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TECHNICAL PAPER

Evaluating moisture damage resistance in asphalt mixtures using amine-free anti-stripping agent for enhanced durability

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Abstract

Moisture-induced durability and strength loss are major concerns in asphalt mixtures. Traditional additives often suffer from environmental concerns or inconsistent performance, highlighting the need for sustainable alternatives. This study evaluates an eco-friendly, amine-free anti-stripping additive designed to enhance binder-aggregate adhesion and maintain stable performance across different materials. Moisture resistance was assessed using indirect tensile strength (ITS), tensile strength ratio (TSR), boiling tests, Marshall immersion, and MATLAB-based image analysis. The additive significantly improved adhesion, between the asphalt binder and aggregates, as evidenced by the tensile strength ratio (TSR) values of 95% and 74% after 24 h and 48 h of conditioning, respectively. Additionally, stability was improved, with treated unconditioned samples exhibiting a peak value of 15.6 kN, compared to 13.72 kN for the untreated samples. Upon immersion for 24 h, stability in the treated mixtures decreased by only 3.2%, in contrast to a decline of 11% in the untreated mixtures. This reduction in stability can be attributed to the diminished adhesive properties between the aggregates and binder caused by prolonged exposure to heat and moisture. The findings underline the additive's effectiveness in enhancing both moisture resistance and mechanical performance, thereby demonstrating its potential for improving the durability and sustainability of asphalt pavements.

Keywords Anti-stripping · Asphalt · Boiling test · Durability index · Moisture damage · Retained stability

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Introduction

Asphalt concrete (AC) is one of the most common types of utilised pavement materials worldwide [3]. Nonetheless, the material is primarily influenced by environmental parameters, such as ageing and moisture transport in asphalt concrete pavements [10]. The combined impacts of the conditions and traffic loads result in several distresses, including potholes, stripping, fatigue and cracking, reducing the in-service life of asphalt pavements [12, 18]. AC stripping, poor mix durability, and short service life are some water damage effects on roadways [23]. AC stripping denotes adhesive bond depletion due to water infiltration into aggregate particles and asphalt binder interfaces [19, 23]. Moisture damage commences when liquid or water vapour transports into AC pavements through permeability, capillary rise, and diffusion [18]. The adhesion and cohesion bonding conditions in asphalt pavements are influenced by interface interactions, resulting in significantly complicated strength structural loss pathways [27]. Consequently, asphalt pavement moisture-induced damage is a primary concern of researchers and industries [24]. Various design and production parameters affect AC stripping, including aggregate, binder, and mixture attributes, and anti-stripping additives employment. Asphaltic mixtures contain 93–95% by weight and 75–85% by volume aggregates. Consequently, morphological characteristics of aggregates significantly influence asphalt mixture mechanical properties including resistance against moisture damage. Aggregate mineralogical attributes also significantly influence AMs moisture damage resistance [9, 23]. The mechanisms of moisture damage have been reported, focusing on decreased aggregates and binder bond strength. The investigations aimed to identify techniques to enhance and fortify the bond, effectively mitigating moisture impact [20]. Numerous reasons result in early water damage in asphalt pavements, including substantial void ratios at pavement sites, and other inherent factors, such as aggregate hydrophilic and oil-repellent characteristics and asphalt film emulsification [25]. The aggregates in asphalt blends are hydrophilic, facilitating water molecule displacements of asphalts at aggregate-asphalt interfaces. Consequently, translocations due to vehicle loading, lead to asphalt and aggregate surface adhesion damage [13, 17, 25]. Six theories have been proposed from microscopic assessments of the negative effects of water penetration into asphalt mixtures, alternatively referred to as stripping mechanisms or asphalt-aggregate system responses to moisture. Caro et al. [8], Mehrara and Khodaii [15] and Al-Saffar et al. [2]: extensively evaluated the six stripping mechanism theories and suggested a thorough explanation for each. For the separation or debonding hypothesis, asphalt films are detached from aggregate surfaces by a thin water layer without an observable break in the binders. On the other hand, material loss entails substance removals from aggregate surfaces facilitated asphalt film ruptures and/or potential aggregate/mastic separations. Cohesion weakening in asphalt binders or mastic due to prolonged diffusion periods, resulting in material loss in the presence of water flow is explained in the mastic dispersion theory. According to the film rupture and microcrack hypothesis, there are mastic or aggregate ruptures that are characterised by mechanical or thermodynamic properties. The desorption theory suggests that flow causes the outer mastic layers to be washed away, whereas spontaneous emulsification describes the inverted water droplet emulsions in binders.

Available asphalt mixture moisture damage resistance evaluations are divided into two processes [14]: assessments of adhesion between the asphalt and the aggregate followed by quantitative analyses of experimental indicators. The AASHTO T283/ASTM D4867 has been predominantly utilised for evaluating asphalt mix moisture damage susceptibility. Surface energy, pull-off, ultrasonic method, Bitumen bond strength, static immersion, rolling bottle (RBT), boiling water (BWT), modified boiling water, and total water immersion assessments have also been applied in conditioned and unconditioned asphalt specimen comparisons. Several anti-stripping agents have been applied to improve aggregate and asphalt binder bonds, which would reduce the notable negative effects of moisture [2] Nonetheless, the most commonly utilised approach is asphalt binder modifications with liquid antistripping agents [7, 19]. For example: Mirzababaei et al. [16] evaluated the water susceptibility-reducing efficacy of liquid nano-materials Zycosoil and Zycotherm. The report compared the results with mixtures modified with Portland cement and hydrated lime. The incorporation of 0.5% Zycotherm followed by 0.5% Zycosoil produced the most substantial moisture damage-reducing potential. Both liquid additives were more effective than complete filler replacements with Portland cement and hydrated lime.

Alam and Aggarwal [4] investigated the effects of incorporating silicon-based (ZycoTherm, WETBOND-S and WETBOND-ES) and amine-based (Super Bond A-99 and Bitubuild) into asphalt mixtures. The study also employed the modified Lottman, surface-free energy, and Texas boiling assessments. The anti-stripping agents reduced the moisture susceptibility of the asphalt mixtures evaluated in the report, with the addition of 0.05% ZycoTherm yielding optimal results. The effects of Evonik (0.1% and 0.3% of asphalt weight), ZycoTherm (0.1% and 0.3% of asphalt weight), and hydrated lime (1% and 2% of asphalt weight) against moisture damage on asphalt mixtures were established by Ameri et al. [6] via the Lottman and boiling evaluations. Based on the findings, 0.3% of Evonik, 2% of hydrated lime, and 0.1% of ZycoTherm documented considerable effects against damages due to moisture. Recently, Al-Saffar et al. [2] determined the characteristics of asphalt binders treated with an amine-free anti-stripping agent. According to the outcomes, incorporating the anti-stripping agent at 0.25–0.5% (by weight of the asphalt binder) considerably improved the tensile strength ratio (TSR) of the binder to 94.9%. The retained stability index of the anti-stripping agent-added samples in the report also exhibited a 98.1% increment, surpassing the 87.6% that of virgin asphalt.

Numerous advantages of anti-stripping agents are highlighted above, including enhanced adhesion and moisture resistance. But a closer look reveals serious flaws that prevent them from being widely used: (1) Environmental Concerns: During production and use, a number of conventional anti-stripping agents that are chemical based have environmental risks. Over time, these compounds might also break down into hazardous byproducts, (2) Compatibility Problems: Performance varies because different anti-stripping agents are not always compatible with different aggregates or binders. (3) Ageing Resistance: Although certain anti-stripping agents improve moisture resistance temporarily, they lose their efficacy when exposed to ageing and high temperatures over an extended period of time, (4) Cost-effectiveness: The high expense of high-quality anti-stripping agent (ASA) typically prevents their use in projects with tight budgets. (5) Performance Metrics: Few studies assess how anti-stripping agents affect other crucial pavement characteristics like fatigue life, susceptibility to rutting, and general sustainability.

The current study aimed to evaluate the effectiveness of an amine-free anti-stripping agent in enhancing the bonding between asphalt binder and aggregates in asphalt mixes. It is anticipated that the materials used in this study will successfully address common challenges related to adhesion failure and moisture damage. Its novel formulation tackles fundamental issues of compatibility, durability, and environmental sustainability. From a performance standpoint, the treated mixtures demonstrated improved resistance to moisture damage and aging, as evidenced by higher TSR and RSI values, and lower FDI and SDI values. Accordingly, physical tests were conducted to determine the optimal dosage of the agent, while analytical methods were used to assess the rheological properties of the modified binders. Moreover, the mechanical performance of the treated hot mix asphalt (HMA) was compared to that of unmodified mixtures through Marshall stability, immersion, indirect tensile strength (ITS), and moisture susceptibility tests, confirming the long-term efficacy and durability of the agent under wet conditions.

Materials and methods

Raw materials

The current study employed an asphalt binder of the 40–50 range penetration grade, which is the primary grade utilised in Iraq. The binder samples in this study were procured from the Ensaaf refinery. Table 1 summarises the binder attributes.

The aggregates utilised in the current study were obtained from an asphalt mix processing facility in Mosul, Iraq, while the mix was sourced from the Al Khazir region of the nation. The physical attributes of aggregates in asphalt are critical in the resultant composition blends, considerably affecting their performance. Table 2 summarises the predominant physical properties of the aggregates evaluated in this study.

The anti-stripping substance used in this investigation was the Sricote agent, which was developed by SRIPATH Innovation LTD. The material's key characteristics are summed up in Table 3. The Sricote agent contains silanes, which give asphalt mixtures exceptional adhesion and fuel resistance, according to the product's sheet data. The substance was created to lessen worker health and safety risks associated with the use of amino compounds as anti-stripping agents in asphalt mixtures and binders [26].

Table 1 Virgin asphalt's characteristics

Physical properties	Test condition	Value	Test condition	Standard specification
Penetration (1/10 mm)	25 °C, 100 gm, 5s	42	40–50	D-5
Specific gravity	25 °C	1.03	–	D-70
Softening point (°C)	Ring & ball	52	–	D-36
Ductility (cm)	25 °C, 5 cm/min	132	≥ 100	D-113
Rotational viscosity (CP)	135 °C	571	< 3000	D4402
	165 °C	145		

Table 2 Physical attributes of the aggregate

Aggregate properties	Fine aggregate	Coarse aggregate	ASTM specification
Bulk-specific gravity	2.58	2.63	–
Crushed percentage	–	95%	90% min
Water absorption	1.51%	0.37%	–
Apparent-specific gravity	2.67	2.71	–
Soundness	–	4.1%	18% max
Loss angeles abrasion	–	22%	45% max
Elongation	–	4%	10% max
Deleterious materials	–	1%	3% max

Table 3 Sricote technical data [26]

Property	Typical value
Specific gravity (g/cm^3)	1.07
pH	7
Color of liquid	Colorless
Boiling point (°C)	290
Potential health effects	Slight irritant upon contact with skin or eyes, or upon ingestion
Flash point COC, (°C)	> 150
Viscosity @ 24 °C, cp	75–125
Refractive index	1.4

Preparation of modified asphalt

Following the manufacturer's instructions, 0.3% of the Sricote anti-stripping agent was added to a virgin asphalt binder to create the treated samples used in this investigation. Firstly, unmodified asphalt was heated in a furnace to induce fluidity. Subsequently, 500 g of the fluidised asphalt was placed in the metal chamber of a mixer. To guarantee constant thermal conditions, the specimens in the chamber were placed on a heater and in a thermal jacket. Predetermined percentages of the anti-stripping agent were progressively added to the heated asphalt binder. Based on preliminary trial-and-error tests, the mixer was set to 135 °C and 500 rpm for 10–15 min, yielding a homogenous mixture.

Methods

Based on the Marshall assessment conducted, 4.4% was the ideal amount of asphalt binder (OAC). On the other hand, the effectiveness of the anti-stripping agent and its resistance against water susceptibility was evaluated through the modified Lottman test (AASHTO T283). The evaluation has been widely employed by researchers.

In this study, 6 samples from each asphalt binder mixture were prepared and compacted until 7 ± 0.5% air void was obtained. Subsequently, the samples were segregated into dry and partially saturated. The partially saturated samples were immersed in distilled water for several minutes at 25 °C and 70 kPa pressure in a vacuum vessel. The saturation levels of the partially saturated samples were determined by dividing the volume of water absorbed (Vs) by the volume of voids (Vv). The saturation levels were presented in %value. According to the ASTM standards, asphalt binder saturation levels must be between 55 and 80%. In this study, the partially saturated samples were soaked in a water bath for 24 h at 60 °C before being immersed for another hour in a water bath at 25 °C. Conversely, the dry subset was submerged in a water bath at 25 °C for 20 min.

A 50.8 mm/min loading rate was applied in the tensile splitting evaluations conducted in this study. Subsequently, the maximum load at failure was determined to obtain the ITS at 25 °C and 60 °C according to Eq. (1). The wet specimen-to-dry specimen tensile strength ratio (TSR) was established by assessing the moisture sensitivity of the asphalt mixes according to the AASHTO T283 guidelines [1].

$$\mathrm{ITS} = 2000\,\mathrm{P}/\pi \mathrm{dh} \tag{1}$$

where,

ITS = Indirect tensile strength (kPa)
P = maximum load (N)
h = specimen height (mm)
d = specimen diameter (mm)
π = 3.14

The ASTM D3625 assessment procedure was employed to establish the stripping capabilities of the non-compacted asphalt-coated aggregate mix under boiling water in this study. During the Texas boiling test, 250 g of the asphalt-coated aggregates were placed in boiling water at 85–95 ℃) for 10 min, 15 min, and 20 min ± 15 s. The glass beaker was removed from the heat source at the end of 10 min, 15 min, and 20 min. Any free bitumen on the water surfaces was skimmed to prevent aggregate recoating.

The wet mix was poured onto a white towel after the samples had cooled to room temperature. The process was repeated twice to obtain three replicates. The amount of asphalt coating retained on the aggregates was visually observed and rated as under or over 95%. The current study utilised the MATLAB software to obtain accurate results. Accordingly, digital photographs were taken of the non-compacted samples before and after the boiling test. The samples were then subjected to several processes to clearly distinguish between stripped areas and binder-covered spots. The stripped area percentage was automatically calculated by the MATLAB software.

An improved water immersion evaluation [21] was conducted to assess the stripping ratio of the asphalt samples in this study. The assessment is widely utilised for establishing asphalt-aggregate adhesion levels. First, 5 cleaned and coarse aggregates were dehydrated at 105 ℃ for 3 h before measuring their mass (m_1). Subsequently, the coarse aggregates were soaked in hot asphalt between 155 and 165 ℃. The samples were cooled at room temperature for 1 h. The total mass of aggregates coated with asphalt (m_2) was determined.

The cooled asphalt-coated aggregates were placed on a dry and clean tray in an electric thermostatic water bath at 90 ℃ for 3 h. After removing the tray from the water bath, the aggregates were delicately removed from the tray with pincers. A weighing paper was employed to contain the aggregates to prevent asphalt loss during heating and the samples were oven-desiccated at 105 ℃ 3 h. The total water-immersed aggregates coated with asphalt (m_3) mass was then determined. Equation (2) was employed to establish the asphalt stripping ratio (γ).

$$\gamma = \frac{m2 - m3}{m2 - m1} \tag{2}$$

where γ is the asphalt stripping ratio and m_1, m_2, and m_3 are the total masses of water-immersed asphalt-coated aggregates, asphalt-coated aggregates, and dried aggregates, respectively.

The Marshall immersion assessment performed in this study was a continuation of the Marshall evaluation. The analysis assessed the moisture sensitivity and the durability of the asphalt mixtures. The ability of the mixtures to withstand the effects of water and temperature was determined during the evaluation. The samples were exposed to hot water at 60 °C for 30 min, 24 h, and 48 h periods. In this study, 3 groups of three samples were employed. The samples in the first category were designated as unconditioned and were immersed in a water bath at 60 ± 1 °C for 30 min. On the other hand, the second and third sets were immersed for 24 h and 48 h, respectively. The groups were classified as conditioned. All three groups were assessed under a 50 ± 5 mm/min constant compression rate until failure.

Primarily, asphalt pavement durability assessment is based on strength or stability loss. The data is typically expressed as an index. The indexes utilised for establishing pavement durability are the retained strength index (RSI) (Eq. 3), the first durability index (FDI), and the second durability index (SDI) (Eqs. 4 and 5) [22]. According to the RSI, a small index value indicates less pavement durability. Conversely, a high durability index (DI) value when indicates a significant strength or stability loss in the pavement evaluated [11]. An experimental workflow is displayed in Table 4.

$$\mathrm{RSI}(\%) = \frac{S_i}{S_0} \tag{3}$$

where;

RSI = Retained Strength Index (%)

Si = stability after immersion at time t_i or stability of the conditioned specimen

S_0 = stability before immersion or stability of the unconditioned specimen

Table 4 Infographic table of experimental workflow

Stage	Details	No. of specimens
Mix types	Virgin asphalt and treated asphalt (0.3% amine-free anti-stripping agent)	–
Mixing conditions	135 °C, 500 rpm, 10–15 min ➤ *To achieve homogeneous mixture*	–
ITS (indirect tensile strength)	at both 25 °C and 60 °C	12
TSR (tensile strength ratio)	Moisture sensitivity evaluation	6
Texas boiling test	at 90 °C for 10, 15, and 20 min ± 15 s	18
Image processing (MATLAB)	Digital images before & after boiling-Automatic stripping area percentage calculation	–
Improved water immersion	Enhanced visual evaluation	6
Marshall immersion test	Samples immersed in 60 °C water for: 30 min, 24 h, 48 h	18
RSI (retained strength index)	Long-term retained strength evaluation	–
FDI (first durability index)	Initial durability measurement	–
SDI (second durability index)	Extended durability measurement	–
Total samples		60

$$FDI = \sum_{i=0}^{n-1} \frac{S_i - S_{i+1}}{t_{i+1} - t_i} \tag{4}$$

$$SDI = \frac{1}{t_n}\sum_{i=0}^{n-1} A_i = \frac{i}{2t_n}\sum_{i=0}^{n-1}\left(S_i - S_{i+1}\right) \times [2t_n - (t_{i+1} - t)] \tag{5}$$

where;

FDI = First Durability Index, S_i = percent retained strength at time t_i, S_{i+1} = percent retained strength at time t_{i+1}, SDI = Second Durability Index, t_i, ti_{+1} = immersion times , t_n = total duration of immersion, A_i = represents the square of lost strength for i immersion period.

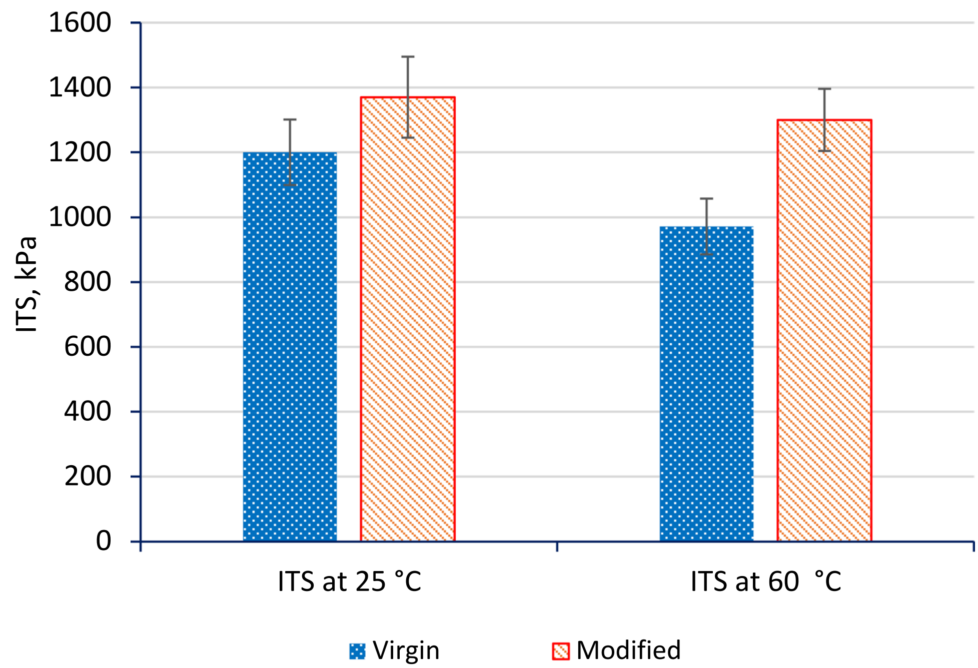


Fig. 1 ITS unconditioned and conditioned after 24 h

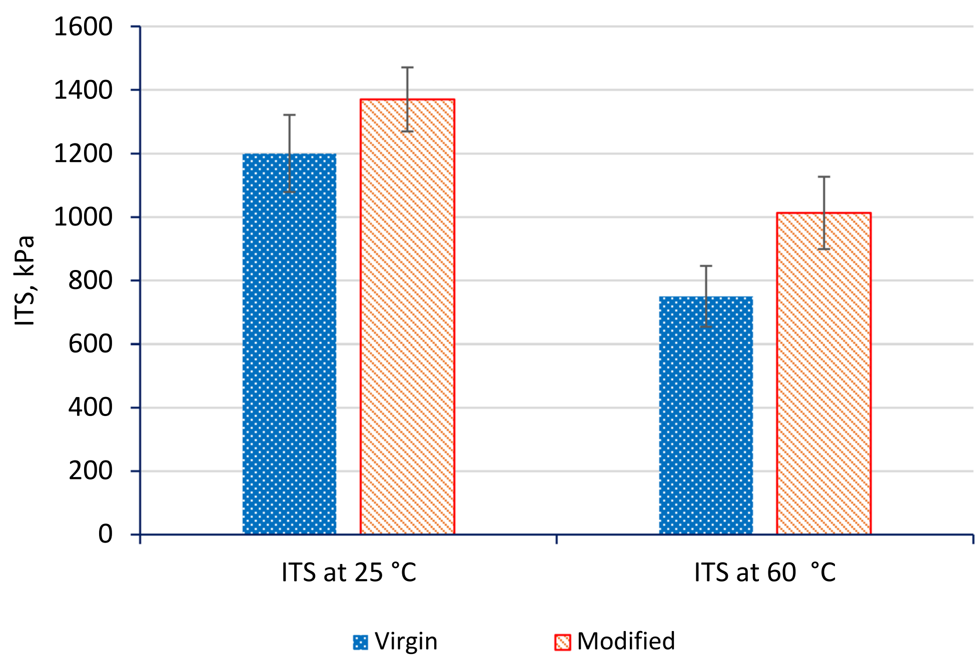
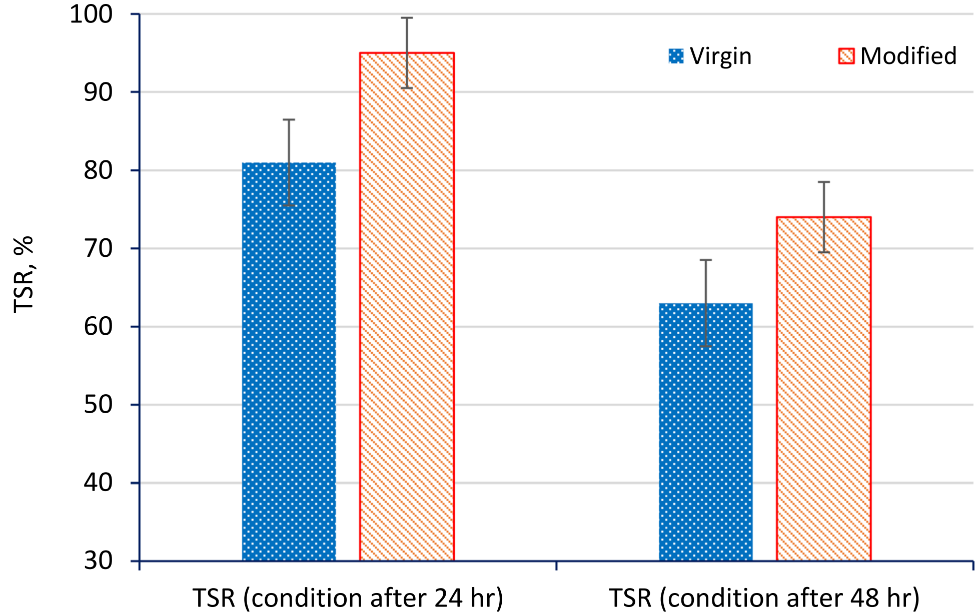


Fig. 2 ITS unconditioned and conditioned after 48 h

Fig. 3 TSR value of asphalt mixtures



Results

ITS and moisture damage

Figures 1, 2, and 3 illustrate the ITS of the conditioned (24 h and 48 h) (wet) and unconditioned (dry) asphalt mixture samples assessed in this study. The results showed patterns in the asphalt mixtures' mechanical characteristics after they were exposed to different circumstances and liquid anti-stripping agent treatments. The ITS of the conditioned asphalt mixes was lower than that of the dry samples, as shown in Fig. 1. Similarly, the ITS of the 48 h conditioned asphalt was consistently below its 24 h counterpart. The disparity underscored the adverse impacts of water on asphalt binder and aggregate particle adhesion. Water weakens the bond between the binders and aggregates in asphalt mixes, resulting in diminished tensile strength [2] as evidenced by the TSR of the 48 h conditioned samples. Accordingly, moisture damage is directly correlated to TSR, where a mix with a higher value will experience less moisture damage than the blend with a low TSR.

TSR values of over 80% are required for Superpave production. The addition of 0.3% of the amine-free anti-stripping agent into the asphalt mixtures in the current study yielded the highest TSR value among the specimens. The treated asphalt mixtures recorded 95% TSR compared to 81% documented by virgin mixtures in the 24 h conditioned category. The 48 h conditioned blends had 74% TSR. The notable improvement in TSR was ascribable to the pivotal role of the anti-stripping agent role in fostering a robust asphalt binder and aggregate particle bond, even with water present. In detail, this marked improvement is primarily attributable to the anti-stripping agent's ability to enhance the chemical affinity and interfacial adhesion between the asphalt binder and the aggregate surfaces. The novel additive contains polar functional groups capable of forming strong physicochemical bonds with the mineral surfaces of the aggregates, which are often hydrophilic in nature. These interactions help displace water molecules from the aggregate surface, thereby reducing the potential for moisture-induced debonding. Moreover, the additive's surface-active properties help it function as a compatibilizer, improving the wettability and coating ability of the binder on aggregate surfaces, especially in the presence of moisture. This leads to a more uniform film of asphalt that resists stripping forces. The performance under extended conditioning (48 h) further highlights the durability of the modified bond, indicating that the additive sustains its effect even as moisture exposure duration increases.

The course aggregate boiling assessment

In the study, the boiling evaluation was utilised to assess stripping and the strength of binding between asphalt and aggregates. The evaluation allowed visual examination of accelerated moisture damage of aggregate-coated asphalt. Figure 4 demonstrates the stripping of asphalt binder from aggregate during the boiling evaluation. The performances of the non-treated and anti-stripping agent-treated samples after 10 min, 15 min, and 20 min are summarised in Table 5.

The boiling assessment was performed to visually determine any potential binder-aggregate adhesion improvements on the samples. The images captured after the evaluation were processed with MATLAB to aid in properly differentiating between the coated and non-coated aggregates. An example of the image processing procedure is illustrated in Fig. 5.

Fig. 4 Coarse aggregate mixture images during the test

Table 5 Boiling test results

Mixture type	Virgin%	Modified%
Stripping ratio after 10 min	55.21	3.32
Stripping ratio after 15 min	61.54	8.44
Stripping ratio after 20 min	70.87	10.71

Based on the results, virgin sample surfaces were notably prone to stripping and recorded the largest stripped area. Nonetheless, incorporating the anti-stripping agent yielded smaller stripped surfaces, indicating an improved moisture resistance when the SriCote agent was applied. The treated samples exhibited 10.71% stripping compared to the 70.87% documented by the non-treated samples (see Fig. 5). The stripping percentages of each sample were established by dividing the stripped surface area by the total surface area of the sample [5]. After 20 min of the boiling test, the coarse virgin sample aggregates were observed to be free of binder coating. The finding revealed that there is a very weak bonding between the virgin asphalt and aggregate, due to the bad quality of virgin asphalt.

As a result, the water inclusion decreased the asphalt-aggregate interface adhesion in virgin samples. The correlation between stripping ratios and adhesion highlights the critical role of anti-stripping agents in improving the asphalt-aggregate bond. The mechanisms of the bond enhancement by the anti-stripping agent correlate with molecular dynamics at the asphalt-aggregate interface. Introducing anti-stripping agents promotes a transformative molecular architecture that mitigates moisture-induced debonding in asphalts.

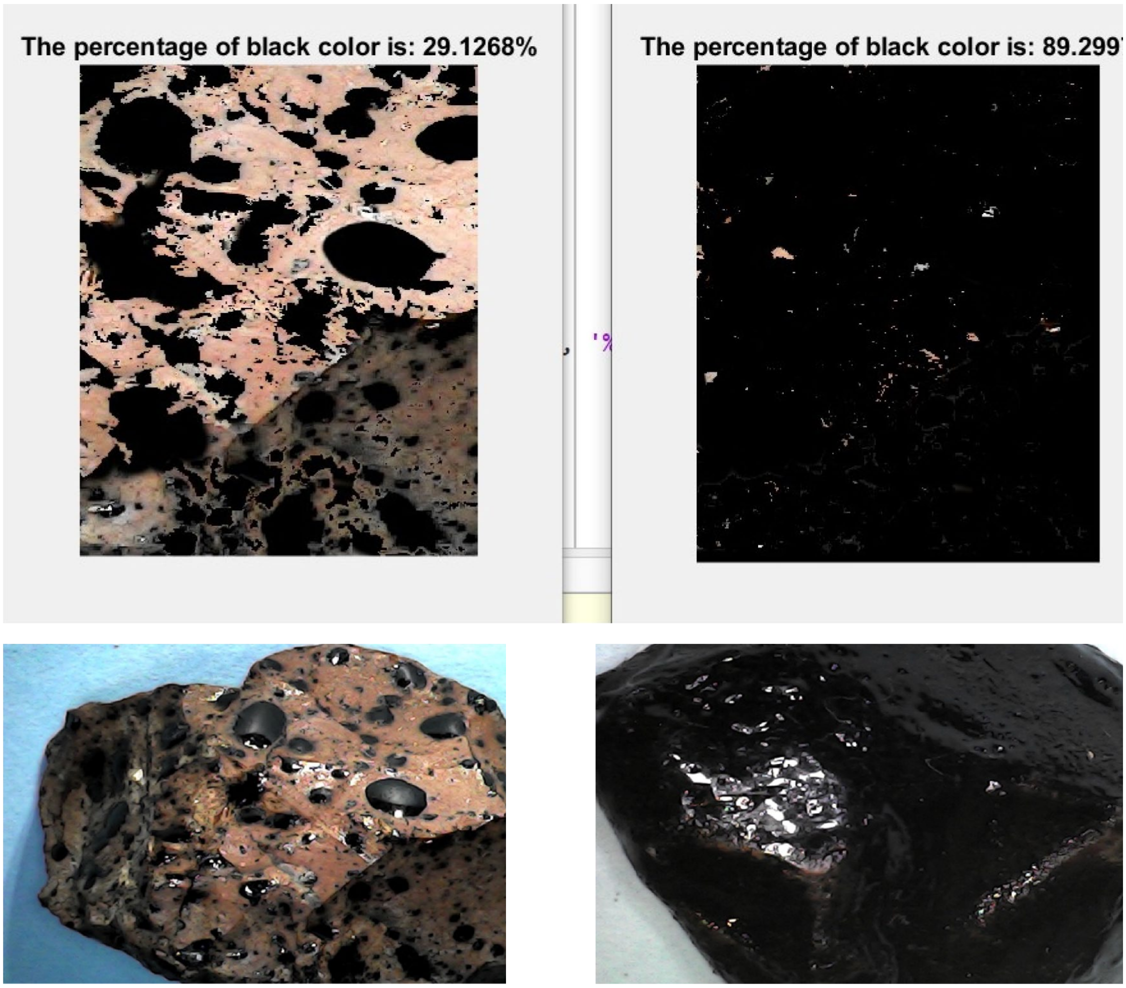
The findings from the water immersion assessment supported TSR results. Figure 6 demonstrates the link between stripping ratio and time. The samples incorporated with the anti-stripping agent were less affected by boiling time than the virgin samples. The addition of 0.3% of the anti-stripping agent effectively reduced the stripping characteristic and moisture susceptibility of asphalt for pavement durability purposes. The finding was attributable to the enhanced adhesion of asphalt binder through the inclusion of the agent.

The asphalt mixture aggregate boiling evaluation

Asphalt mixture moisture damage failures are categorised as adhesive or cohesive. Failures due to the detachment of asphalt films from the aggregate bonding (adhesion) loss are known as stripping. On the other hand, cohesive failures occur due to loss in bonding within asphalt matrixes. Table 6 and Fig. 7 demonstrate the boiling results. The assessment was conducted to ascertain the resistance of the asphalt-coated aggregate against stripping. Visually, the heated samples were dull, whereas their non-heated counterparts appeared shiny. The dull appearance was due to the loss of asphalt from the aggregates during heating. Subsequent image analyses indicated that the conventional HMA recorded over 5% aggregate coating loss. Consequently, the mix obtained an under 95% retained bitumen coating rating. Greater stripping area ratios denote increasing ease of asphalt mastic film water displacements from aggregate surfaces [28].

Visual observations of the non-treated samples in this study revealed that moisture-induced damages could be roughly divided into five stages. The first phase is asphalt membrane thickness reduction. In the second stage, the asphalt membranes are partially stripped. Large-scale asphalt membrane stripping and partial mortar stripping of mortar denote stages three and four. In the final phase, the weak mortar is severely stripped. The findings agreed with the data reported by Xu et al. [29] (see Fig. 8).

Conversely, the treated mixtures retained 100% asphalt coating, revealing that the samples were not susceptible to stripping damage. The addition of the anti-stripping agent to the mixtures improved their binder adhesion properties, providing enhanced moisture resistance. Based on the coating retention rates, the virgin HMA evaluated in the current study recorded below 95%, while the treated HMA had over 95%. Although the evaluation provided asphalt mixture stripping potential assessment, notable differences were only observed between the HMA and the treated samples.



Untreated asphalt after boiling

Treated asphalt after boiling

Fig. 5 Coarse aggregate mixture images after boiling

Nevertheless, the findings supported the TSR and boiling data of the coarse samples.

Improved immersion test

The improved water immersion results are demonstrated in Table 6 and Fig. 9. The data provided the stripping ratios of the asphalts assessed. Based on Table 7, the virgin asphalt stripping ratios surpassed the treated samples, affirming the efficiency of the anti-stripping agent in enhancing adhesion. The treated samples recorded a 45% stripping ratio, while the virgin samples had 65%. The inverse correlation between stripping ratios and adhesion indicates the crucial role of anti-stripping agents in improving the bond between asphalt and aggregates.

The introduction of anti-stripping agents induces molecular realignment, providing a formidable defence against the negative effects of water, and preserving the asphalt-aggregate matrix integrity. Nonetheless, the concentration of anti-stripping agents employed requires careful consideration.

Marshall immersion test

Figure 10 illustrates the stability outcomes across varying immersion durations applied in the present study. The treated unconditioned samples, which were immersed for 40 min, exhibited the highest stability, recording 15.6 kN, in contrast to the 13.72 kN of the untreated samples. Nevertheless, the value decreased across all mixtures with increasing immersion periods. The decline might be due to diminished adhesive properties between aggregates and asphalt binders from heat and water exposure.

Following 24 h of immersion, stability values obtained in the current study demonstrated decrements of 11% and 3.2% for the untreated and treated mixtures, respectively, relative

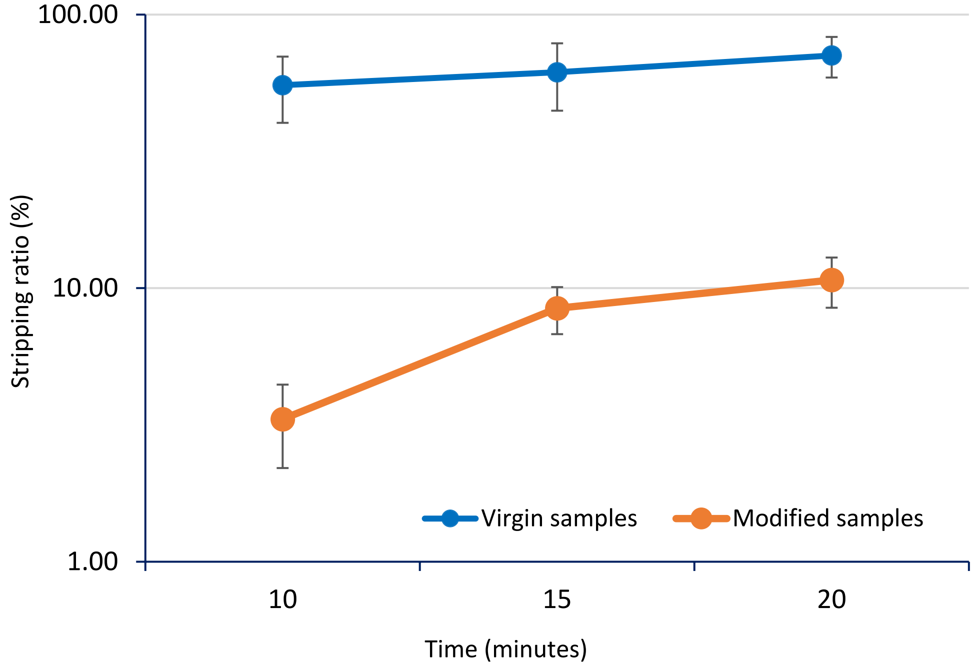


Fig. 6 The relationship between stripping ratio and time

Table 6 Asphalt mixture's retained asphalt coating after stripping test

Mixture type	Virgin HMA	Treated HMA
Rating		
Below 95%	***	
Above 95%		***

to the unconditioned samples. Reductions of 13.9% and 7.6% were also observed for untreated and treated mixtures, respectively, when compared to the unconditioned samples after an 18 h immersion. The Marshall stability results indicated that treated mixtures outperformed their untreated counterpart. The findings suggested that the anti-stripping agent improved the resistance of the asphalt binder against the deleterious effects of water and heat.

RSI values of the samples assessed in the present study are presented in Fig. 11. A notable enhancement was observed in the treated mixtures, which achieved 96.8% and 92.3% RSI values after being immersed for 24 h and 48 h, respectively. In contrast, the untreated asphalt mixture yielded 88.9% and 86% RSI values when immersed for similar durations. The improved RSI in the treated samples is a direct result of the strengthened adhesive forces between the asphalt binder and aggregate surfaces. The anti-stripping agent likely facilitated better interfacial adhesion through chemical interactions such as hydrogen bonding or electrostatic attraction, particularly with siliceous aggregates. These bonds reduce the likelihood of binder displacement by water molecules, thereby maintaining cohesive strength. This improvement can be attributed to the chemical interaction between the additive and both the binder and aggregate

Treated asphalt after boiling Untreated asphalt after boiling

Fig. 7 Asphalt mixture images after boiling

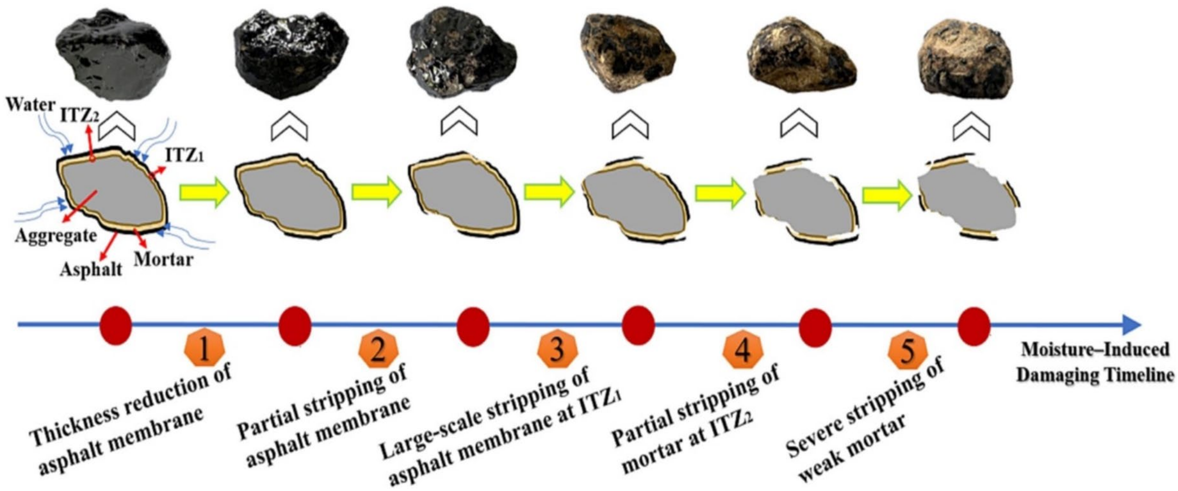


Fig. 8 Moisture-induced damaging timeline [28]

Fig. 9 Microscopic image of virgin samples after test

Table 7 Asphalt stripping ratio in the enhanced water immersion test

Asphalt/anti-stripping asphalt	Stripping ratio of asphalt (%)
Virgin asphalt (VA)	65
0.3% anti stripping agent + VA	45

surfaces. The agent's polar functionalities likely form strong ionic or hydrogen bonds with the mineral components of the aggregate, thus minimizing the susceptibility of the asphalt film to water displacement. As a result, the cohesive and adhesive properties of the asphalt mixture are preserved, even after prolonged exposure to water.

Furthermore, the durability indexes, namely the Fatigue Durability Index (FDI) and Stiffness Durability Index (SDI), presented in Fig. 12, also underscore the enhanced performance of the modified mixtures. The FDI of the treated asphalt blends decreased to 7.7%, compared to 13.9% for the untreated samples. Likewise, the SDI dropped to 4.2% in the treated mixtures, while the control group registered 4.99%. The reduction in FDI indicates that the treated mixtures experienced less deterioration in fatigue life after moisture exposure, suggesting better load distribution and energy dissipation under repeated loading. Similarly, the lower SDI implies that the stiffness of the treated mixtures remained more stable, meaning the asphalt retained its structural resistance without excessive softening or embrittlement.

Lower values of both FDI and SDI indicate reduced degradation in fatigue resistance and stiffness, respectively, after moisture conditioning. This implies that the anti-stripping agent not only improves initial moisture resistance but also

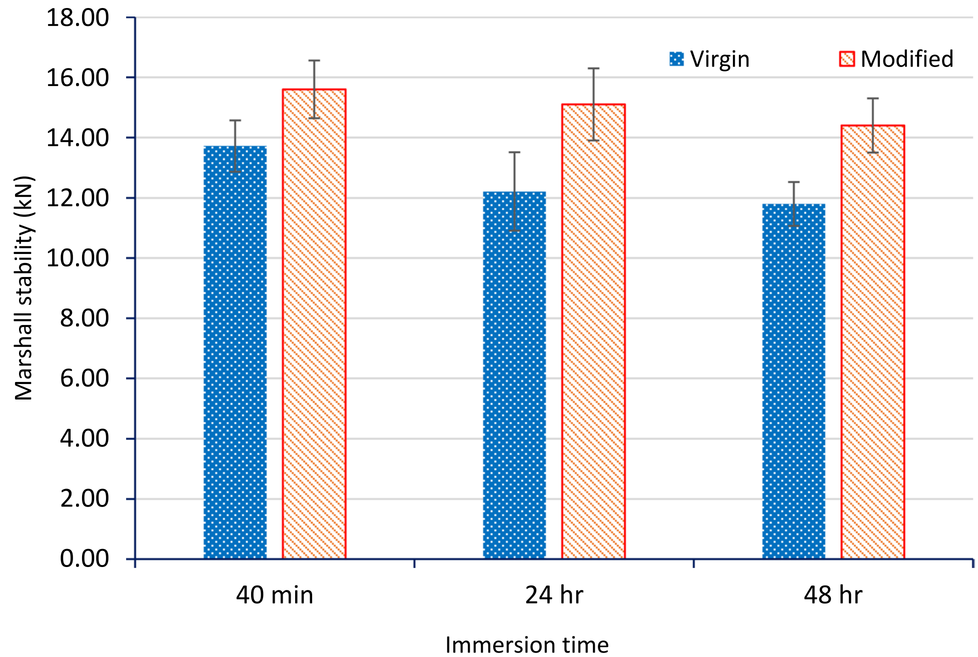


Fig. 10 Marshall stability test results

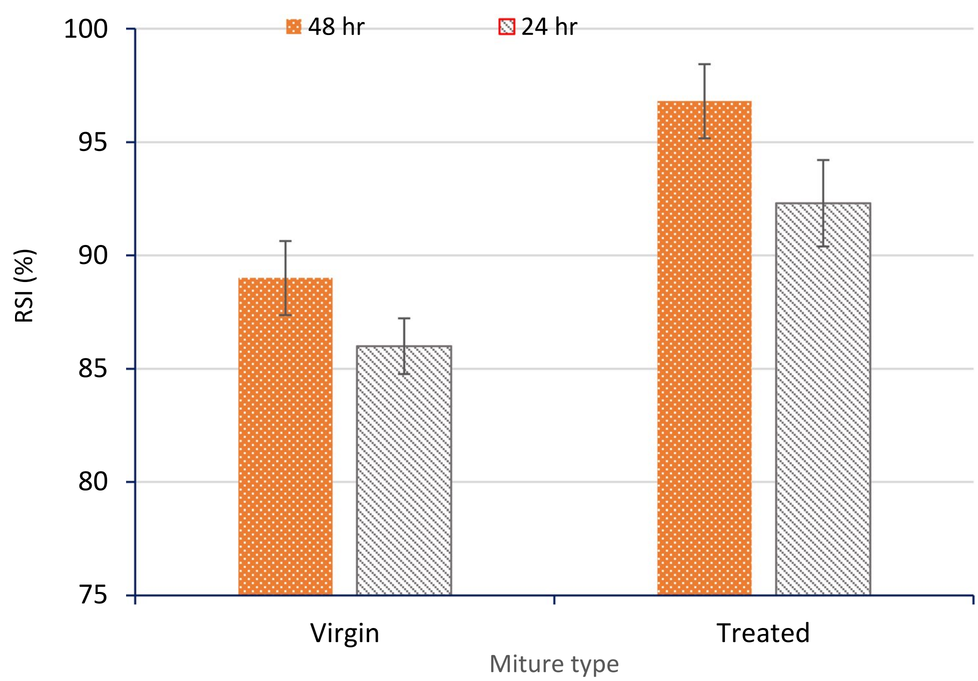


Fig. 11 RSI test results

preserves the long-term functional characteristics of the mixture. This long-term benefit is particularly important for pavements in humid or water-prone environments, where repeated cycles of wetting and drying, combined with traffic loading, can accelerate stripping and mechanical failure. The consistent performance across both short- and extended conditioning durations reflects the chemical stability and strong binder-aggregate interaction promoted by the additive.

According to the previous results, the anti-stripping agent's ability to improve the adhesion between the aggregate and binder in the presence of water demonstrates its effectiveness in preventing moisture damage. However, polar interactions with the aggregate surface are how conventional amine-based anti-stripping agents accomplish this. However, due to worries about their toxicity and volatility, amine-free substitutes, like silane-based additives, have been developed. Organosilane compounds, which work via covalent and hydrogen bonding mechanisms, are present in the Sricote agent used in this investigation. Silanes, which have the general structure R–(CH_2)n–$Si(OR')_3$, are hybrid

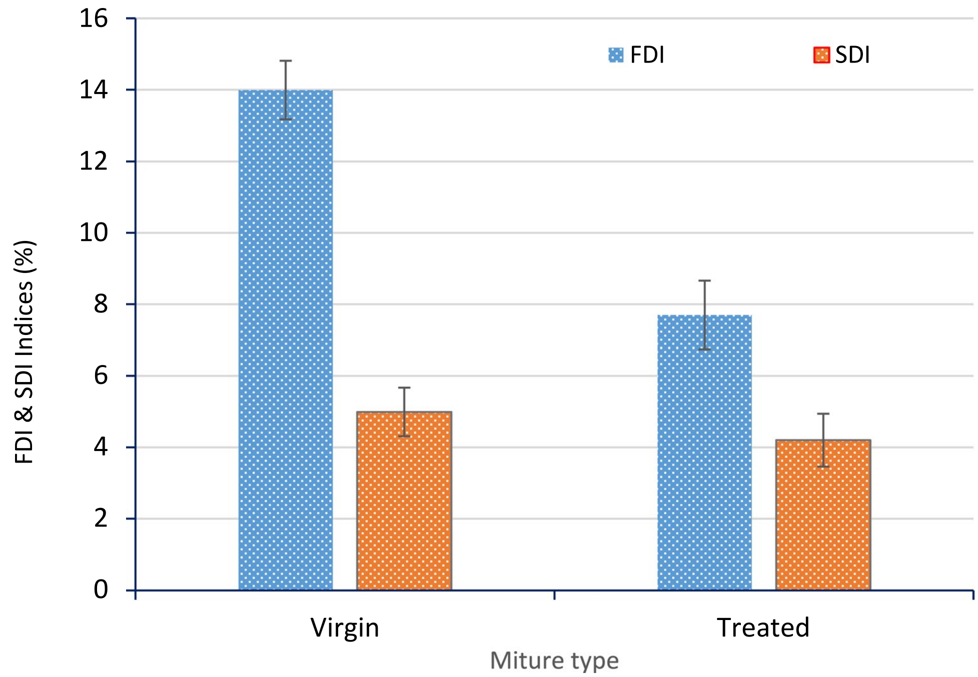


Fig. 12 FDI & SDI test results

organic–inorganic molecules. When silanes are applied, they hydrolyse to produce silanol groups (Si–OH), which can condense with hydroxyl groups on mineral aggregate surfaces to create long-lasting siloxane bonds (Si–O–Si). Concurrently, the silane molecule's organofunctional side (R group) shows compatibility with the organic asphalt binder, encouraging chemical bridging between the non-polar bituminous matrix and the polar mineral surface. By greatly increasing interfacial adhesion, this dual reactivity lessens the binder-aggregate bond's vulnerability to moisture-induced stripping.

Conclusions

An environmentally friendly, amine-free anti-stripping additive intended to enhance binder–aggregate adhesion for asphalt mixtures and preserve consistent performance across a range of materials was assessed in this study. The following conclusions were drawn in light of the experimental analyses:

1. Improved binder–aggregate adhesion was confirmed by the boiling test results, which revealed that treated samples had substantially less stripping (10.71%) than virgin mixtures (70.87%). This improvement was confirmed by MATLAB image analysis, which also demonstrated the anti-stripping agent's ability to lessen moisture-induced damage.
2. Boiling water and water immersion tests revealed that asphalt mixtures containing 0.3% of the amine-free anti-stripping agent had significant stripping resistance. The enhanced performance is ascribed to the additive's improved adhesion between the asphalt binder and aggregates, confirming its efficacy in enhancing pavement durability.
3. Improved TSR values show that the anti-stripping agent greatly increased the asphalt mixtures' resistance to moisture. After 24 h of conditioning, treated mixtures had a TSR of 95%, while 48 h conditioned blends kept a respectable 74% TSR, while virgin mixtures had a TSR of 81%. This significant improvement is ascribed to the liquid anti-stripping agent's vital function in fortifying the bond between the aggregate particles and asphalt binder, especially when water is present.
4. In comparison to the untreated asphalt mixtures, the treated asphalt mixtures displayed lower FDI (7.7%) and SDI (4.2%) values, suggesting increased durability. This demonstrates how well the additive works to maintain long-term performance in environments that are prone to moisture.
5. When compared to untreated samples, the treated asphalt mixtures showed noticeably higher RSI values (96.8% at 24 h and 92.3% at 48 h). Stronger binder–aggregate adhesion made possible by the anti-stripping agent is responsible for this improvement.

Recommendation

Despite the advantages of the anti-stripping agent employed in this study, further investigations and field performance evaluations, particularly regarding the short and long-term effects of ageing, are necessary. Furthermore, advanced performance and molecular-level anti-stripping-binder interaction evaluations could provide more comprehensive insights into the binder modifications observed. Future studies should also establish the surface-free energy (SFE) and binder bond strength (BBS) of asphalt pre and post-ageing to comprehend the bonds and interactions between aggregates and rejuvenated asphalts.

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Data availability All data available in the study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This manuscript has not been published in whole or in part elsewhere: the manuscript is not currently being considered for publication in another journal.

Consent for publication Not applicable.

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