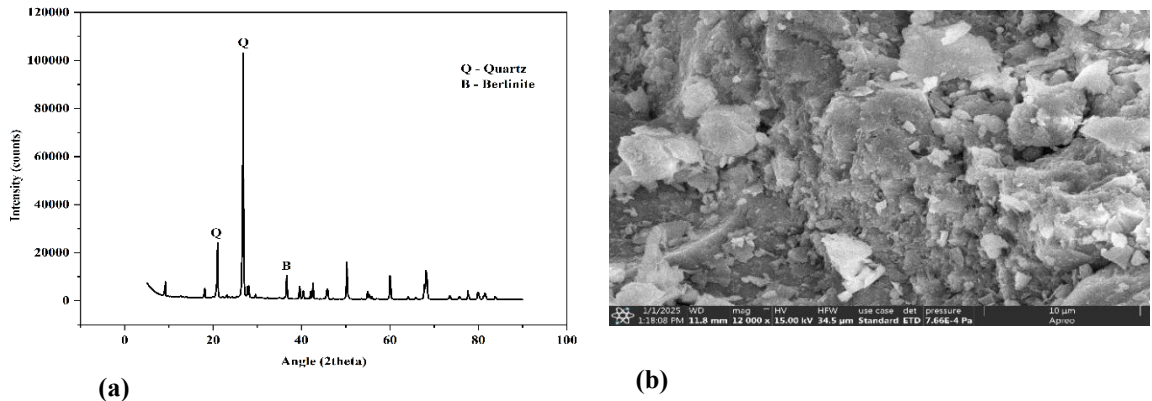


Fig. 2. SEM (a) and XRD (b) images of sandstone

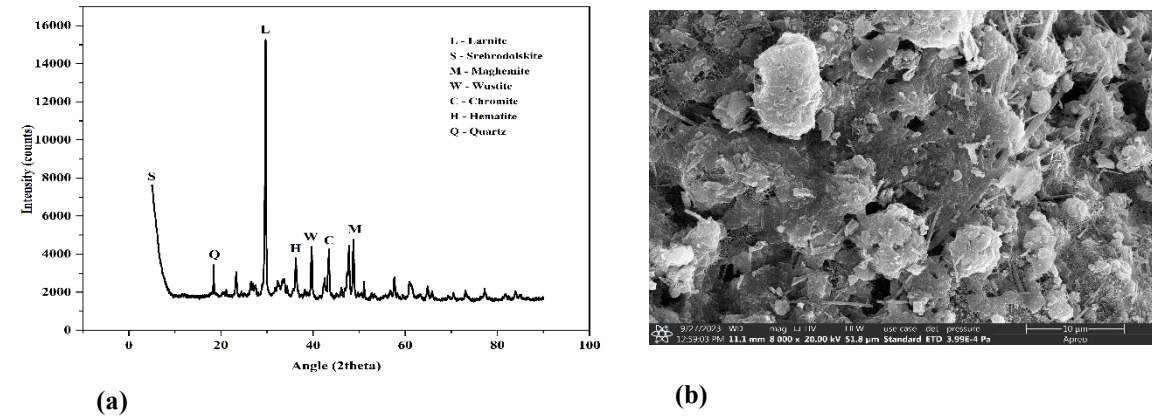


Fig. 3. SEM (a) and XRD (b) images of steel slag

Table 2. Physical properties of aggregates

Test parameters	Natural aggregate	Steel slag	Specific limit (MORTH 5th REVISION.Pdf, 2013)
Specific gravity (coarse)	2.68	3.12	-
Water absorption (coarse)	0.54	1.46	<2
Los Angeles abrasion (%)	18.83	13.14	<30
Aggregate impact (%)	19.62	12.46	<24
Aggregate crushing (%)	20.10	14.78	-
Specific gravity (fine)	2.74	2.91	
Water absorption (fine)	<2	<2	
Volume expansion (%)	-	0.68	<1

Methodology

Preparation of long term aged binders

For long-term aging of the asphalt binders, the Pressure Aging Vessel (PAV) method was employed. In this procedure, a 3.2 mm thick film of short-term aged binder was placed in the PAV and conditioned under controlled conditions for 20 h at a pressure of 2.1 MPa. The conditioning temperature in the PAV generally depends on the climatic conditions of the project location. As no specific guidelines are currently available for Indian conditions, a temperature of 90 °C was adopted in this study.

Surface Free Energy (SFE)

Surface Free Energy (SFE) analysis was employed in this study to assess the thermodynamic compatibility between the control asphalt binders and the aggregates, including natural basalt and steel slag. SFE provides a quantitative measure of the energy required to separate two materials at their interface and is governed by the polar and dispersive components of their surface energies (Hefer et al., 2006). The SFE of a material was determined using Equations (1), (2), and (3)

$$\frac{(1+\cos \theta)Y_L}{2} = \left[\sqrt{Y_{KN}^{LW}Y_{UN}^{LW}} + \sqrt{Y_{KN}^{+}Y_{UN}^{-}} + \sqrt{Y_{KN}^{-}Y_{UN}^{+}} \right] \quad (1)$$

$$Y^{PO} = 2\sqrt{Y^{+}Y^{-}} \quad (2)$$

$$Y^{SFE} = Y^{PO} + Y^{LW} \quad (3)$$

Here, the subscript “KN” refers to the probe liquid, whereas the subscript “UN” denotes the unknown material, such as the asphalt binder, aggregate, or steel slag. The static contact angle method was adopted to determine the surface interaction parameters. In this approach, three probe liquids—distilled water, ethylene glycol, and formamide were placed as droplets on the polished surfaces of the aggregates and binders, and the corresponding contact angles were measured. The SFE parameters derived from these measurements were then used to calculate SFE performance parameters, including dry (D_A) and wet adhesion (w_A) energy.

Atomic Force Microscopy (AFM)

Atomic force microscopy (AFM) analysis was performed to evaluate the micro-scale adhesive energy and surface morphology of basalt, steel slag, and asphalt binder. A small quantity of each material (approximately <1 g) was spread uniformly onto clean microscopic glass slides and allowed to cure under ambient laboratory conditions prior to testing. The AFM measurements were carried out using a Park Systems NX10 Atomic Force Microscope operating in contact mode. The testing parameters were set as follows: cantilever spring constant of 42 N/m, scan speed of 0.2 Hz, and scan sizes of $10\ \mu\text{m} \times 10\ \mu\text{m}$ for the asphalt binder and $1\ \mu\text{m} \times 1\ \mu\text{m}$ for the solid substrates (sandstone and steel slag). The AFM probe tip radius used for the asphalt binder measurements was approximately 7 nm (Ji et al., 2020). The adhesive force was determined from the force–distance curves generated during the interaction between the AFM probe tip and the sample surface by applying Hooke’s law. The Derjaguin–Muller–Toporov (DMT) model was employed to calculate the adhesive energy for sandstone and steel slag surfaces, while the Johnson–Kendall–Roberts (JKR) model was used for the asphalt binder. In addition, surface roughness parameters were obtained from the AFM topographical images to further characterize the surface morphology of the materials. In this study, the Atomic Force Microscopy (AFM) approach involves two main analyses: quantification of the work of adhesion (adhesive work) and characterization of surface morphology.

Step 1: Calculation of adhesive forces via Hooke’s law

The adhesive forces between the AFM probe and the respective materials (sandstone/steel slag and asphalt binder) were determined from the probe deflection recorded in the force–distance curves. These forces were calculated by applying Hooke’s law, as expressed in the following equation.

$$A_f = P \times \epsilon \times \Delta Y \quad (4)$$

where: A_f is the adhesive force, P is the elastic constant of the cantilever, ϵ is the correction factor, and ΔY represents the displacement of the cantilever from its neutral (unbent) state to complete detachment from the surface.

Step 2: Determination of work of adhesion using contact models

The work of adhesion between the AFM probe and each material was evaluated using classical contact mechanics models. Two models were employed depending on the material properties. The Johnson–Kendall–Roberts (JKR) model (Suryawanshi et al., 2025) was applied to soft materials with high surface adhesion, such as asphalt binder, whereas the Derjaguin–Muller–Toporov (DMT) model (Ji et al., 2020) was used for stiffer materials with lower adhesion and smaller tip radius, such as sandstone aggregates or steel slag.

$$P_{MR-S} = 2R\pi W_{MR-S} \quad (5)$$

$$P_{TR-S} = \frac{3}{2} R \pi W_{TR-S} \quad (6)$$

where: P_{MR-S} and P_{TR-S} are the measured adhesive forces for steel slag/ aggregate and asphalt binder with tip respectively, and W_{MR-S} and W_{TR-S} represent the adhesive work between the AFM tip and asphalt/aggregate/steel slag, and R is the tip-sample contact radius.

Step 3: Calculation of surface energy parameters using Fowkes model

The Fowkes theory is used to determine the surface energy parameters of the asphalt binder and slag/aggregate based on the measured adhesive energy values.

$$X_{MR-S} = 2\sqrt{G_{MR}G_S} \quad (7)$$

$$X_{TR-S} = 2\sqrt{G_{TR}G_S} \quad (8)$$

where: G_{MR} and G_{TR} denote the surface energies of asphalt and steel slag/ sandstone aggregate, respectively, G_s is the known surface energy of the AFM probe

Step 4: Calculation of asphalt binder and solid substrate Adhesive work

The interfacial work of adhesion was calculated using the following equation

$$P_{TR-MR} = 2\sqrt{G_{MR}G_{TR}} \quad (9)$$

P_{TR-MR} indicates the thermodynamic work of adhesion between the asphalt and sandstone or steel slag surface

Binder bond strength (BBS)

For this study, a custom-fabricated pull-off tensile strength device integrated with DynaPress software was employed. The system enabled accurate monitoring of the pressure–time response with a resolution of up to 1500 microseconds. The maximum burst pressure at which the metallic stub detached from the aggregate or steel slag surface was recorded, providing high-sensitivity information on adhesion performance. The BBS test setup consisted of a metallic stub with a 0.8 mm cavity for holding the binder, a fabricated pneumatic adhesion tester, a pressure hose and piston assembly, a reaction plate, and a pull-off system equipped with real-time digital data logging through DynaPress software. The Binder Bond Strength (BBS) test, conducted in accordance with AASHTO T361 (AASHTO T361, 2017), measures the tensile force required to detach the asphalt binder from the aggregate surface, thereby quantifying the adhesive strength of the binder–aggregate interface. For sample preparation, aggregates, asphalt binder, and metallic stubs were heated at 60 °C for 30 minutes. The heated asphalt binder was poured into silicone molds of 8 mm diameter and then transferred into the cavity of the metallic stub. Subsequently, the heated aggregate surface was gently pressed onto the binder-filled stub.

Engineering performance of asphalt mixes

Asphalt mix design, and Marshall properties

Bituminous Concrete (BC-2) mixtures with a 13.2 mm nominal maximum aggregate size (NMAS), commonly used for surface courses in India, were designed using different aggregate–binder combinations: VG30, CRMB and PMB with (i) sandstone (control mix), and (ii) BOF steel slag used as coarse aggregate. The mixing and compaction temperatures followed MS 2 guidelines (MS-2, 2009). The specimens were compacted using a Marshall compactor with 75 compactions on both faces. The Optimum Binder Content (OBC) was determined by targeting 4 % air voids. After determination of OBC the mechanical properties of asphalt mixes were evaluated at their OBC. The adopted gradation for this study is displayed in Fig. 4.

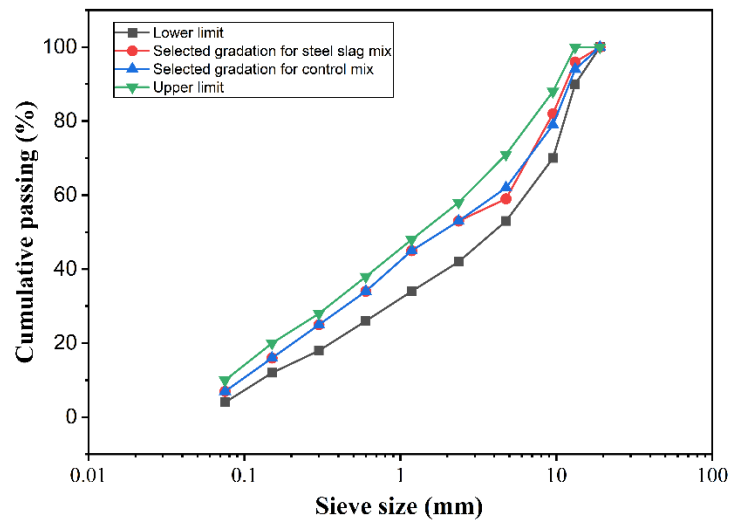


Fig. 4. Aggregate gradation of this study

Rutting test

The Hamburg Wheel test (HWT) was conducted following AASHTO T324-16 ((AASHTO), 2013) standards at a temperature of 50°C. Cylindrical specimens, measuring 150 mm in diameter and 62 mm in height, were compacted. During the test, steel wheels rolled over the specimens at a rate of 52 passes per minute while submerged in water. Each specimen set was subjected to either 20,000 passes or until a rut depth of 20 mm was reached. The rutting curve was recorded for further analysis

Resilient Modulus Test

The resilient modulus (M_R) of bituminous mixtures plays a crucial role in the design of flexible pavements. In this study, the modulus for each mix combination was determined using a repeated load testing setup. Vertical compressive loads with a haversine waveform were repeatedly applied. Each loading cycle consisted of a 0.1-second load application followed by a 0.9-second rest period. The asphalt mixture specimens, were tested under these conditions. During the resilient modulus test, 10% of the failure load obtained from the Indirect Tensile Strength (ITS) test at 35 °C was applied, in accordance with the procedures outlined in ASTM 4123–82 (ASTM D4123, 1995).

Cracking resistance

The IDEAL-CT test was conducted as per ASTM D8225 (“Astm D8225-19,” 2019) to evaluate the fracture resistance of asphalt mixture specimens at 25 °C. Specimens with dimensions of 150 mm in diameter and 62 mm

in thickness, were used in the tests. A servo-hydraulic loading system was applied to the specimens. The resulting load-displacement curves were used to calculate the Cracking Tolerance Index (CT_{index}) using Equation 10.

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \quad (10)$$

Where, G_f represents the failure energy, determined by dividing the total work of failure by the cross-sectional area of the specimen; $|m_{75}|$ is the absolute value of the slope of the post-peak segment at 75% of the peak load; l_{75} denotes the displacement corresponding to 75% of the peak load in the post-peak region; D is the diameter of the specimen; and t is its thickness.

Moisture susceptibility resistance

To investigate the effect of moisture on prepared asphalt concrete mixes, the tensile strength ratio (TSR) was appraised in accordance with AASTHO T283 (AASHTO-T283, 2003). Six specimens with 4% air voids were prepared for each mix. These test samples were then divided into two groups (conditioned and unconditioned). The conditioned test samples were initially vacuum saturated and then immersed in a water bath for 24 hours at 60° C, followed by conditioning in a water bath set at 25°C for an additional 2 hours to determine the indirect tensile strength under wet conditions. Unconditioned test samples were kept in an environmental chamber set at 25 °C for 2 hours to determine the tensile strength under dry conditions. TSR of the samples was calculated using the Subsequent equation.

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \times 100 \quad (11)$$

Results

Dry adhesion energy (A_D)

The work of adhesion (A_D) quantifies the energy needed to separate the binder from the aggregate surface under dry conditions. It directly reflects the inherent bonding strength at the binder–aggregate interface, which plays a crucial role in determining the initial structural integrity of asphalt mixtures (Singh et al., 2018). The A_D values for sandstone and steel slag aggregates, evaluated with VG30, CRMB, PMB, and their long-term aged variants, are presented in Fig. 5. For natural sandstone aggregates, PMB demonstrated the highest work of adhesion (98.5 mJ/m²), marginally exceeding that of the unaged VG30 binder (76.3 mJ/m²) and CRMB binder (91.3 mJ/m²). This observation highlights the positive influence of polymer modification in strengthening the binder–aggregate interaction under dry conditions. The enhanced polarity and improved cohesive characteristics of PMB likely promote stronger molecular bonding with the mineral surface, particularly for chemically active aggregates such as steel slag. Following long-term aging, a reduction in adhesion energy was observed for both binders. The work of adhesion decreased to 68.41 mJ/m² for VG30L, 79.52 mJ/m² for CRMBL, and to 88.43 mJ/m² for PMBL. This decline is consistent with oxidative aging processes in asphalt binders, where volatilization of lighter fractions and chemical oxidation lead to reduced molecular mobility and changes in surface properties, ultimately weakening wetting and adhesion behavior. Despite this reduction, PMBL maintained higher adhesion energy compared to VG30L, indicating its improved resistance to oxidative degradation and its ability to better preserve binder–aggregate bonding over time. The adhesion behavior changes markedly when steel slag is used as the aggregate. For all binder types, steel slag demonstrates consistently higher adhesion compared to basalt. This can

be attributed to its elevated surface energy, porous texture, and chemically active constituents such as calcium, iron, and magnesium oxides. Among the combinations studied, PMB with steel slag exhibited the highest A_D (105.96 mJ/m^2), followed by unaged CRMB (101.8 mJ/m^2), indicating the synergistic effect of binder modification and the reactive surface characteristics of steel slag. Long-term aging, however, leads to a noticeable decline in adhesion values. The A_D of VG30 decreases to 74.11 mJ/m^2 , CRMB decrease to 87.62, and PMB drops to 96.3 mJ/m^2 . Despite this reduction, these values remain significantly higher than those observed for basalt, underscoring the inherently superior adhesive nature of steel slag. The decline with aging highlights the impact of oxidative processes, which increase binder stiffness and reduce its ability to conform to the aggregate surface, particularly in the case of chemically active, alkaline materials like steel slag. Across all conditions, PMB consistently delivers the highest A_D , emphasizing the role of polymer modification in enhancing binder–aggregate bonding under dry conditions. The improved performance of steel slag can be linked to both its rough surface morphology, which promotes mechanical interlocking, and its chemical composition, which facilitates stronger physicochemical interactions. Long-term aging further weakens adhesion, with VG30 showing a more pronounced reduction compared to Long-term aged PMB and CRMB. Nevertheless, the performance of aged PMB remains relatively stable, highlighting its superior resistance to aging-induced degradation. Overall, the combination of PMB and steel slag provides the most effective bonding performance under dry conditions, offering potential advantages in minimizing early-stage distress such as cracking in asphalt pavements.

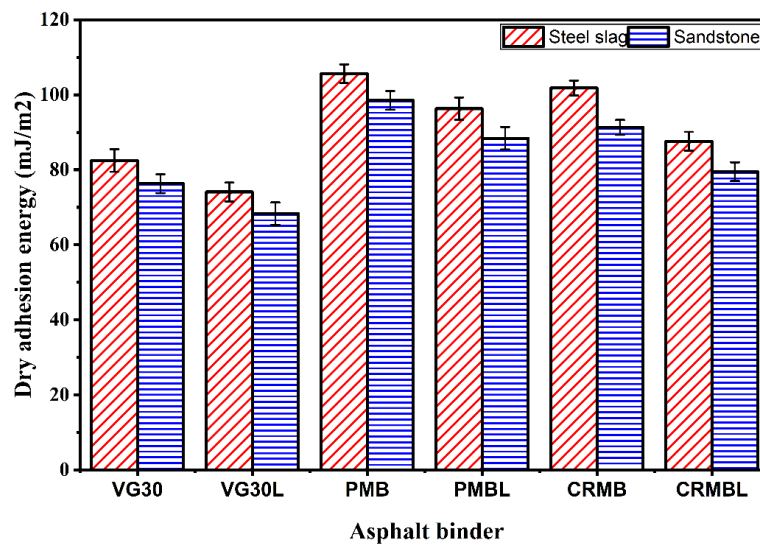


Fig. 5. Dry adhesion energy between asphalt binders and aggregates

Wet adhesion energy (A_w)

The A_w represents the energy associated with binder–aggregate separation in the presence of moisture (as shown in Fig. 6). It is an important indicator of the moisture susceptibility of asphalt mixtures, reflecting the extent to which water can weaken or displace the binder at the aggregate interface. In this study, all A_w values are negative, indicating that debonding is energetically favorable under moisture-rich conditions. More negative A_w values suggest a greater susceptibility to moisture-induced damage.

Sandstone-based systems demonstrated moderate resistance to moisture-induced debonding. Among the unaged binders, PMB exhibited the least negative A_w value (-44.35 mJ/m^2), followed by CRMB (-46.11 mJ/m^2), and

VG30 (-63.52 mJ/m^2). This indicates that binder modification enhances the binder's resistance to moisture damage, likely by improving cohesive strength and maintaining interfacial stability under wet conditions.

After aging, A_w values became more negative, reaching -67.32 mJ/m^2 for VG30L, -51.65 mJ/m^2 for CRMBL and -48.86 mJ/m^2 for PMBL. The larger reduction observed for VG30 suggests that long-term aging significantly decreases the moisture resistance of neat binders, likely due to oxidation-induced stiffening and loss of flexibility. In contrast, PMBL maintained comparatively stable debonding resistance, highlighting the ability of polymer-modified binders to preserve interfacial strength after aging. Overall, the moderately negative A_w values for sandstone mixtures indicate a balanced wetting–debonding behavior, particularly when modified binders are used.

In comparison, steel slag mixtures exhibited substantially less negative A_w values, indicating lesser susceptibility to moisture-induced interfacial failure. For unaged binders, VG30 showed an A_w value of -57.52 mJ/m^2 , while CRMB showed -43.11 mJ/m^2 , and PMB recorded -41.35 mJ/m^2 . Although PMB and CRMB again provided slightly improved performance compared to VG30, these values were considerably less negative than those of sandstone mixtures, reflecting the less hydrophilic characteristics of steel slag.

The effect became more pronounced after aging, with A_w values reaching -64.32 mJ/m^2 for VG30L, -49.65 mJ/m^2 for CRMBL and -45.86 mJ/m^2 for PMBL. These findings suggest that moisture can more easily penetrate and weaken the binder–sandstone interface, particularly when aging increases binder brittleness. The micro-porous structure and high surface energy of steel slag, while beneficial for dry adhesion, may also reduce interfacial degradation under wet conditions. Mixtures prepared with modified binders exhibited better performance than those containing unmodified VG30, highlighting the improved moisture resistance provided by binder modification.

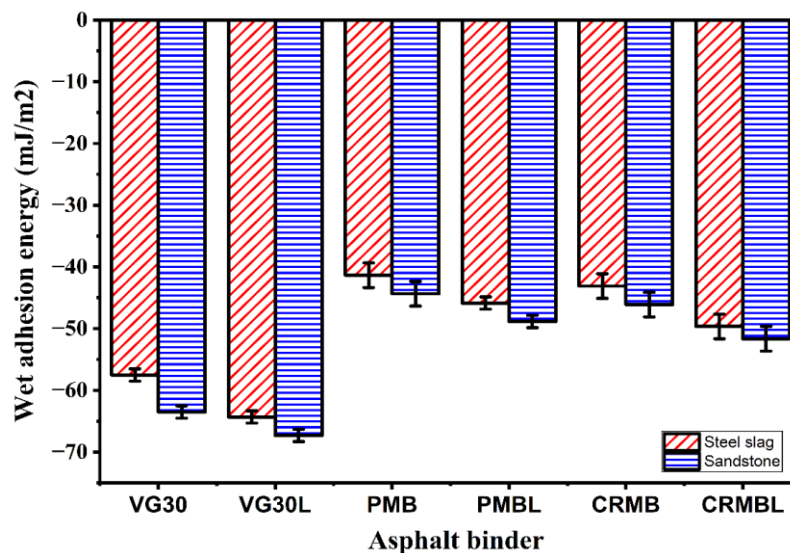


Fig. 6. Wet adhesion energy between asphalt binders and aggregates

Asphalt surface energy

The measured adhesive forces for the different binders are presented in Fig. 7. PMB40 exhibited the highest adhesive force (32.65 nN), indicating its superior elastic recovery, increased polarity, and enhanced cohesive strength attributed to the presence of polymeric chains. The adhesive force of unaged CRMB was higher than that

of unaged VG30 but lower than that of unaged PMB. Long-term aging (VG30L/CRMBL/PMBL) reduced adhesive force across all binders, attributed to oxidative hardening and the formation of polar oxidation products that modify their surface chemistry. The observed differences among PMB, CRMB, and VG30 indicate that polymer modification enhances the binder's ability to develop stronger interactions, particularly under conditions simulating nanoscale contact with mineral particles. These findings are consistent with earlier SFE-based work of adhesion (W_A) results, where PMB systems demonstrated higher adhesion compared to CRMB and VG30, thereby confirming the superior bonding performance of PMB binders at both macroscopic and nanoscale levels.

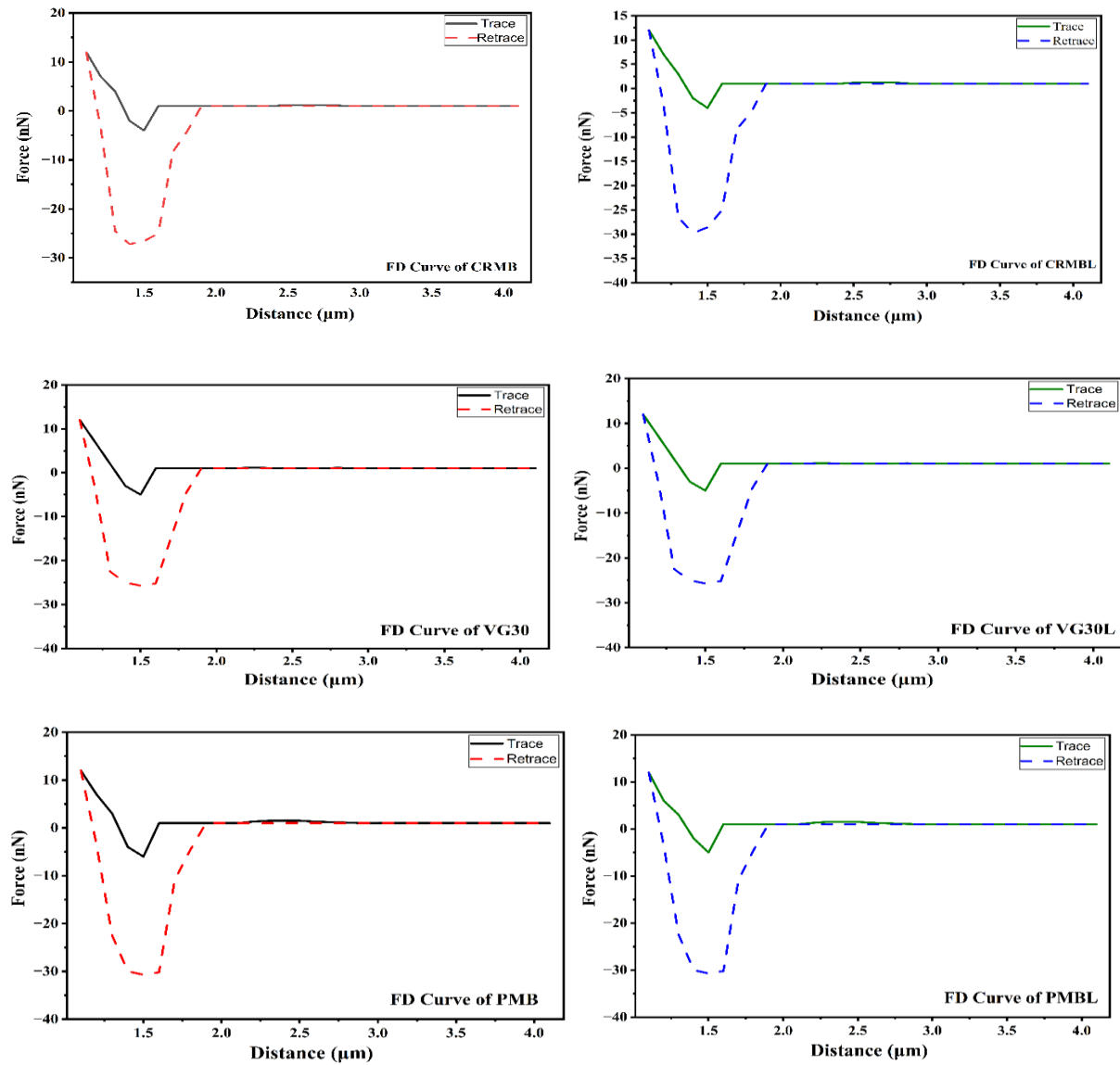


Fig. 7. FD curves obtained using AFM for various asphalt binders

Work of adhesion (WOA) using AFM

The work of adhesion (WOA), derived from AFM force–distance curves, represents the energy required to separate two surfaces per unit area. This study reflects the bonding strength between asphalt binders and aggregates (sandstone or steel slag). Given the deformability of the interacting materials, the JKR model was applied to asphalt binder interactions, while the DMT model was used for rigid mineral surfaces, such as

aggregates. The WOA values for different asphalt binder–slag/aggregate combinations are presented in Fig. 8. Across all combinations, PMB–steel slag exhibited the highest WOA (324.56 mJ/m^2), indicating the strongest binder–aggregate interaction. This observation is consistent with earlier WOA and adhesive force results, further confirming the superior bonding characteristics of polymer-modified binders. Aging led to a reduction in W_A across all systems, which can be attributed to oxidative hardening. Specifically, VG30L, CRMBL, and PMB40S showed a 12–16% decrease in WOA compared to their unaged counterparts, suggesting a loss of binder polarity and flexibility due to thermo-oxidative aging. In terms of aggregate type, BOF steel slag consistently exhibited higher WOA values than sandstone across all binders. For instance: (a) VG30: steel slag (231.58 mJ/m^2) > sandstone (211.35 mJ/m^2), (b) CRMB: steel slag (288.46 mJ/m^2) > sandstone (263.56 mJ/m^2), and (c) PMB: steel slag (324.56 mJ/m^2) > sandstone (293.75 mJ/m^2). A similar trend was observed after aging. This behavior highlights the superior surface compatibility of steel slag, which may be attributed to its smoother and more uniform mineral surface, CaO-rich composition that promotes hydrogen bonding with polar components of the binder, and improved wettability and microtexture that facilitate uniform binder coating.

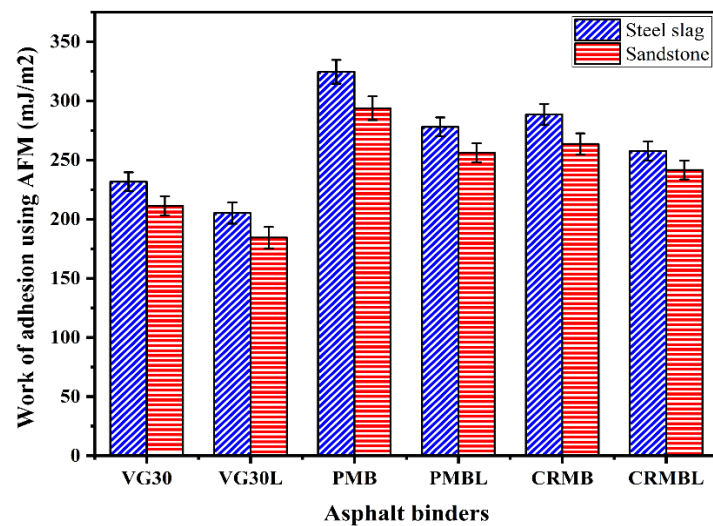


Fig. 8. Work of adhesion using AFM

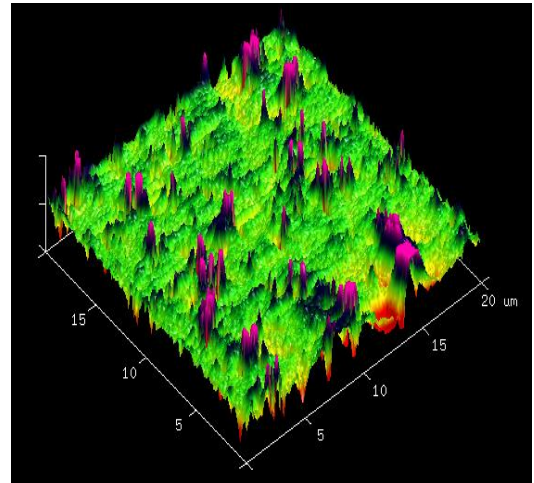
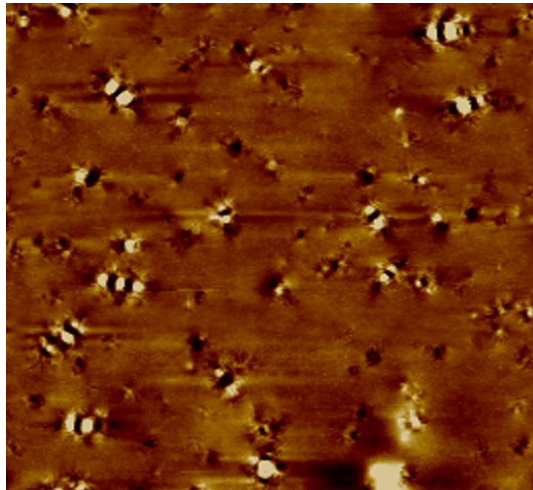
Surface Topography and Roughness Analysis via AFM

Atomic Force Microscopy (AFM) was used to characterize the nanoscale surface topography and roughness of asphalt binders and aggregates (Fig. 9). The morphological analysis of asphalt binders identified three distinct microstructural phases (Xing et al., 2022), (Pipintakos et al., 2021): (i) the bee phase, observed as prominent bee-shaped structures and typically associated with waxy or crystalline components; (ii) the peri phase, which surrounds the catana phase and appears as a dispersed domain; and (iii) the para phase, representing the continuous matrix that dominates the overall binder morphology. Surface roughness was quantified using two parameters. The average roughness (R_a) is the arithmetic mean of the absolute surface height deviations from the mean plane, providing a general indication of surface texture but not the distribution of peaks and valleys. In contrast, the root mean square roughness (R_q) corresponds to the standard deviation of the surface height profile and is more sensitive to microscopic variations, including peaks and valleys. Figs. 9 present the 2D and 3D surface morphology of asphalt binders. Among the unaged binders, VG30 exhibited $R_a = 0.354 \text{ nm}$ and $R_q = 0.814 \text{ nm}$, indicating a moderately rough surface. In contrast, PMB showed a comparatively smoother texture ($R_a = 0.215$

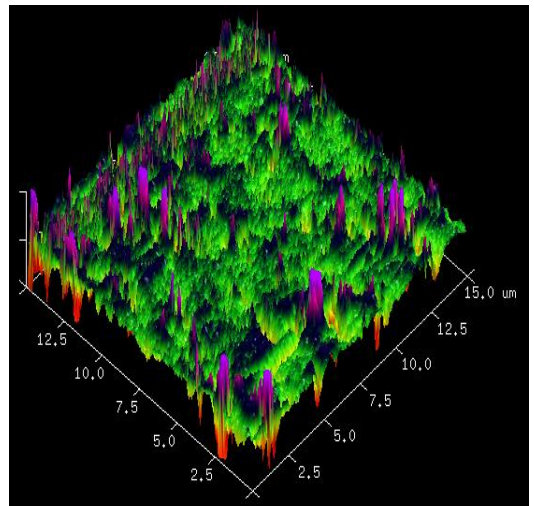
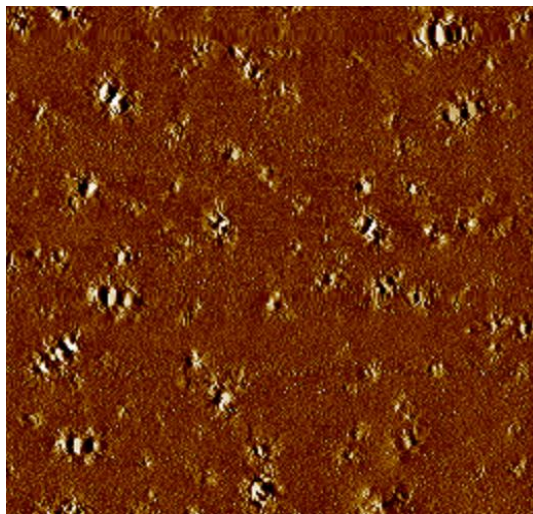
nm and $R_q = 0.564$ nm), likely due to the uniform dispersion of polymer chains within the matrix, which reduces surface irregularities. Following PAV aging, an increase in surface roughness was observed for all binders. VG30 exhibited the highest roughness ($R_a = 1.254$ nm and $R_q = 1.721$ nm), indicating significant oxidative aging and phase separation. Although PMB40L remained smoother than VG30L, it still showed increased roughness ($R_a = 0.765$ nm and $R_q = 1.274$ nm) compared to its unaged state, suggesting morphological changes due to aging, albeit to a lesser extent than VG30. The CRMB binder exhibited intermediate roughness, between VG30 and PMB.

From an adhesion perspective, lower R_q values are associated with improved binder–aggregate bonding, as they facilitate greater interfacial contact and interaction. Accordingly, PMB and CRMB are expected to demonstrate superior adhesion performance compared to their VG30 counterparts. Likewise, the relatively smooth surface of basalt promotes stronger adhesion with asphalt binders. In contrast, the higher surface roughness of steel slag, although it may reduce chemical adhesion, enhances mechanical interlocking. Moreover, the relatively rougher surfaces of CRMBL, PMBL, and steel slag can enhance cracking resistance and dry strength by promoting stronger physical interlocking. This observation aligns with the literature, which shows that increased surface roughness tends to reduce chemical adhesion but improve mechanical interlock, particularly for industrial by-products such as steel slag. Therefore, while smoother surfaces are more favorable for chemical adhesion, the inherent roughness of materials like steel slag can offer both sustainable and performance benefits when appropriately optimized in asphalt mix design.

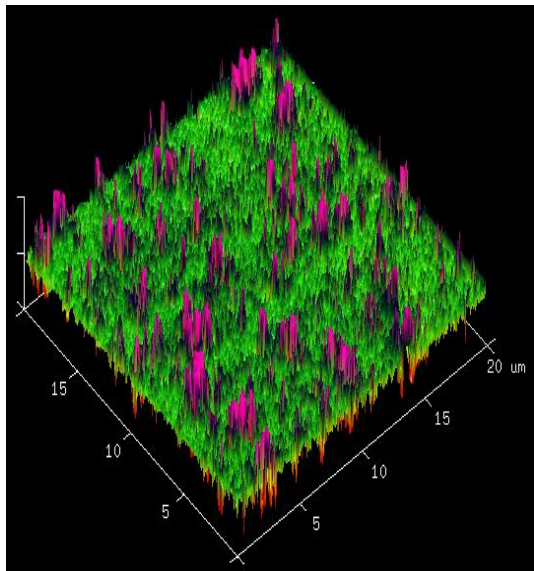
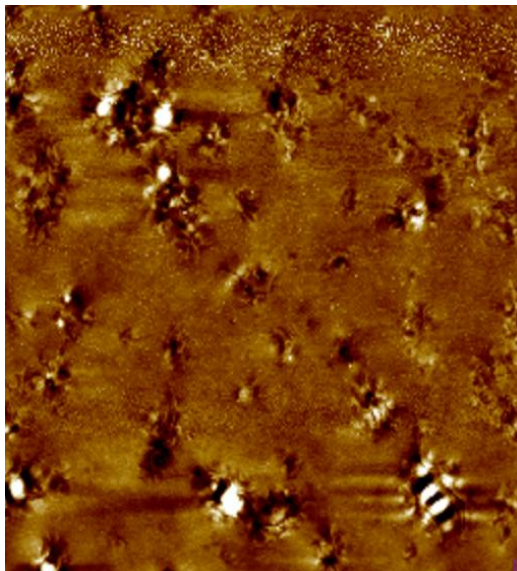
CRMB



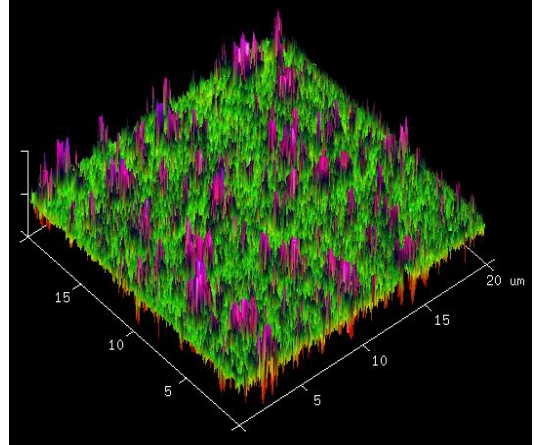
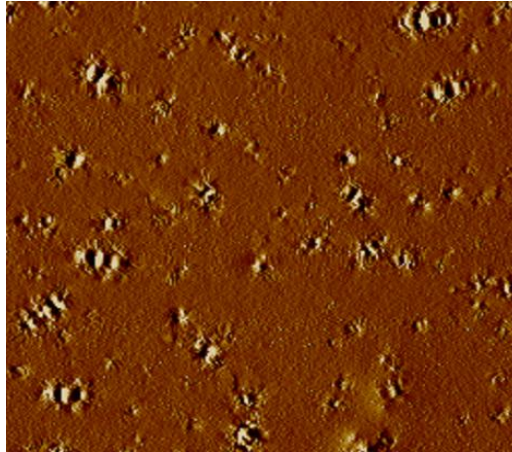
CRMBL



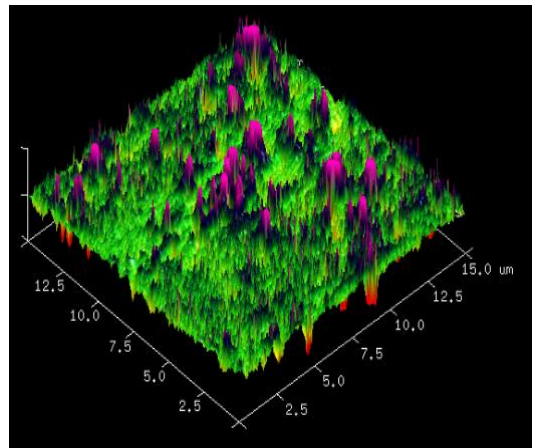
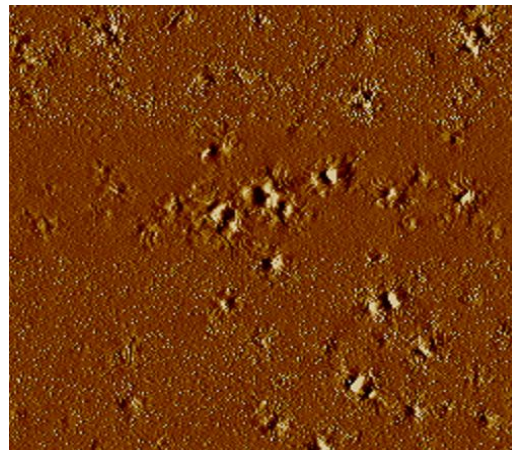
PMB



PMBL



VG30



VG30L

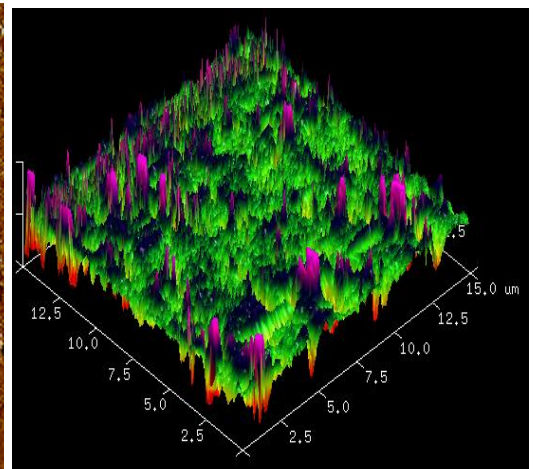
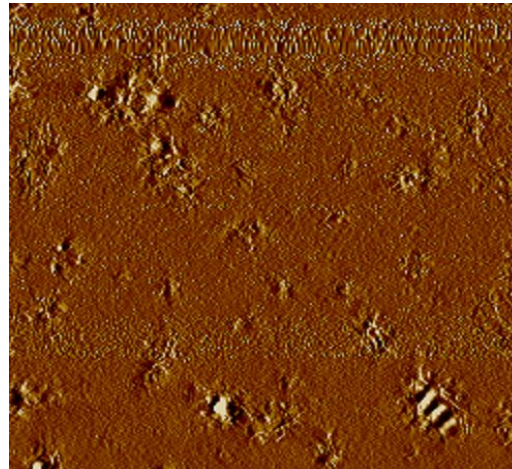


Fig. 9. AFM images showing 2D and 3D surface morphology of different asphalt binders

Binder bond strength (BBS)

The BBS test was performed to assess the adhesion characteristics between asphalt binders and aggregates under both dry and moisture-conditioned conditions. Key parameters evaluated included the pull-off tensile strength (POTS) in dry and wet states (Fig. 10), the mode of failure (adhesive or cohesive), and the bond strength ratio (BSR) (Fig. 11), which indicates the extent of strength retained after exposure to moisture. For BOF steel slag aggregate, the unaged VG30, CRMB, and PMB binders exhibited relatively high pull-off tensile strength (POTS) values under dry conditions, recorded as 2.26 MPa, 2.63 MPa, and 2.86 MPa, respectively. Notably, all binders demonstrated cohesive failure in the dry state, indicating that the internal strength of the binder surpassed the adhesive bond at the binder–aggregate interface, thereby reflecting strong interfacial adhesion. Following moisture conditioning, a slight reduction in POTS was observed, with values decreasing to 2.05 MPa for VG30, 2.45 MPa for CRMB, and 2.61 MPa for PMB. In contrast to the dry condition, all binders exhibited adhesive failure after moisture exposure, suggesting weakening of the binder–aggregate interface in the presence of water. Despite this reduction, the bond strength ratio (BSR) values remained high, particularly for PMB, highlighting its superior resistance to moisture-induced damage. Under long-term aging conditions, VG30L showed a further decline in bonding performance, with POTS values of 1.85 MPa in the dry state and 1.79 MPa in the wet state, accompanied by adhesive failure in both cases, although the BSR remained above 90%. In comparison, PMBL demonstrated better retention of bonding characteristics, with POTS values of 2.55 MPa (dry) and 2.41 MPa (wet). It exhibited cohesive failure under dry conditions and maintained a high BSR of 94.12%, indicating enhanced durability. Similarly, CRMBL outperformed VG30L, recording POTS values of 2.39 MPa in the dry state and 2.27 MPa under wet conditions, reflecting improved adhesion performance after aging. For natural sandstone aggregates, VG30, CRMB, and PMB exhibited cohesive failure under dry conditions, with POTS values of 2.02 MPa, 2.48 MPa, and 2.67 MPa, respectively. This indicates strong binder cohesion along with good adhesion between the binder and aggregate in the absence of moisture. However, under wet conditions, all binders transitioned to adhesive failure, accompanied by a reduction in POTS values to 1.88 MPa for VG30, 2.30 MPa for CRMB, and 2.43 MPa for PMB. Following aging, a further decline in POTS was observed for all binders. VG30L showed a decrease to 1.78 MPa (dry) and 1.61 MPa (wet), while CRMBL reduced to 2.23 MPa (dry) and 2.16 MPa (wet). Similarly, PMBL recorded values of 2.36 MPa under dry conditions and 2.21 MPa under wet conditions, indicating that aging adversely affected both cohesive strength and moisture resistance. These observations are consistent with the previously reported SFE and wet adhesion energy results, which indicated comparatively lower bonding energies and energy ratios for steel slag relative to basalt. The prevalence of cohesive failure in VG30, CRMB, and PMB binders under dry conditions, particularly in the case of steel slag, suggests a strong binder–aggregate interaction, where the failure is governed by the internal strength of the binder rather than the interface.

Overall, PMB40 and PMBL exhibited superior performance with both aggregates, especially in terms of maintaining higher bond strength and better resistance to degradation under varying conditions.

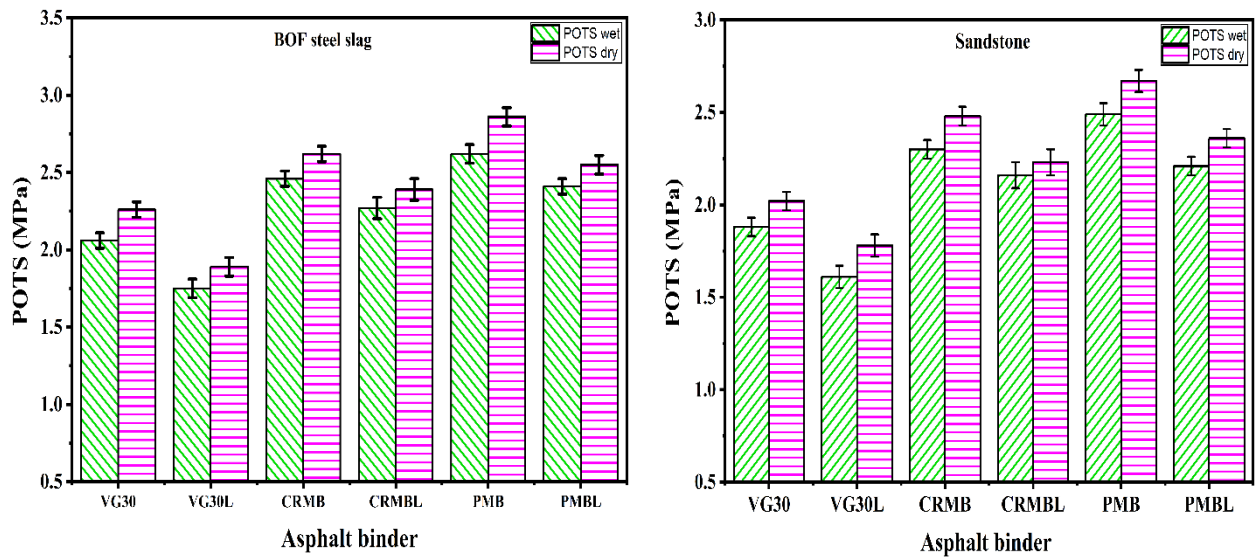


Fig. 10. POTS of asphalt binders with (A) sandstone and (B) steel slag substrates

The trends observed in the BBS results are in strong agreement with the previously reported AFM findings on surface morphology and adhesion behavior. Asphalt binders exhibiting smoother surfaces (characterized by lower R_q values) and stronger interactions with the AFM probe demonstrated superior bonding characteristics. This consistency between micro-scale analyses (AFM and SFE) and macro-scale measurements (BBS) enhances the reliability of the results and highlights the critical importance of binder–aggregate compatibility in ensuring long-term pavement durability. A comprehensive assessment integrating SFE, AFM, and BBS analyses clearly indicates that BOF steel slag provides improved adhesion performance with asphalt binders compared to conventional sandstone aggregates. Beyond performance benefits, the incorporation of BOF steel slag, an industrial by-product, aligns with sustainable construction practices by promoting resource efficiency and supporting circular economy principles.

To further investigate the mechanical behavior of BOF steel slag-based asphalt mixtures, a phased replacement approach was implemented. In this methodology, natural sandstone aggregates (control mix) were gradually substituted with steel slag, ultimately achieving full replacement of the coarse aggregate fraction. The following sections present detailed evaluations of cracking resistance (CT index), rutting susceptibility, resilient modulus, and tensile strength ratio (TSR), providing insights into both dry and moisture-conditioned performance of the developed mixtures.

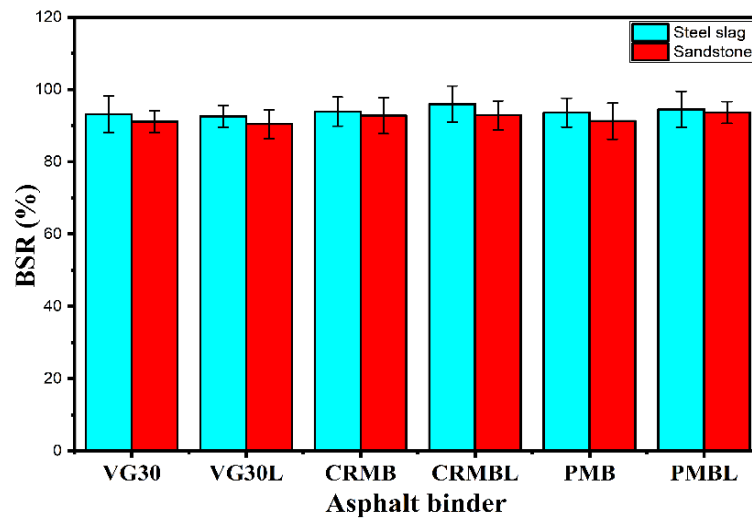


Fig. 11. BSR for asphalt binders with both aggregates

Rutting

The rutting resistance of the various asphalt mixes is presented in Fig. 12 in terms of rut depth. In general, a lower rut depth indicates higher rutting resistance. The results showed that, regardless of binder type, steel slag mixes exhibited lower rut depths than sandstone mixes. For unaged steel slag mixes, VG30 displays a rut depth of 2.31 mm, while the rut depths of PMB and CRMB mixes were 1.64 and 1.81, respectively. Even after long-term aging, the steel slag mixes showed significantly greater rutting resistance and lower rut depths than sandstone mixes. Under-aged conditions, the rut depth of steel slag VG30 mix was 2.86 mm, while the rut depth of PMB and CRMB mixes were 1.89 and 1.95, respectively. This improved performance can be attributed to the rough surface morphology and higher basicity of steel slag, which promote stronger adhesive bonding with the binder and ultimately enhance rutting resistance (Biswas & Soheli, 2025), (Ransinchung, 2026). Under un-aged conditions, VG30 sandstone mixture displayed a rut depth of 6.24 mm. The rut depth of modified mixes under unaged conditions was significantly lower than that of VG30 mixes. For instance, the rut depth of PMB sandstone and CRMB sandstone mixes at unaged conditions were 4.81 and 5.22, respectively. Aging also significantly affected the rut depth of the mixes. After long-term aging, the rut depth increased in mixes containing both aggregate types. During the aging process of asphalt binders, the saturation fraction remains relatively stable with minimal variation, whereas the aromatic fraction is more susceptible to oxidative polymerization, leading to the formation of colloids. Subsequently, the polar functional groups present in the colloidal components undergo intermolecular polymerization and condensation reactions, leading to the formation of asphaltenes (Nur et al., 2018). In general, the binder components progressively transform from aromatics to colloids and finally to asphaltenes, causing an increase in heavier fractions during aging. Consequently, aging leads to a reduction in colloid content and an increase in asphaltene content, which ultimately deteriorates the adhesion performance of the asphalt binder. Under-aged condition, the VG30 sandstone mixture recorded a Rut depth of 6.87 mm. In comparison, the PMB and CRMB sandstone mixtures demonstrated significantly lower rut depths of 5.31 mm and 5.71 mm, respectively. CRMB and PMB mixes performed better after long-term aging compared to VG30. With aging, the dispersion component of modified asphalt binders becomes higher than that of virgin asphalt binders, whereas the polar component shows the opposite trend. This behavior may be attributed to the presence of a large number of

small non-polar molecules in the modifier, which enhances the molecular mobility within the aged asphalt binder. Consequently, highly polar components such as resins and asphaltenes become more uniformly dispersed, thereby improving the overall performance of the asphalt binder. The test specimen is displayed Fig. 12(b).

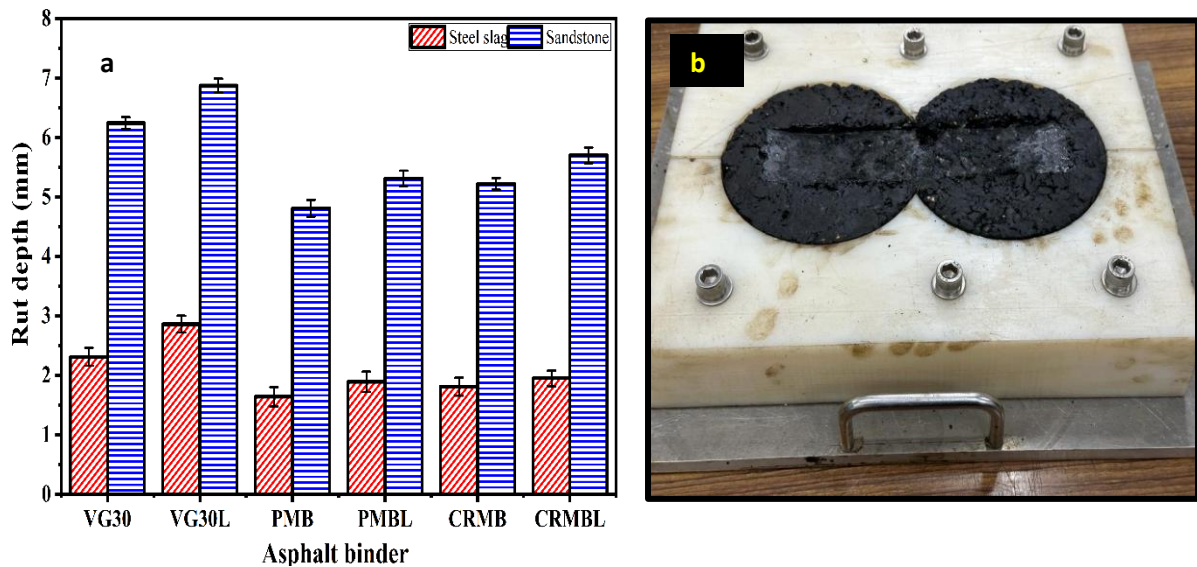


Fig. 12. Rut depth of mixes (a) and test specimen (b)

Resilient modulus

The resilient modulus of various mixes was evaluated with the resilient modulus test at 35° C. The resilient modulus results and test setup is displayed in Fig. 13(a,b). Similar to the rut depth results, asphalt mixes fabricated with steel slag exhibited higher resilient modulus values than sandstone mixes, irrespective of binder condition. Under unaged conditions, the VG30 system exhibited a resilient modulus of 2130 MPa for the sandstone mix and 2735 MPa for the steel slag mix. Similarly, the CRMB system showed resilient modulus values of 2490 MPa for the sandstone mix and 3080 MPa for the steel slag mix. Among all the mixes under unaged conditions, the PMB steel slag mix exhibited the highest resilient modulus value of 3125 MPa, while the corresponding sandstone mix showed a resilient modulus of 2680 MPa. After aging, the resilient modulus of all asphalt mixes decreased. However, even under long-term aged conditions, the steel slag mixes exhibited higher resilient modulus values than the conventional sandstone mixes, irrespective of binder type. Under long-term aging conditions, the VG30 system exhibited resilient moduli of 1860 MPa for the sandstone mix and 2540 MPa for the steel slag mix. Similarly, the CRMB system showed resilient modulus values of 2265 MPa for the sandstone mix and 2770 MPa for the steel slag mix. The PMB steel slag mix displayed a resilient modulus of 2920 MPa, while it was 2410 MPa for the PMB sandstone system. The high resilient modulus of steel slag mixes is primarily attributed to their uneven surface morphology, which creates better interparticle bonding within the mix. Similar to the rutting performance, aging significantly affected the resilient modulus of the asphalt mixes, leading to a notable reduction in modulus values (Swathi et al., 2021). With aging, the dispersion component of modified asphalt binders becomes higher than that of virgin binders, while the polar component exhibits the opposite trend. This behavior may be attributed to the presence of a large number of small non-polar molecules in the modifier, which enhance molecular mobility within the aged binder. As a result, highly polar components such as resins and asphaltenes become more uniformly dispersed, thereby improving the overall performance of the asphalt binder.

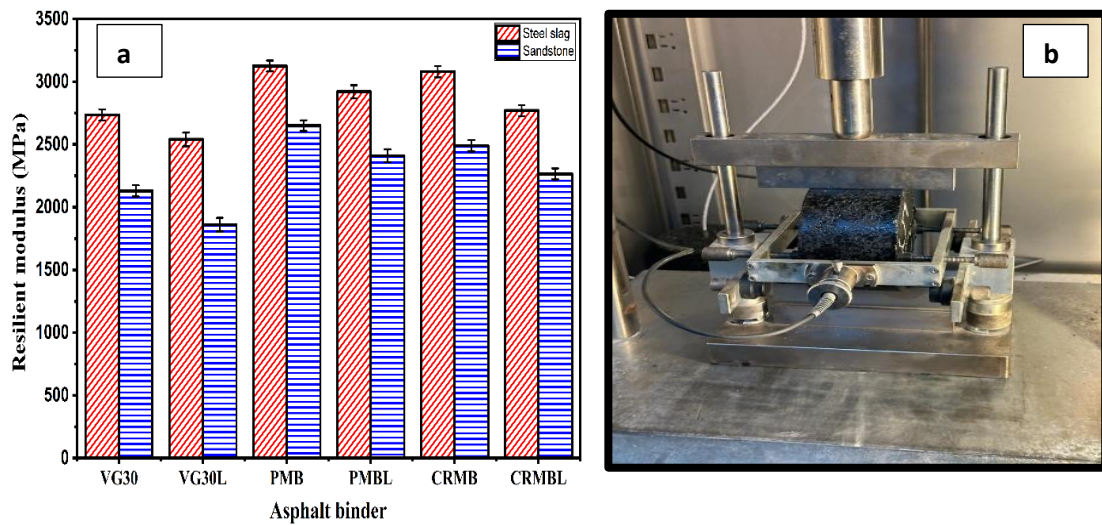


Fig. 13. Resilient modulus of mixes (a) and test set up (b)

Cracking resistance

The cracking resistance of various asphalt mixes were evaluated in terms of CTindex and displayed in Fig. 14a. Among all the mixes, the mix with steel slag displayed a higher CT index than the sandstone mixes, irrespective of the binder types. The steel slag mixtures exhibited the expected performance trend, with PMB and CRMB modified binders consistently outperforming VG30 binders under both aged and unaged conditions owing to their superior elasticity. Under unaged conditions, the VG30 sandstone mixture recorded a CTindex value of 85.61 %. In comparison, the PMB and CRMB sandstone mixture demonstrated significantly higher CTindex values of 92.91% and 90.53%, respectively. A similar performance trend was also observed under long-term aged conditions.

Under-aged condition, the VG30 sandstone mixture recorded a CTindex value of 85.61 %. In comparison, the PMB and CRMB sandstone mixture demonstrated significantly higher CTindex values of 92.91% and 90.53%, respectively. Steel slag mixes exhibited superior performance, which can be attributed to the rougher surface texture and irregular particle shape of steel slag aggregates. These characteristics enhance interparticle friction within the mixture, ultimately improving the cracking resistance of the steel slag mixes (Biswas & Sham, 2025),(Biswas & Sham, 2026). With long-term aging, the performance of the mixes deteriorated irrespective of the aggregate type used. The reduced performance of the aged binder suggests a loss of binder polarity and flexibility due to thermo-oxidative aging. Irrespective of the binder type, the steel slag mixes exhibited superior performance, further demonstrating that the replacement of natural aggregates with industrial by-products such as steel slag not only promotes sustainability but also enhances pavement performance. The test set up is displayed in Fig. 14b.

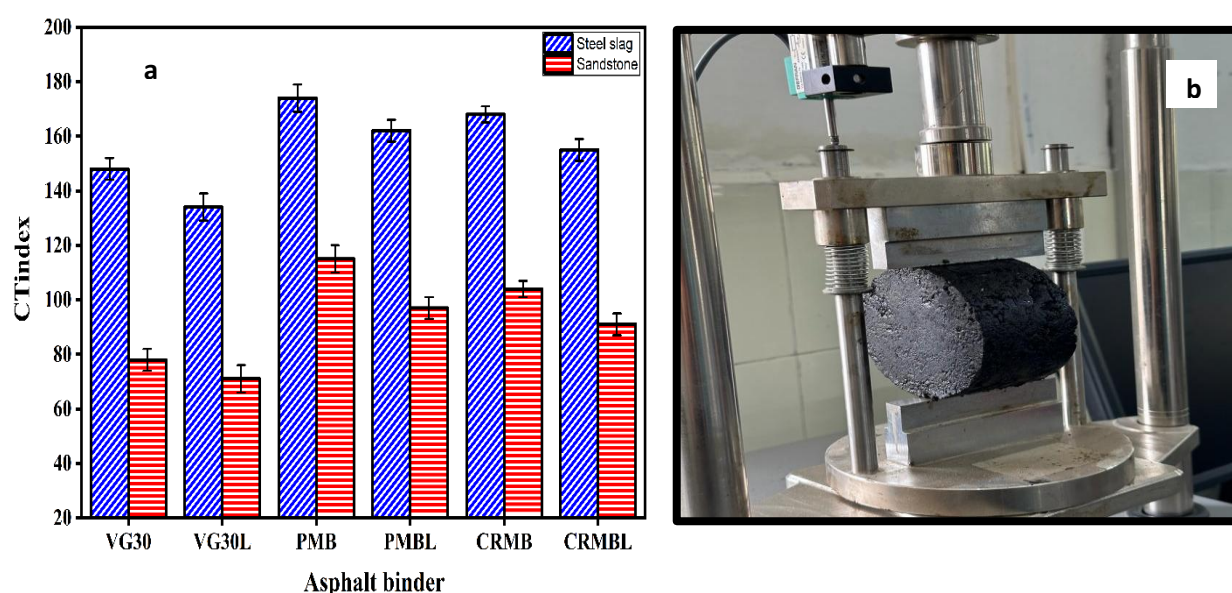


Fig. 14. CTIndex test results (a) and test set up (b)

Moisture damage resistance

Fig. 15 illustrates the corresponding TSR results for mixtures containing basalt and steel slag aggregates under both unaged and long-term aged conditions. The sandstone control mixtures exhibited the expected performance trend, with PMB and CRMB modified binders consistently outperforming VG30 binders under both dry and wet conditions owing to their superior elasticity and enhanced moisture resistance. Under unaged conditions, the VG30 sandstone mixture recorded a TSR value of 85.61 %. In comparison, the PMB and CRMB sandstone mixture demonstrated significantly higher TSR values of 92.91% and 90.53%, respectively. A similar performance trend was also observed under long-term aged conditions. These findings are consistent with the earlier AFM and BBS results, which showed that steel slag exhibited satisfactory bonding characteristics under dry conditions. Moreover, the present observations agree with those of Biswas et al. (Ransinchung, 2026) and Pathak et al. (Pathak et al., 2020), who reported that partial replacement of natural aggregates with industrial by-products can improve pavement performance while promoting sustainable construction practices. Overall, incorporating steel slag into asphalt mixtures offers a technically feasible and environmentally sustainable alternative, particularly when used as a partial aggregate replacement. This approach not only facilitates the circular utilization of industrial waste materials but also enables asphalt mixtures to achieve, and in some cases exceed, the performance levels of conventional mixtures.

Fig. 16 illustrates the correlation between BSR and TSR for sandstone mixtures. The obtained R^2 value of 0.98 for sandstone indicates a strong positive relationship, demonstrating that higher interfacial bond strength contributes to improved moisture resistance. This suggests that the adhesive strength at the binder–sandstone interface can effectively predict the durability performance of the mixture under moisture exposure. In contrast, corresponding to steel slag mixtures, exhibits a strong correlation with an R^2 value of 0.95. The excellent linear relationship confirms that bond strength plays a dominant role in governing the moisture resistance of steel slag

mixtures. The high correlation observed for both mixtures indicates that their mechanical performance is strongly influenced by the quality of adhesion at the binder–aggregate interface.

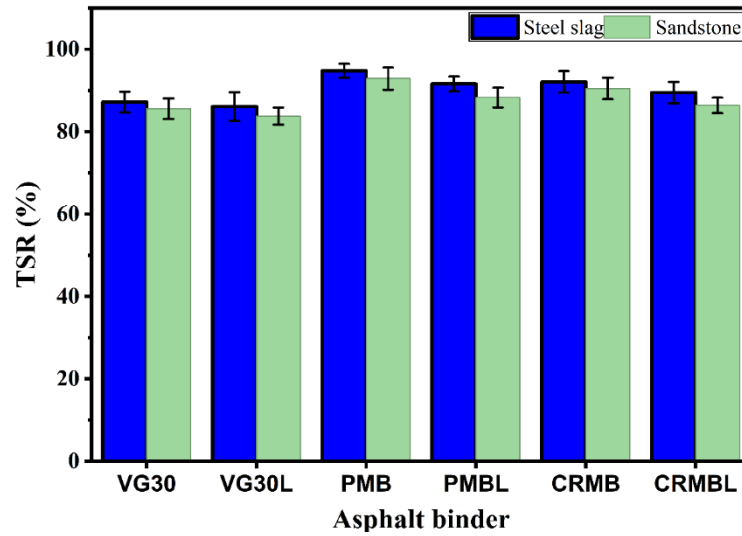


Fig. 15. TSR of studied mixes

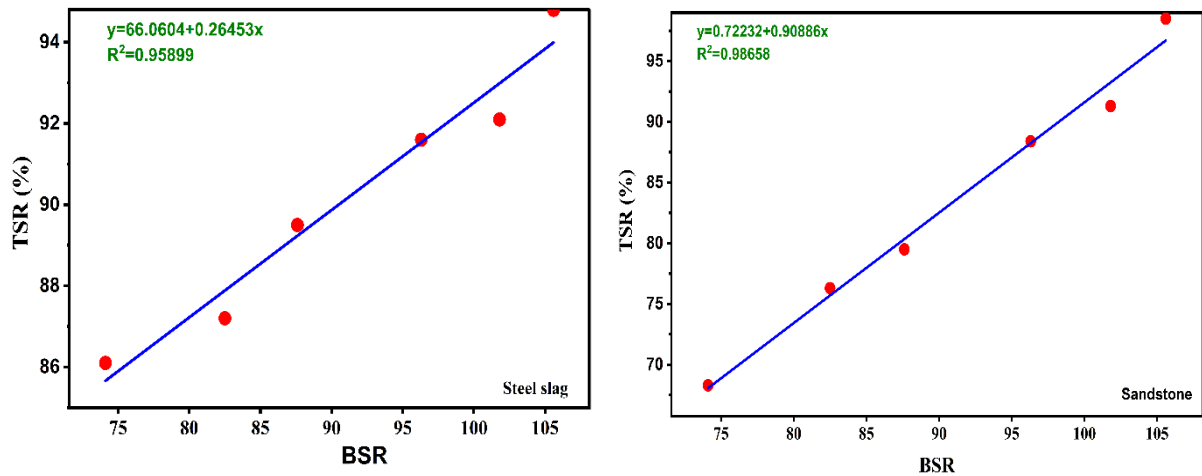


Fig. 16. Correlation between BSR and TSR for mixtures

Analysis of Leaching Potential

The incorporation of steel slag into asphalt mixtures may raise potential environmental and health concerns due to the possible leaching of heavy metals. Therefore, it is essential to assess the heavy metal concentrations in the leachates of the tested mixtures and compare them with the regulatory limits specified in IS 10500 (IS 10500 (2012), 2012). The heavy metal analysis results for the various asphalt mixtures are presented in Table 3. The findings revealed that the concentrations of all evaluated heavy metals were below the prescribed regulatory thresholds. These results indicate that the steel slag-based asphalt mixtures developed in this study do not pose any significant environmental or human health risks.

Table 3. Amount of heavy metals observed in studied mixtures.

	VG30		VG30L		CRMB		CRMBL		PMB		PMBL		Limit (IS
													10500
													(2012),
													2012)
	SS	NA	SS	NA	SS	NA	SS	NA	SS	NA	SS	NA	
Cadmium	0.02	0.01	0.01	0.01	0.02	0.01	0.03	0.01	0.03	0.01	0.02	0.01	0.04
Copper	0.54	0.38	0.63	0.38	1.16	0.38	0.55	0.38	0.49	0.38	0.51	0.38	2.00
Chromium	0.28	0.21	0.21	0.21	0.26	0.21	0.31	0.21	0.25	0.21	0.26	0.21	0.50
Nickel	0.16	0.11	0.15	0.11	0.21	0.14	0.18	0.11	0.13	0.11	0.15	0.11	0.40
Lead	0.27	0.13	0.23	0.13	0.28	0.13	0.37	0.13	0.29	0.13	0.24	0.13	0.50
Zinc	2.34	1.16	1.94	1.16	2.47	1.16	2.54	1.16	2.25	1.16	2.27	1.16	4.00

Conclusions

This study investigated the bonding characteristics and mechanical performance of asphalt mixtures incorporating sandstone and steel slag aggregates with VG30, PMB, CRMB, and their PAV-aged counterparts (VG30L, PMBL, and CRMBL). A multi-scale evaluation framework was employed, including Surface Free Energy (SFE) analysis, Atomic Force Microscopy (AFM), Binder Bond Strength (BBS) testing, rutting resistance, resilient modulus, cracking resistance, and Tensile Strength Ratio (TSR) assessments. The main objective was to evaluate the suitability of steel slag as a sustainable substitute for natural sandstone in bituminous mixtures and to examine its performance under both aged and unaged binder conditions.

- Steel slag aggregates combined with PMB and PMBL binders exhibited the strongest interfacial bonding and the highest moisture resistance across all evaluation techniques.
- Steel slag demonstrated superior dry and wet bonding characteristics, exhibiting higher POTS values and greater nanoscale adhesion work than sandstone.
- Complete replacement of aggregates with steel slag (100%) resulted in the highest Tensile Strength Ratio (TSR) and resilient modulus among all the mixes.
- Due to the rough surface texture and strong adhesive bonding characteristics of steel slag, asphalt mixes fabricated with steel slag exhibited superior rutting and cracking resistance compared to sandstone mixes, irrespective of the binder type.

- The leaching analysis of asphalt mixtures fabricated with waste materials indicated that the toxicity of the mixtures was higher than that of the conventional mix; however, it remained lower than the permissible threshold limit.

Based on these findings, future studies should focus on evaluating the field performance of long-term aged steel slag-based asphalt mixtures. The sustainable utilization of industrial waste materials in pavement construction demonstrates significant potential and warrants further investigation.

Statements and declaration

Acknowledgments: The authors gratefully acknowledge the financial support provided by the Ministry of Human Resource Development (MHRD), Government of India, in the form of student fellowships and grants.

Conflict of interest: The authors declare no conflict of interest.

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