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Exploring the Efficacy of Amine-Free Anti-Stripping Agent in Improving Asphalt Characteristics

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Abstract: This research addresses the significant challenge posed by early water damage in highway asphalt pavement, a critical concern affecting pavement service performance. To counteract this issue, the utilization of anti-stripping agents in asphalt is explored as a highly effective technical intervention. In this investigation, a carefully selected amine-free additive was employed to modify the asphalt binder. A comprehensive array of physical and rheological tests, covering aspects such as storage stability, penetration, softening point, ductility, elastic recovery, rolling thin-film oven, retained penetration, the ductility of residue, and rotational viscometer assessments, were conducted to examine the multifaceted impact of the anti-stripping agent on the asphalt binder. Additionally, we assessed the asphalt mixture's sensitivity to moisture through Marshall stability tests after conditioning for 40 min and 24 h, followed by an enhanced immersion test and moisture susceptibility measurement. The results reveal a nuanced interplay of chemical and physical mechanisms influencing the behavior of the asphalt binder. Notably, the incorporation of an anti-stripping agent at a concentration of 0.25–0.5% (by weight of asphalt binder) led to a substantial improvement in the tensile strength ratio (TSR) to 94.9%, a noteworthy enhancement compared to the 80.6% observed with virgin asphalt mixture. Furthermore, the retained stability index (RSI) exhibited a remarkable increase to 98.1%, surpassing the 87.6% recorded for virgin asphalt. This study not only provides crucial insights into the intricate dynamics of asphalt binder performance but also emphasizes the pivotal role of anti-stripping agents in augmenting the structural integrity and resilience of asphalt pavement.

Keywords: asphalt; anti-stripping; adhesion properties; moisture damage; retained stability

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Citation: Al-Saffar, Z.H.; Mohamed Hasan, H.G.; Oleiwi Aletba, S.R. Exploring the Efficacy of Amine-Free Anti-Stripping Agent in Improving Asphalt Characteristics. *Infrastructures* **2024**, *9*, 25. https://doi.org/10.3390/infrastructures9020025

Academic Editor: Marjan Tusar

Received: 3 December 2023
Revised: 22 January 2024
Accepted: 29 January 2024
Published: 31 January 2024

1. Introduction

Asphalt pavements serve as the fundamental infrastructure for transportation, enduring daily challenges from traffic loads and environmental fluctuations. Over time, these pavements may experience various issues, such as permanent deformation, cracking, and moisture damage [1]. Among these concerns, moisture damage, arising from the presence of moisture within asphalt pavements, stands out as a significant issue. This manifests as the detachment of aggregate and asphalt binder, commonly referred to as the "stripping phenomenon." This occurrence often leads to cracking, shoving, and ravelling of the asphalt pavement layer [1–3], ultimately impacting the service life and functionality of the pavement [4]. Multiple factors play a crucial role in influencing the stripping of asphalt mixtures. These include the chemical composition and gradation of aggregates, the type and quantity of the binder, the modifier, the air void (Av) content of the mixtures, and the type/quantity of anti-stripping agent [2]. A comprehensive understanding of these mechanisms is necessary for alleviating the harmful effects of moisture damage. The adhesion between binder and aggregate, induced by cohesive and adhesive forces, significantly contributes to preserving the integrity of pavements [5]. The extent of adhesion failure within the mixture depends on the adhesion degree between the binder and aggregates [6]. In addition, the quality of the asphalt mixture constituents play a pivotal role in determining adhesion strength [7].

Previous studies examined the mechanisms underlying moisture damage, focusing on decreasing the bonding strength between the aggregates and the binder. These investigations aim to identify methods of enhancing and fortifying this bond to effectively mitigate the impact of moisture [8]. The causes of early water damage in asphalt pavements are diverse. In addition to the substantial void ratio at the pavement site, the issue is intricately linked to other inherent factors. These factors include the hydrophilic and oil-repellent characteristics of the aggregate, along with the emulsification of the asphalt film itself [9]. The hydrophilic nature of the aggregate is particularly noteworthy, as it facilitates the easy displacement of asphalt by water molecules at the aggregate–asphalt interface. This displacement, occurring under vehicle loading, leads to the destruction of adhesion between the asphalt and the aggregate surface [9–11]. The microscopic repercussions of water penetration into asphalt mixtures have been extensively examined, resulting in the development of six theories. These theories are alternatively referred to as stripping mechanisms in some research and characterized as the asphalt–aggregate system response to moisture in others. Caro and her colleagues have synthesized an extensive survey of these theories, offering a thorough elucidation for each [3,12]: "(a) Separation (debonding): Involves the detachment of an asphalt film from an aggregate surface, occurring through a thin layer of water, without an observable break in the binder layer. (b) Material loss: Entails the removal of substance from the aggregate surface, facilitated by a rupture in the asphalt film and/or potential separation of the aggregate/mastic. (c) Mastic dispersion: Encompasses the weakening of cohesion in the asphalt binder or mastic due to prolonged diffusion periods, resulting in the loss of material in the presence of water flow. (d) Film rupture and micro-crack: Involves ruptures in the mastic or aggregates, characterized by either a mechanical or thermodynamic nature. (e) Desorption: Signifies the washing away of outer layers of mastics due to the presence of flow. (f) Spontaneous emulsification: Refers to the inverted emulsion of water droplets in binders".

Meanwhile, diverse approaches have been utilized to assess the adhesive properties of asphalt binder to aggregates. For instance, methods like the tensile strength ratio (TSR), Marshall stability (retained stability index), and water immersion tests [13] have been implemented. These assessments aim to determine the asphalt binder's susceptibility to strip from aggregates when exposed to moisture. The onset point in these tests signifies the quality of adhesion. Additionally, techniques involving surface free energy (SFE) measurements, such as contact angle measurements [14], offer insights into the wetting of asphalt binder and its adhesion to aggregates [15,16]. By employing these evaluations, and adhering to relevant standards, a comprehensive analysis of asphalt binder–aggregate adhesiveness is ensured, contributing to effective pavement performance.

The primary approach to enhancing the water damage resistance of asphalt mixtures revolves around improving the adhesion between the asphalt and aggregate [17]. The conventional method involves the addition of an anti-stripping agent to asphalt [17–20]. Anti-stripping agents facilitate physical adsorption or chemical reactions between the asphalt and aggregate, resulting in a robust asphalt–aggregate interaction interface [21]. This notably enhances the water damage resistance of asphalt pavements [9,22]. Various anti-stripping materials have been widely employed to fortify the bond between the aggregate and asphalt binder, aiming to alleviate the detrimental effects of moisture. These materials include: lime, Portland cement, liquid anti-stripping agents [21], warm mix asphalt additives [23], liquid antistrips (amino–functional silanes) [7,24], emulsified asphalt [25], warm mix asphalt (WMA) technologies [26], nano-engineered anti-stripping agents [27], polymer modifiers [7], terpolymer-based additives [28], sulfur-based anti-stripping agents [29], epoxy-based anti-stripping agents [30], amine-based anti-stripping agents [31], passive adhesion promoters (PAPs) and active adhesion promoters (AAPs), amines, poly-amines, and amido–amine adhesion promoters (AMAPs) [32], in addition to the Tack coats or bond coats, and polymer-modified asphalt binders. Keep in mind that the selection of an anti-stripping agent is contingent upon the particular project, prevailing environmental conditions, and the specific types of aggregates and asphalt binders being employed. Furthermore, a promising approach for enhancing asphalt–aggregate affinity involves the utilization of waste plastic to pre-coat aggregates, resulting in the production of hydrophobic aggregate [33]. Sarkar et al. [34] investigated the asphalt mixtures made by plastic-coated overburnt brick aggregate and results exhibited a noteworthy positive impact, contributing to a 9% increase in tensile strength ratio. More recently, Xiao et al. [15] introduced a novel coating technology, termed thermoplastic polyethylene powder coating (TPPC), for the pre-treatment of aggregates in asphalt mixtures using polyethylene powder.

Nevertheless, the effectiveness of these substances may fluctuate depending on the particular application and environmental considerations. Common constraints linked to various types of anti-stripping agents encompass their diminished efficacy at elevated temperatures, potential compatibility issues with asphalt binders, performance challenges under extreme temperature variations, uncertainties regarding their prolonged effectiveness and environmental ramifications, and the possibility of a reduced performance due to incompatibility. These limitations may result in an inconsistent performance across diverse conditions and insufficient long-term moisture resistance.

Based on the aforementioned research, this study endeavors to evaluate the potential of incorporating an amine-free anti-stripping agent to augment the bond between the asphalt binder and aggregate in asphalt mixtures. The anticipated outcome is an enhanced safeguard against the damage that is commonly incurred when road pavements are subjected to moisture. To attain these goals, the research methodology entails a methodical exploration of physical tests to ascertain the ideal quantity of anti-stripping agent that is required for integration into the asphalt binder. Once optimal amounts are identified, in-depth rheological evaluations of the asphalt binders are carried out, utilizing a diverse set of analytical techniques. Additionally, the mechanical performance of the modified hot mix asphalt (HMA) mixtures undergoes scrutiny, followed by a comparative analysis against unmodified mixtures. This comparative assessment encompasses a variety of tests, including Marshall properties, improved immersion test, indirect tensile strength (ITS), and evaluations of moisture-induced damage.

2. Materials and Methods

2.1. Raw Materials

The experimental framework implemented in this study involved the use of an asphalt binder characterized by a penetration grade within the 40–50 range, a standard specification in Iraq. This specific binder was procured from the LANAZ refinery, strategically located approximately 365 km north of Baghdad, the capital of the nation. The detailed characteristics of this binder are provided in Table 1. The aggregate utilized in this investigation was obtained from an asphalt mixture processing facility situated in Zakho city, Iraq, with the source originating from the Khabour River region. The physical attributes of these aggregates play a crucial role in shaping the composition of asphalt blends, significantly influencing the ultimate performance of the resulting mixtures. The key physical characteristics of the aggregate material employed in this study are outlined in Table 2. Lastly, the Sricote agent developed by SRIPATH Innovation LTD served as the anti-stripping material, and its essential attributes are presented in Table 3. The Sricote agent is a proprietary blend of silanes that provides exceptional adhesion and fuel resistance to asphalt mixtures. It was developed to alleviate worker health and safety concerns regarding the use of amino compounds as an anti-stripping agent in asphalt binder and mixtures.

Table 1. Characteristics of virgin asphalt.

<table>
<tr><th>Physical Properties</th><th>Value</th><th>Unit</th><th>Test Condition</th><th>ASTM Designation No.</th></tr>
<tr><td>Penetration</td><td>43</td><td>1/10 mm</td><td>25 °C, 100 gm, 5 s</td><td>D-5</td></tr>
<tr><td>Ductility</td><td>160</td><td>cm</td><td>25 °C, 5 cm/min</td><td>D-113</td></tr>
<tr><td>Softening point</td><td>54</td><td>°C</td><td>Ring & ball</td><td>D-36</td></tr>
<tr><td>Specific gravity</td><td>1.03</td><td>---</td><td>25 °C</td><td>D-70</td></tr>
<tr><td rowspan="2">Rotational viscosity</td><td>571</td><td>cP</td><td>135 °C</td><td rowspan="2">D4402</td></tr>
<tr><td>145</td><td>cP</td><td>165 °C</td></tr>
</table>

Table 2. Physical attributes of the aggregate that was used.

Aggregate Properties	Coarse Aggregate	Fine Aggregate	ASTM Specification
Bulk-specific gravity	2.669	2.659	-
Apparent-specific gravity	2.729	2.733	-
Water absorption	0.72%	1.13%	-
Loss angeles abrasion	22%	-	45% max
Soundness	4.1%	-	18% max
Crushed percentage	95%	-	90% min
Deleterious materials	0.5	-	3% max

Table 3. Sricote technical data.

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

2.2. Preparation of Modified Asphalt

The present study involved the preparation of treated samples by incorporating four different ratios (0.25%, 0.5%, 0.75%, and 1.0%) of the Sricote anti-stripping agent into a virgin asphalt binder. The initial step entailed subjecting the unmodified asphalt to a heating process within a furnace to induce fluidity. The resulting fluidized asphalt binders, each amounting to 500 g, were then introduced into the metal chamber of a mixer. To ensure consistent thermal conditions, the asphalt specimens within the metal chamber were positioned in a thermal jacket placed atop a heater. Subsequently, the anti-stripping agent was gradually added to the heated asphalt binder, adhering to the predetermined percentage allocations. To ensure the homogeneity of the resulting mixture, a mixer operating at 135 °C and attaining 500 rpm was employed to facilitate blending for a duration of 10–15 min.

2.3. Conventional Properties Tests

The initial phase of the study involved an examination of the potential separation of the anti-stripping agent from the modified samples during storage. This assessment was conducted using the storage stability test in accordance with ASTM D5892 guidelines. Subsequently, the standard physical characteristics of the asphalt binders were explored, including penetration to assess asphalt consistency at a temperature of 25 °C (following ASTM D5), softening point to measure the resistance to flow of asphalt at elevated temperatures encountered in service (complying with ASTM D36), and ductility at 25 °C to evaluate the asphalt's ability to undergo deformation or elongation (as per ASTM D113). The elastic recovery of asphalt binders was also determined using ASTM D6084.

Furthermore, the rolling thin film oven (RTFO) test was conducted according to ASTM D2872 to simulate short-term aging in the production of asphalt mixtures. The outcomes of this test were determined based on measurements of asphalt properties before and after the test, including mass change, retained penetration, and ductility before and after the RTFO test. The percent of retained penetration was calculated to characterize the increase in hardness, as per Equation (1):

$$PRP = \frac{P2}{P1} * 100 \quad (1)$$

where $P1$ and $P2$ present the penetration of asphalt before and after RTFOT; PRP is the percent retained penetration.

Next, the assessment of elastic recovery, quantifying the percentage of the sample that returned to its initial state following elongation, was carried out in accordance with ASTM D6084, as per Equation (2). Following that, the rotational viscometer (RV) test was performed to examine the flow properties of asphalt binders under conditions of elevated temperature.

$$Recovery,\ \% = \frac{E - X}{E} * 100 \quad (2)$$

where E is the original elongation of the specimen, cm, and X is the elongation of the specimen. Equipment of the conventional tests are shown in Figure 1.

2.4. Performance Properties Tests

The Marshall mix design procedure, as outlined in ASTM D6927, was employed to optimize the compositions of hot mix asphalt (HMA). For each type of mixture, six replicate samples were prepared. These samples were blended at a specified asphalt ratio and mixed within an appropriate temperature range of 160–170 °C using a mechanical mixer for a duration of 2 min. Following the mixing process, the samples were adjusted to a compaction temperature set 10 °C below the corresponding mixing temperature using a Marshall mechanical compactor. Compaction involved subjecting the specimens to a heavy-duty treatment consisting of 75 Marshall blows per surface, simulating a tire pressure of 1379 kPa [35].

After compaction, the samples were divided into two groups. Unconditioned samples were immersed in a water bath maintained at a temperature of 60 °C for a duration of 40 min, while the conditioned samples were tested after being submerged in water for 24 h at 60 °C. Subsequently, a load was diametrically applied to a cylindrical specimen with a diameter of 101 mm, employing a loading rate of 50.8 mm/min. The resulting maximum load achieved during this process was duly recorded. The attained stability, indicative of the sample's maximum load-bearing capacity, was documented. The retained stability index (RSI) value of each sample group was then determined using Equation (3).

$$RSI = \frac{S2}{S1} * 100 \quad (3)$$

where *S*1 represents the stability of the control samples after being submerged for 40 min, while *S*2 denotes the stability of the conditioned samples after being submerged in water for 24 h.

Figure 1. Equipment for conventional tests.

Subsequently, following the aforementioned procedures, the moisture susceptibility evaluation, specifically the tensile strength ratio (TSR) in accordance with the ASTM D4867 standard, was conducted on the HMA mixtures. These mixtures were compacted to achieve an average air-void content ranging from 6.5% to 7.5%. In this context, three Marshall specimens were meticulously prepared for the dry subgroup, and an equivalent number of specimens was readied for the wet subgroup. For the wet subset, a controlled level of saturation ranging from 55% to 80%, as stipulated by ASTM guidelines, was achieved. The samples underwent a partial saturation state, followed by immersion in water at an elevated temperature of 60 °C for 24 h, followed by an additional hour at a standard temperature of 25 °C. In contrast, the dry subgroup underwent a relatively shorter soaking period of 20 min at a temperature of 25 °C.

According to the ITS test research outcomes, determined at 25 °C and 60 °C, respectively, TSR computation comprises the calculation of the proportion between wet and dry combinations. Furthermore, the final proportion has a comparative effect on the strength of the substance whenever water humidity conditions are involved. Higher resilience to water statuses is a reason for a higher TSR value and a reduced susceptibility of strength to the aforementioned statuses. The perception of the moisture resilience of the HMA combinations can be formed using the evaluation that was performed, which also assists in determining the attributes' performance and firmness. The following stage covers an advanced water inundation test, which will be executed to examine the stripping ratio of asphalt. The main methodology of the test was as follows [1]: (a) The selection of five cleaned and coarse aggregates which were then dehydrated at 105 °C for 3 h.

The mass of the dried aggregates (m_1) was then measured. (b) The coarse aggregates were submerged in hot asphalt at temperatures ranging between 155 and 165 °C. Afterward, they were retrieved and allowed to cool at room temperature for 1 h, and the total mass of aggregates coated with asphalt (m_2) was measured. (c) The cooled aggregates coated with asphalt were placed on a dry and uncontaminated tray and maintained at 90 °C in an electric thermostatic water bath for 3 h. (d) The tray containing the aggregates coated with asphalt was taken out of the water bath, and the aggregates were delicately removed from the tray using pair of pincers. They were then positioned on a weighing paper to prevent asphalt loss during heating and desiccated at 105 °C in an oven for 3 h. The total mass of water-immersed aggregates coated with asphalt (m_3) was weighed. Finally, the stripping ratio of asphalt (γ) was calculated according to Equation (4):

$$\gamma = \frac{m2 - m3}{m2 - m1} \quad (4)$$

where γ represents the stripping ratio of asphalt; and $m1$, $m2$, and $m3$ represent the total masses of dried aggregates, aggregates coated with asphalt, and water-immersed aggregates coated with asphalt, respectively.

3. Results

3.1. Segregation-Storage Stability Test

The evaluation of the discrepancy in softening points serves as a conventional method for appraising the storage stability of altered asphalt. A diminished softening point difference indicates a closer correlation in performance between the upper and lower components of the modified asphalt, suggesting an improved storage stability [36]. As delineated in Table 4, outcomes from the segregation-storage stability examination disclose that the softening point values of the modified asphalt binders conformed to the specified criterion of ±2.2 °C across all mixes. This finding emphasizes the favourable compatibility and storage stability established between the anti-stripping agent and asphalt binder, effectively meeting the stipulated criteria.

Table 4. Storage stability test results.

Additive	Top Reading (°C)	Bottom Reading (°C)	Difference (°C)	Requirement (<2.2)
0.0%	-	-	-	-
0.25%	57.1	58.2	1.1	Pass
0.50%	57.6	58.5	0.9	Pass
0.75%	58	59	1	Pass
1.0%	58	59	1	Pass

3.2. Conventional Properties Tests

Figures 2 and 3 illustrate the impact of the anti-stripping agent on the asphalt binder's penetration and softening point. The findings disclose that with an increase in the Sricote anti-stripping agent dosage in the asphalt binder, the penetration initially reduces before subsequently increasing.

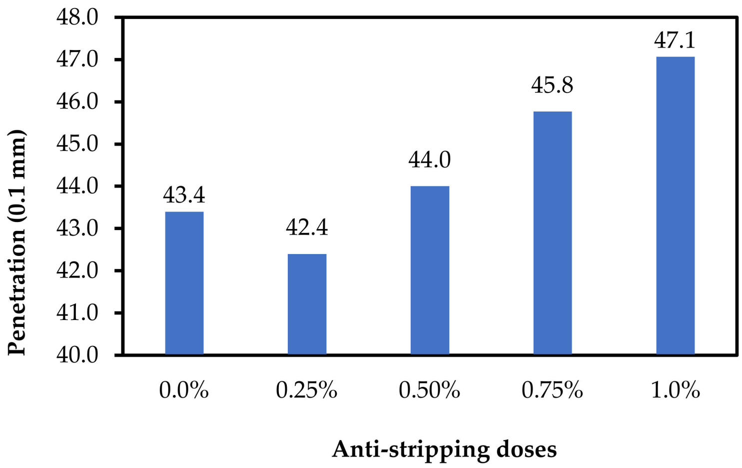

Figure 2. Penetration results of asphalt binders.

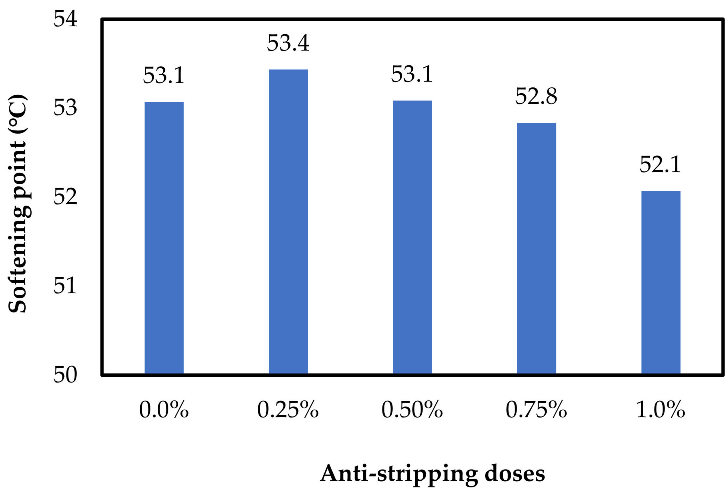

Figure 3. Softening point of asphalt binder.

By adding 0.25% of the anti-stripping agent, the softening point increased, but decreased with further increments in the additive. Variations in softening point and penetration can be attributed to a complex interplay of chemical and physical mechanisms caused by the varying Sricote anti-stripping agent dosages in the binder. In contrast, at a 0.25% dosage, penetration decreased and the softening point increased as the binder became stiffer. An improved interaction between asphalt molecules and the Sricote additive might facilitate this stiffening effect by increasing cohesion within the binder matrix. It is also possible that the anti-stripping agent is saturated or overloaded as penetration increases and the softening point decreases with the increasing dosage. It may also indicate that an excess of the anti-stripping agent could disrupt cohesive forces within the asphalt binder, decreasing stiffness and potentially rendering the binder more susceptible to deformation at elevated temperatures.

Conversely, Figure 4 presents the influence of the anti-stripping agent on the ductility of the asphalt binder. The results reveal ductility values of +150 cm for the virgin binder, and the binders treated with 0.25% and 0.5% of the anti-stripping agent. However, the values decreased when the agent was increased by more than 0.5%. Nevertheless, all results remained well above the specification limit (>100 cm). The marginal decrease in ductility value, attributed to the addition of the anti-stripping agent to the asphalt binder, can be explained by the agent's impact on the physical and chemical properties of the binder. The anti-stripping agent may alter the molecular structure of the binder, slightly affecting its ability to elongate.

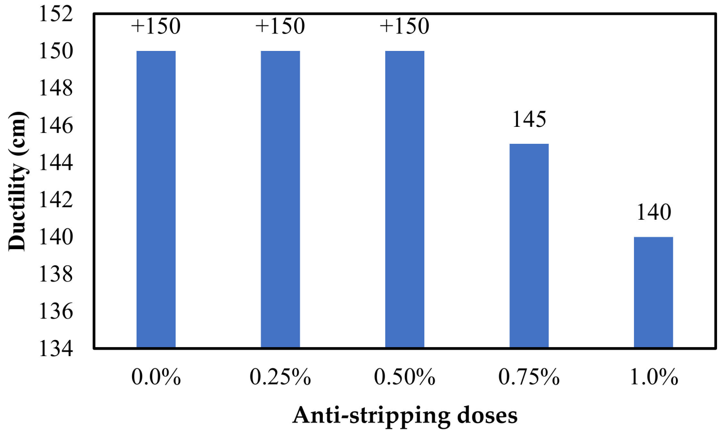

Figure 4. Ductility results of asphalt binder.

In summary, the observed effects seem to arise from the delicate balance between the anti-stripping agent and the asphalt binder. The optimal dosage is likely dependent on specific project specifications and environmental factors. It is crucial to thoroughly evaluate performance attributes at different dosage levels to achieve the desired balance between increased resilience against moisture damage and the preservation of essential mechanical properties in the asphalt mixture.

3.3. Rotational Viscometer Results

Figure 5 illustrates the impact of various dosages of the anti-stripping agent on the rotational viscosity of asphalt binder at temperatures of 135 °C and 165 °C. The trend reveals that as the dosages added to the asphalt binder increase, the viscosity of the binders initially rises, reaching a peak at a 0.25% dosage, and subsequently declines with further increments in the anti-stripping agent dosage. Notably, the observed decrease in penetration and increase in softening point when the anti-stripping agent is initially introduced (at a 0.25% dosage) aligns with the anticipated elevation in viscosity. However, at higher doses, where penetration increases and the softening point decreases, it implies that the viscosity may be influenced by more intricate interactions, potentially involving saturation or overloading of the anti-stripping agent. These findings are consistent with Zhu et al. [37] who similarly reported that the addition of an anti-stripping agent can augment viscosity up to a certain threshold before decreasing, contingent on the specific type of anti-stripping agent.

3.4. Elastic Recovery Test Results

Table 5 demonstrates the changes in the elastic recovery of samples when adding the Sricote anti-stripping agent. Basically, the original shape is regained due to the improvement in the binder's ability to bounce back. This enhancement may be linked to improved cohesion, indicating that the anti-stripping agent fortified the connections between binder molecules, resulting in a more elastic and resilient binder.

Moreover, an asphalt binder with modified rheological properties may result from the chemical and physical alterations caused by the anti-stripping agent. Such modified properties include a heightened elasticity and recovery. Furthermore, this directly affects the asphalt pavement in terms of increasing its resistance to permanent deformation and enhancing its durability against the stresses of traffic and environmental factors.

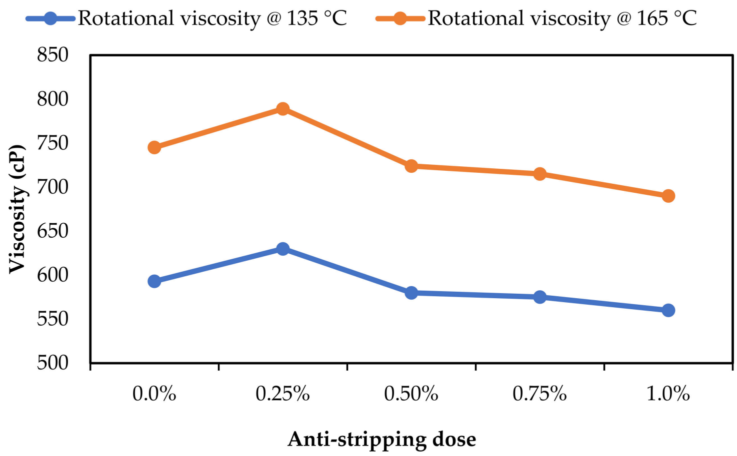

Figure 5. Rotational viscometer results.

Table 5. Elastic recovery results.

Sample Type	Virgin Asphalt	Asphalt Binder with Anti-Stripping Agent			
		0.25%	**0.5%**	**0.75%**	**1.0%**
Residual length *X* (cm)	18.9	18	17.5	17	16.6
Elastic recovery rate (%)	5.5	10	12.5	15	17.8

3.5. Conventional Test Results after Aging

Table 6 presents the results of the rolling thin film oven (RTFO) test, which simulates short-term aging on specific samples. It is noteworthy that all samples recorded a loss value under 0.75%, adhering to the maximum permissible weight loss due to air and heat, as specified in the ASTM D2872 standards. However, the inclusion of a 1% dosage of the anti-stripping agent yielded results closely approaching the ASTM limit, emphasizing the need for caution when employing high dosage percentages. Simultaneously, Table 6 highlights a substantial increase in the percentage of penetration of asphalt that was retained following the introduction of the anti-stripping agent, while the ductility of the residue values decreased with the agent's addition. These outcomes can be clarified by considering the intricate interactions among the asphalt binder, anti-stripping agent, and the aging process. In essence, the anti-stripping agent contributes to enhanced moisture resistance, preserving the penetration properties and resulting in heightened retained penetration. Concurrently, the alterations induced by the anti-stripping agent, coupled with the aging process, can lead to a less ductile residue. The elevated loss in terms of weight after short-term aging suggests a potential influence of the anti-stripping agent on the aging process, impacting the loss in the mass of the binder.

Table 6. Loss by weight, retained penetration, and ductility of residue.

Additive (%)	Loss by Weight (%)	Retained Penetration (%)	Ductility of Residue
-	<0.75% (ASTM 2872)	>55% (ASTM D5)	>25 cm (ASTM D113)
0.0	0.445	67.8	41
0.25	0.563	63.6	40
0.5	0.612	61.8	36
0.75	0.624	61.2	35
1.0	0.716	59.9	31

3.6. Marshall Stability Results

The findings presented in Figures 6 and 7 reveal a noteworthy enhancement in the Marshall stability of asphalt mixtures conditioned for 40 min and 24 h when incorporating 0.25% of the Sricote anti-stripping agent, followed by a decline in stability at higher doses. This suggests a complex interplay of factors influencing asphalt mixture performance. In essence, the anti-stripping agent seems to improve adhesion between the asphalt binder and aggregate at this lower dose, promoting enhanced cohesion within the mixture. This improved adhesion has the potential to increase stability by minimising the binder stripping risk and aggregate displacement. Specifically, the 0.25% concentration of the anti-stripping agent effectively addresses stripping concerns without negatively affecting other critical stability factors. Conversely, excessive amounts of the anti-stripping agent may lead to an "overloading" effect, negatively impacting the binder and aggregate interaction. Essentially, higher dosages can alter the properties of the asphalt binder beyond the optimal point for adhesion, compromising its ability to provide required viscosity and elasticity for a stable mixture.

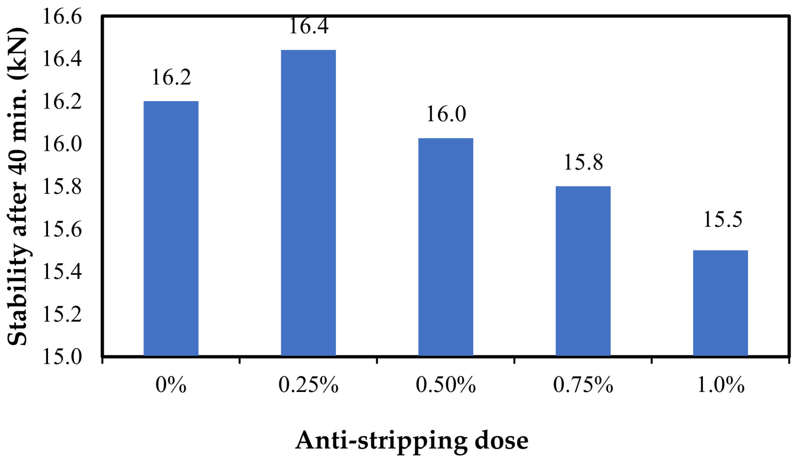

Figure 6. Marshall stability results after 40 min conditioning.

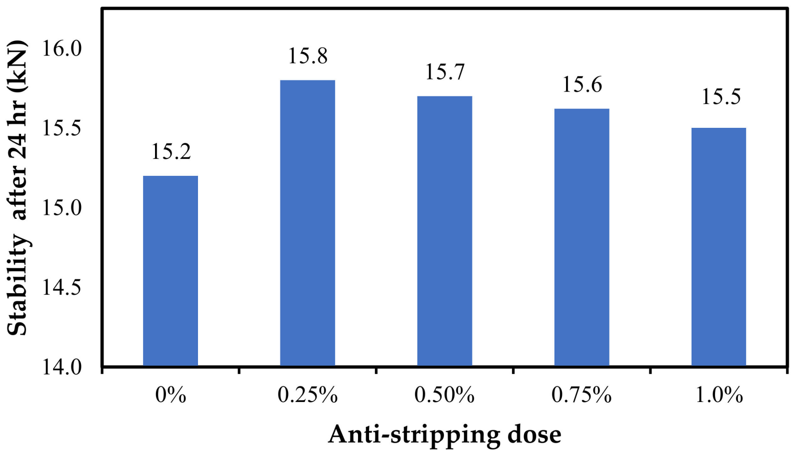

Figure 7. Marshall stability after 24 h conditioning.

In contrast, Table 7 shows a significant trend in the retention stability index (RSI), showing an increase in the retention stability index (RSI) with the addition of the Sricote anti-stripping agent of up to 0.5%, while a higher concentration led to a decrease. The observed response varied as a function of dosage, highlighting the significant impact of the precise dosage of the anti-stripping agent on the long-term stability of the mixture. Importantly, all results consistently exceeded those for untreated asphalt mixtures, indicating a differential impact of Sricote on long-term stability.

Table 7. Retained stability index results.

Anti-Stripping (%)	Stability after 40 min (kN)	Stability after 24 h (kN)	Retained Stability Index (%)
0	16.2	14.2	87.6
0.25	16.4	15.8	96.3
0.5	16.0	15.7	98.1
0.75	15.8	15.4	97.4
1.0	15.5	14.6	94.1

The stability values demonstrate the potential of anti-stripping agents to serve as valuable additives that can improve the overall performance and durability of asphalt mixtures. The initial increase in RSI indicates that, at lower concentrations, the Sricote anti-stripping agent improves adhesion and cohesion within the asphalt mixture, promotes better asphalt–aggregate interaction, and helps improve long-term stability. This improvement highlights the critical role of anti-sparing agents in improving binder–aggregate bonding, which is critical to the long-term resiliency of pavements. Conversely, higher concentrations alter the rheological properties of the binder, potentially compromising its ability to withstand permanent deformation in the long term. In addition, excessive amounts of the Sricote additive cause the aggregate to become overcoated, which negatively affect the interlocking of the aggregate and result in reduced long-term stability. The potential coverage effects highlight the need for a nuanced understanding of the internal dynamics of asphalt mixtures and careful consideration of the dosage levels to avoid unintended consequences regarding aggregate interlocking.

However, it is worth noting that, despite the decreasing trend at higher concentrations, the consistently higher values compared to the untreated asphalt mixture indicate that the addition of a release agent, even though the yield may decrease, has an impact on the asphalt mixture. The enhancement, even at higher doses, highlights the resilience of the asphalt mixture in accommodating the influence of the Sricote anti-stripping agent, underscoring its enduring positive contribution to long-term stability.

3.7. ITS and Moisture Damage

The results of the ITS assessments for asphalt mixture samples, both conditioned and unconditioned, as well as the corresponding TSR values, are portrayed in Figure 8. A comprehensive analysis of this figure highlights significant trends in the mechanical attributes of the asphalt mixtures subjected to different conditions and treated with a liquid anti-stripping agent. Figure 8 illustrates that the ITS values of conditioned asphalt mixtures were consistently lower than those of their dry counterparts. This discrepancy underscores the detrimental influence of water on the bond between the asphalt binder and aggregate. The presence of water weakens this bond, resulting in a reduction in tensile strength. This observation aligns with the established understanding that moisture-induced damage can significantly threaten the performance of asphalt mixtures.

It is worth noting that characterizing this mechanical behavior through ITS tests provides valuable insights into the load-bearing capacity of these asphalt samples under various environmental conditions. Such ideas play an important and decisive role when designing pavements capable of withstanding all environmental exposure and loads.

Distinctively, adding an anti-stripping agent into the asphalt mixtures could lead to augmentations in the TSR results. This particular improvement is clearly seen in conditioned mixtures treated with 0.25% and 0.5% of the anti-stripping agent, where the TSR values reached 92.9% and 94.9%, respectively. Meanwhile, untreated asphalt mixture recorded a TSR value of 80.5%. The significant rise in TSR could be attributed to the anti-stripping agent's role in encouraging a robust asphalt binder–aggregate bond, even in the presence of water.

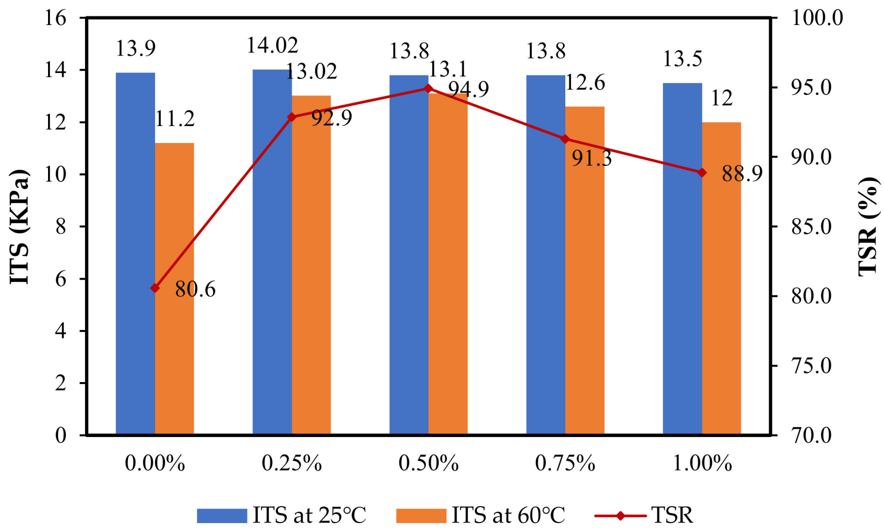

Figure 8. ITS and TSR results.

However, there was a decline in TSR values when the dosage of the anti-stripping agent exceeded 0.5%. The decrease means that higher concentrations of the anti-stripping agent result in diminishing returns or adverse impressions on the moisture resistance of asphalt mixtures.

The identification of specific dosages of the anti-stripping agent that yield optimal TSR values emphasizes the importance of a careful approach to formulating asphalt mixtures. This underscores the need for a nuanced understanding of anti-stripping agent dosages to strike a balance between improved adhesion and the potential disadvantages associated with higher concentrations. Furthermore, the observed decrease in TSR values with higher anti-stripping agent dosages calls for further exploration into the underlying mechanisms.

The results play the decisive role in finding an anti-stripping agent that can form a strong connection in the asphalt binder and the aggregate, especially when exposed to water. By decreasing the failure caused by moisture and avoiding separation of the asphalt binder from the aggregate, the anti-stripping agent plays a main role in maintaining the integrity of the aggregate and binder. Thus, it contributes to improving long-term road performance, increasing durability, and creating long-lasting road surfaces.

3.8. Improved Immersion Test Results

The investigation results obtained from testing the improved water immersion measurement are shown in Table 8. The tested asphalt samples showed distinct differences in stripping ratios, confirming that clear adhesion enhancements were observed in the efficacy of the agents with an added anti-stripping agent. Furthermore, a close inspection of the treated asphalt samples showed varying degrees of adhesion improvements, suggesting that the Sricote anti-stripping agent exerts differential effects on various asphalt formulations. This variation shows the importance of understanding the asphalt composition and its interaction with anti-stripping agents.

Table 8. Stripping ratio of asphalt in the improved water immersion test.

Asphalt/Anti-Stripping Asphalt	Stripping Ratio of Asphalt (%)
Virgin asphalt (VA)	65
0.25% anti-stripping agent + VA	50
0.5% anti-stripping agent + VA	66
0.75% anti-stripping agent + VA	68
1.0% anti-stripping agent + VA	72

Asphalt treated with a 0.25% anti-stripping additive shows a notable reduction in stripping ratios, revealing a considerable improvement in the adhesion between the asphalt binder and aggregate. The obtained data also showed that the stripping ratio for the treated binder was approximately 50%, compared to 65% for virgin asphalt, whereas the reduction exceeded 15 points. Further analysis of the data indicates a positive consistent impact of Sricote on various asphalt binder samples, indicating its potential to enhance the performance of asphalt.

The investigayed correlation between adhesion and stripping ratios underscores the pivotal function of the Sricote anti-stripping agent in fortifying the bond between asphalt and aggregate. The molecular dynamics at the asphalt–aggregate interface unveil the intricacy of this phenomenon. Anti-stripping agents promote a chemical re-arrangement that reduces the asphalt's vulnerability to moisture-induced debonding. Importantly, the alteration in molecules not only enhanced the adhesion but also contributed to the overall durability of the asphalt. This evedance is crucial for withstanding the mechanical and environmental pressures faced in practical situations. Investigating the reasons behind the observed trends indicated that achieving a balance is contingent on the concentration of the anti-stripping agent. A total of 0.25% of the Sricote yield was the most substantial reduction in stripping ratios. Furthermore, it is imperative to acknowledge that the chemical modifications induced by the agent may impact adhesion and other facets of the asphalt properties, including fatigue resistance and temperature sensitivity.

4. Conclusions

A comprehensive investigation into the impact of the anti-stripping additive Sricote on asphalt and its mixtures reveals profound alterations in key physical, rheological, and mechanical properties. The experimentation and analysis yielded valuable insights, as summarized below:

1. The introduction of the anti-stripping agent induces significant changes in fundamental asphalt binder properties. Notably, a 0.25% dosage leads to a decrease in penetration, coupled with an increase in softening point and viscosity. Conversely, higher dosages produce contrasting effects.
2. The treated asphalt displays an improvement in elastic recovery with increasing anti-stripping agent dosage, emphasizing the dosage-dependent nature of these changes.
3. The remarkable increase in the percent retained penetration of asphalt, accompanied by a decrease in ductility of residue values, underscores the complex interactions among the asphalt binder, anti-stripping agent, and the aging process.
4. The addition of a low dose (0.25–0.5%) of anti-stripping agent significantly enhances the retained stability index and TSR values in asphalt mixtures. This positive outcome is attributed to the crucial role played by the liquid anti-stripping agent in fostering a robust bond between the asphalt binder and aggregate particles, particularly in the presence of water.
5. Notably, asphalt treated with 0.25% anti-stripping agents exhibits a conspicuous decline in stripping ratios compared to the virgin mixture, highlighting the efficacy of these dosages in mitigating stripping.
6. Despite these advantages, a call for caution is sounded, emphasizing the imperative of further investigations and field performance evaluations, particularly regarding the potential long-term effects of aging. Advanced chemical and rheological tests, along with molecular analyses of anti-stripping–binder interactions, are proposed to provide deeper insights into observed binder modifications and deliver valuable insights into the optimal dosage for achieving the desired long-term performance.

Author Contributions: Z.H.A.-S.: conceptualization, writing—original draft, methodology, investigation. H.G.M.H.: formal analysis, resources, funding acquisition. S.R.O.A.: reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data used in this research can be provided upon request.

Acknowledgments: Authors would like to acknowledge of Northern Technical University, Iraq and Duhok Polytechnic University, Iraq for the supporting this research. The authors also extend their gratitude to Sripath Technologies, LLC, Mahwah, NJ, USA for their support in this research through the provision of materials.

Conflicts of Interest: The authors declare no conflicts of interest.

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