The Effect of Short and Long Term Aging on Moisture Susceptibility of SMA Mixtures Stabilized with Waste Jute Fibers

Aeshah A. Ahmed
Civil Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq
aisha.arkan2301@coeng.uobaghdad.edu.iq (corresponding author)

Mohammed Q. Ismael
Civil Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq
drmohammedismael@coeng.uobaghdad.edu.iq

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ABSTRACT

Stone Matrix Asphalt (SMA) is a hot, gap-graded asphalt mixture known for its outstanding durability and resistance to rutting. It relies on stabilizing agents to prevent the binder drainage caused by its stone-on-stone contact. This research investigates the effect of incorporating Waste Jute Fiber (WJF) on the moisture susceptibility of SMA mixtures under three aging conditions: unaged, Short-Term (ST), and Long-Term (LT). Three WJF lengths (5, 10, and 15 mm) were used at four concentrations (0.1%, 0.3%, 0.5%, and 0.7%) by total mixture weight. The Marshall test was utilized to evaluate volumetric and mechanical properties, while the drain-down test assessed binder drainage. Indirect Tensile Strength (ITS) and compressive strength tests were conducted to evaluate the moisture susceptibility after aging. The results showed that all WJF contents and lengths yielded a higher Tensile Strength Ratio (TSR) and Index of Retained Strength (IRS) values compared to the control mixtures. Moreover, ITS and compressive strength increased with aging due to binder hardening. The TSR and IRS values of the aged samples indicate that increasing the WJF content up to an optimal level significantly reduces the susceptibility to moisture and oxidative aging. The mixture with 0.5% WJF at 10 mm length exhibited the greatest improvements, with TSR increases of 14.12%, 16.69%, and 19.39%, and IRS increases of 18.95%, 21.77%, and 26.44% for unaged, ST, and LT aging, respectively.

Keywords-stone matrix asphalt; waste jute fiber; moisture susceptibility; tensile strength ratio; retained strength index

I. INTRODUCTION

Multiple pavement distresses, including raveling, cracking, and fatigue, are attributed to the degradation of bitumen over time. As asphalt binder ages, it loses cohesion with the aggregate, resulting in rutting under traffic and moisture-induced deterioration upon exposure to water [1]. The LT performance of asphalt roadways is strongly influenced by the aging of the asphalt binder, which occurs through several complex mechanisms, such as oxidation, volatilization, and polymerization [2]. Aging is generally categorized into two phases: ST and LT aging [3]. ST aging refers to the hardening of the asphalt binder during the mixing and compaction stages of asphalt concrete. Exposure to elevated temperatures causes the evaporation of lighter fractions, while heavier fractions remain, leading to significant changes in the binder's physical and chemical properties. This may result in premature failure of the asphalt pavements. LT aging, on the other hand, takes place throughout the pavement's service life [4]. During LT aging, the pavement surface is exposed to the harshest environmental conditions, including direct sunlight and extreme temperatures [5]. As a result, an aging gradient develops within the pavement structure over time, which becomes a key feature of the in-service aging behavior [6]. Therefore, the durability of asphalt mixtures is highly dependent on their resistance to aging [7].

Moisture damage is another critical and complex issue affecting the asphalt pavements. It occurs due to the weakening of adhesion between the asphalt binder and aggregates or degradation of the binder itself, leading to reductions in mixture stiffness, strength, and durability [8]. Environmental factors, such as temperature, water, and air along with intrinsic properties, like binder cohesion and adhesion, play a significant role in this degradation process [9]. Due to the need for asphalt mixtures to resist moisture and aging, binder-rich SMA mixtures have demonstrated superior preliminary mechanical performance under unaged conditions. These mixtures also exhibited less variability between the unaged and aged states, indicating greater durability compared to the conventional asphalt mixtures [10]. SMA is a type of hot mix asphalt composed of approximately 6–7% bitumen, 70–80% coarse aggregates, 8–12% mineral filler, and 0.3–0.5% fibers. Compared to other asphalt types, SMA is known for its high durability and excellent rutting resistance [11].

Stabilizing additives, such as cellulose, polymers, and mineral fibers are commonly used in SMA mixtures to prevent bitumen drainage and enhance cohesion and ITS [12]. Fibers improve performance after both ST and LT aging [13]. Their incorporation via the dry process enhances the mechanical properties, mitigates the aging effects, and prolongs the pavement life [14]. Jute's renewable nature, rapid growth cycle (4–6 months), and high cellulose content make it a sustainable alternative to synthetic fibers [15]. Jute Fiber (JF) has been identified as one of the most promising natural fiber materials in terms of both environmental impact and mechanical performance. It offers biodegradability, a low carbon footprint, and low cost. Additionally, its rough surface enables strong adhesion to asphalt, enhancing the strength of the mixture. These characteristics make jute a viable and sustainable alternative to synthetic materials in asphalt engineering applications [16–18]. Table I presents a comparison between jute, synthetic, and glass fibers.

TABLE I. COMPARISON BETWEEN JUTE, SYNTHETIC, AND GLASS FIBERS

Characteristics	Jute fiber	Synthetic fiber	Glass fiber
Source	Natural, plant-based, biodegradable	industrial, petroleum-derived	Industrial, non-biodegradable
Environmental sustainability	Very high, recyclable, and contributes to waste reduction	Moderate, non-biodegradable, but lightweight	Low, energy-intensive production, and contributes to non-biodegradable waste
Cost	Very low	Medium	High
Improved deformation resistance	Significant improvement in rutting resistance	Effective against cracking and enhances flexibility	Good cracking resistance, but relatively brittle
Binder content effect	Increases Optimum Asphalt Content (OAC) by approximately 4–5%	Minor effect on asphalt content	May require modification of mix design due to high density
Easy integration and processing	Easily incorporated after cutting and drying; improved when alkali-treatedi	Easy to integrate, no pre-treatment required	Requires special equipment and may be fragile during mixing
Performance under aging	Retains mechanical properties well, especially with treated fibers	Performs well in hot and humid conditions	Stable under aging, may degrade in alkaline environments
Reference	[19-21]	[19-21]	[19-21]

A local study [22] examined the mechanical performance of SMA mixes incorporating three recycled polymer additives, observing improvements in Marshall stability and tensile strength due to the inclusion of recycled polymers. The effect of coconut fiber length and content on SMA mixtures has also been investigated [23]. Fiber lengths of 5–20 mm, 20–40 mm, and 40–60 mm were evaluated with contents of 0, 0.1%, 0.3%, 0.5%, and 0.7% by weight of the mix. Coconut fibers improved the Marshall stability and reduced deformation, particularly at lengths of 5–20 mm and contents of 0.3–0.4%.

Research on sisal-reinforced SMA showed that an optimum fiber content of 0.3% resulted in improved Marshall stability and reduced binder drainage [24]. Further investigations involving jute, polyester, and carbon fibers at contents of 0.25%, 0.5%, and 0.75% and lengths of 5 mm, 7.5 mm, and 10 mm indicated that a 0.5% content and 7.5 mm length yielded the best performance in terms of rutting resistance and Marshall stability. Among the fibers studied, carbon fibers offered the highest improvements, while jute fibers were especially effective in reducing the binder drain-down [25].

The use of banana fibers at 0.3% and lengths of 5, 10, 15, and 20 mm demonstrated significant enhancements in mechanical performance, particularly with 15 mm and 20 mm lengths [26]. The incorporation of cellulose, polyester, and glass fibers into SMA improved the Marshall properties, reduced the drain-down, and enhanced the tensile strength, with polyester fibers being the most effective [27]. Reviews on the application of sisal and coir fibers concluded that these natural additives enhance the strength and durability while mitigating the binder loss [28]. The ITS test was used to assess asphalt concrete specimens subjected to oven aging at 85 °C for 1, 5, 10, 15, 20, and 25 days, as well as loose mixtures aged at 135 °C for 8, 16, 32, 48, 72, and 100 h [29]. LT aging increased ITS by 17.7%, 28%, and 31% after 1, 5, and 25 days, respectively. In the case of ST aging, ITS increased by 33% during the first 40 h of conditioning and subsequently declined, with a total reduction of 9% after 100 h.

Other studies evaluated multiple ST aging protocols using different temperatures and durations. One investigation tested nine combinations involving 2, 4, and 6 h of conditioning at 120, 135, and 150 °C on loose SMA mixtures [30]. The unaged samples exhibited the lowest Tensile Strength Ratio (TSR) of 0.731, which was 9.3% lower than that of plant-aged mixes. The TSR values were found to be 4.2% higher for 6-h aging compared to 2-h aging, with the most significant temperature effects observed at shorter durations. All tested protocols at 150 °C resulted in higher TSR values than the plant-produced mix. Authors in [31] study evaluated ST aging at 0, 2, and 4 h and temperatures of 0, 135, and 150 °C, concluding that both duration and temperature significantly influenced TSR values. Generally, TSR increased with longer aging time, and higher temperatures improved resistance to moisture susceptibility.

It has also been demonstrated that regardless of the aging method, the process leads to a notable enhancement in ITS due to binder hardening [32]. Aged specimens consistently exhibited higher ITS values compared to the unaged ones.

Although the use of natural and synthetic fibers in asphalt applications has grown, limited data exist on the performance of fiber reinforced asphalt mixtures under LT aging conditions, highlighting a notable research gap [4, 33]. In particular, the use of WJF in SMA mixtures and its performance under different aging conditions remains largely unexplored. This study addresses this gap by investigating the effect of incorporating WJF as a stabilizing agent into SMA mixtures, evaluated under three aging conditions: unaged, ST, and LT. The aim is to enhance the mixtures' resistance to moisture-induced damage while providing a sustainable method for utilizing WJF as an environmentally friendly material.

II. MATERIALS

All materials utilized conform to the standard of the Iraqi Specification for Roads and Bridges (SCRB/R9) [34] and are available locally.

A. Asphalt

Asphalt cement with a penetration grade of 40/50 was provided by the Al-Daurah refinery in Baghdad. Table II presents the physical characteristics of the asphalt cement used in this study.

TABLE II. PHYSICAL CHARACTERISTICS OF ASPHALT CEMENT

Test	Unit	ASTM	Result	SCRB
Penetration (25°C, 100 g, 5 sec)	0.1mm	D5	44	40-50
Softening point (Ring and Ball)	°C	D36	54	
Specific gravity @ 25°C		D70	1.04	
Ductility (25°C, 5 cm/min)	cm	D113	119	>100
Flash point (Cleveland Open Cup)	°C	D92	314	>232
Residue from thin-film-oven-test, D1754				
Retained penetration (% of original)	%	D5	80	> 55
Ductility (25°C, 5 cm/min)	cm	D113	69	> 25

B. Aggregate

Coarse and fine aggregates were obtained from the Al-Nibaai quarry, located in Baghdad. The coarse aggregates designated for the wearing course conformed to sieve sizes ranging from 3/4 inch (19 mm) down to No. 4 (4.75 mm), while the fine aggregates fell within the range of No. 4 (4.75 mm) to No. 200 (0.075 mm). The physical properties of both aggregate types, including specific gravity, water absorption, and Los Angeles abrasion, are summarized in Table III. Additionally, limestone dust provided by the Iraqi lime factory in Karbala was employed as a mineral filler. This filler was passed through a 0.075 mm sieve to ensure uniformity and compatibility, and its physical properties are listed in Table IV. The overall aggregate gradation was established in accordance with the AASHTO M 325 standard [35], targeting a nominal maximum aggregate size of 12.5 mm, suitable for wearing course applications. Figure 1 presents the selected aggregate gradation curve, which was carefully designed to fulfill both the structural and durability requirements.

TABLE III. PHYSICAL CHARACTERISTICS OF COARSE AND FINE AGGREGATE

Test	ASTM designation No.	Coarse aggregate	Fine aggregate
Los Angeles abrasion,%	C-131	16.3	-
Flat and elongated, %	D-4791	1.8	-
Absorption, %	C-127, C-128	0.562	0.724
Soundness, %	C-88	3.87	1.94
Bulk specific rgavity	C-127, C-128	2.611	2.651
Liquid limit, %	D-4318	-	6.4

TABLE IV. PHYSICAL CHARACTERISTICS OF LIMESTONE DUST

Test	ASTM designation No.	Results	SCRB specification limits
Bulk specific gravity	C-188	2.794	-
% Passing sieve no. 200	-	95	70-100

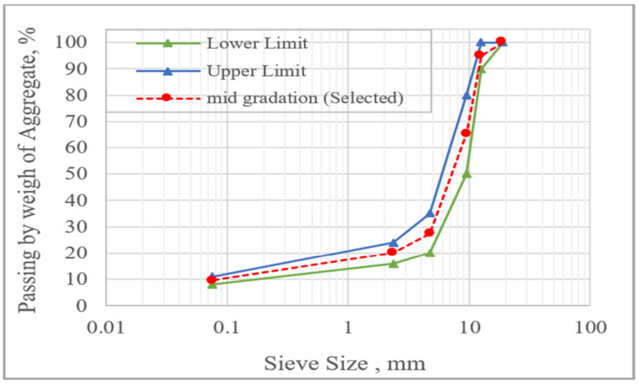

Fig. 1. Aggregate gradation.

C. Waste Jute Fiber

JF is a natural fiber used in varying quantities and lengths, as illustrated in Figure 2. Jute is a plant-derived fiber primarily composed of cellulose, hemicellulose, and lignin [18]. Due to its high tensile strength, affordability, and eco-friendly characteristics, JF is the second most widely produced natural fiber globally, after cotton [36, 37]. It is commonly used in the packaging sector. WJF was obtained from discarded packing bags available in commercial markets for food products and was reused for incorporation into asphalt mixtures. Table V presents the selected properties of WJF, which were determined through experimental testing using a Tinius Olsen H50KT universal tensile testing machine (manufactured in the UK), following standard laboratory procedures. The fiber content and lengths used in this study were selected based on previous research [25, 26, 38].

Fig. 2. WJF.

TABLE V. CHARACTERISTICS OF WJF

Property	Unit	WJF
Density	g/cm³	1.41
Diameter	mm	1
Yield force	N	41.5
Elongation at yield	%	4.95
Tensile strength	MPa	52.8
Max. force	N	41.5
Elongation at max.	%	4.95
Elongation	%	19.67

III. METHODS AND EXPERIMENTS

A. Marshall Test

After preparing the mixture components, WJF was added to the aggregates at four concentrations 0.1%, 0.3%, 0.5%, and 0.7%, relative to the total weight of the mixture, using three fiber lengths (5, 10, and 15 mm). The fibers were incorporated individually by the dry process. A visual inspection was performed during mixing to prevent fiber clumping, ensuring a uniform distribution [39]. The Marshall method was used to determine the OAC for the specified aggregate gradation. The asphalt content ranged from 4.5% to 7% by total mixture weight. The specimens were prepared and compacted in accordance with ASTM D6927 [40], and three samples were produced for each mixture. The average value of each set was used for analysis. Figure 3 illustrates the preparation of the Marshall specimens. After 24 h of cooling, the Marshall stability and the corresponding flow values were recorded. According to the Asphalt Institute's guidelines, 4% air voids were adopted as the primary criterion for determining the OAC in this design methodology. Other volumetric and mechanical properties, such as stability, flow, bulk density, Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) were also evaluated to verify compliance with the required specifications.

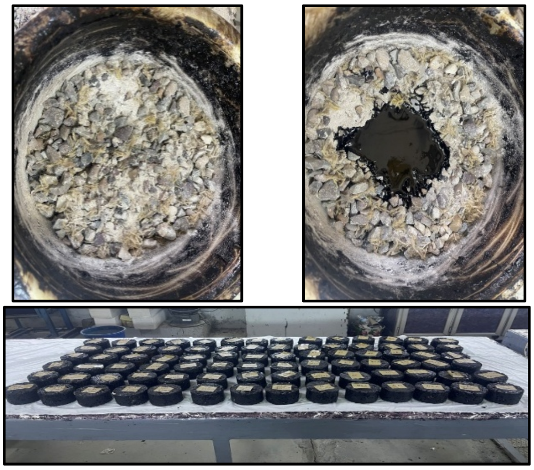

Fig. 3. Preparation of Marshall specimens.

B. Drain Down Test

The procedure for performing this test is thoroughly described in ASTM D6390 [41]. The ratio of drained mass to the initial sample weight (1200 g), as defined in (1), is referred to as the drain-down level. According to AASHTO T305 [42], the allowable limit for the drain-down is a maximum of 0.3%. Figure 4 displays the drain-down test. Three samples were prepared for each mixture, and the average value was used for analysis:

$$Drain\ down\ (\%) = \frac{D-C}{B-A} * 100\% \qquad (1)$$

where C is the mass of the empty pan in grams, D is the mass of the pan and sample after removal from the oven in grams, A is the mass of the empty basket in grams, and B is the mass of the basket and sample in grams.

Fig. 4. Drain down test.

C. Aging Simulation

The aging of the asphalt mixtures was performed using the procedure outlined in AASHTO R 30 [43].

D. Tensile Strength Ratio

To evaluate the effects of moisture, the ITS test was conducted according to ASTM D4867 [44] under three aging conditions: unaged, ST, and LT. Six samples were fabricated for each mixture and aging condition, using the Marshall compaction method. Figure 5 depicts the ITS test setup. The ITS and TSR were calculated using:

$$\text{ITS (kPa)} = \frac{2000*P}{\pi*t*d} \qquad (2)$$

$$\text{TSR (\%)} = \frac{\text{ITS}_{\text{con.}}}{\text{ITS}_{\text{uncon.}}} * 100\% \qquad (3)$$

where ITS is the indirect tensile strength (kPa), P is the ultimate load failure (N), t is the thickness of the specimen (mm), d is the diameter of the specimen (mm), TSR is the tensile strength ratio, $\text{ITS}_{con.}$ is the indirect tensile strength for wet specimens, $\text{ITS}_{uncon.}$ is the indirect tensile strength for dry specimens.

Fig. 5. ITS test.

E. Compressive Strength Test

This testing procedure was used to determine the compressive strength of compacted bituminous mixtures under water exposure, as specified in ASTM D1074 [45]. The tests were conducted under three aging conditions: unaged, ST, and LT. The specimen preparation followed the guidelines of ASTM D1075 [46]. Figure 6 presents the compressive strength test setup.

Fig. 6. Compressive strength test.

IV. RESULTS AND DISCUSSION

A. Marshall Test Results

Table VI presents the Marshall test results for mixtures incorporating WJF at different lengths and contents. All WJF-reinforced mixtures exhibited a higher OAC than the control mixture. This increase is attributed to the higher fiber content and the expanded specific surface area, which led to increased asphalt absorption. The OAC results agree with previous findings [23].

The addition of WJF improved the Marshall stability for up to 0.5% fiber content after which stability decreased for all three fiber lengths. This trend can be explained by the fiber adhesion and networking effects. An excessive amount of fiber in the mix reduces the number of contact points between the aggregates, thereby decreasing stability. Among the tested lengths, the mixtures reinforced with 10 mm WJF demonstrated higher Marshall stability than those with 5 mm or 15 mm fibers. Increasing the amount of 5 mm fibers caused overlapping and agglomeration, which in turn reduced the effective contact area. Compared to the control mixture, the highest increase in Marshall stability, 19.1%, was observed at 0.5% WJF with a fiber length of 10 mm. These results are supported by the findings in [24, 25].

Incorporating WJF into the mixtures also reduced the flow values across all lengths and contents. This reduction is attributed to the decreased flexibility caused by the presence of fibers. Longer fibers further contributed to lower flow values due to increased internal bonding within the mixture. These observations are consistent with those in [28, 40].

Additionally, the inclusion of WJF decreased the specific gravity of the mixtures, as the fiber density is lower than that of the asphalt and aggregates. Increasing the fiber content and length also led to higher values of air voids, VMA, and VFA, due to the expansion of the total surface area of both the fibers and aggregates. These findings align with those in [26].

TABLE VI. MARSHALL TEST RESULTS

WJF %	**O.A.C %**	**S kN**	**F mm**	**D g/cm³**	**A.V %**	**V.M.A %**	**V.F.A %**
Control							
0	5.9	10.16	4.28	2.348	4	16.12	75.18
WJF length=(5 mm)							
0.1	6.09	10.45	3.75	2.342	4	16.52	75.78
0.3	6.25	10.8	3.65	2.336	4	16.85	76.26
0.5	6.45	11.05	3.57	2.333	4	17.15	76.67
0.7	6.64	10.17	3.49	2.327	4	17.53	77.18
WJF length (10 mm)							
0.1	6.12	10.92	3.69	2.332	4	16.91	76.34
0.3	6.3	11.38	3.56	2.325	4	17.28	76.85
0.5	6.51	12.1	3.48	2.322	4	17.61	77.28
0.7	6.7	10.72	3.42	2.315	4	18	77.77
WJF length=(15 mm)							
0.1	6.13	10.7	3.56	2.322	4	17.27	76.83
0.3	6.33	11.03	3.5	2.316	4	17.65	77.33
0.5	6.54	11.56	3.43	2.313	4	17.94	77.7
0.7	6.75	10.54	3.36	2.306	4	18.36	78.21

B. Drain Down Test

The outcomes of the drain-down tests are illustrated in Figure 7. The drain-down values were noticeably higher in the original control mixtures. Increasing the fiber dosage generally led to a reduction in the drain-down levels. Specifically, incorporating WJF at a concentration of 0.7% and a length of 5 mm reduced the drain-down value to as low as 0.05%. This effect is attributed to the inherent properties of WJF, such as its slightly coarse structure, which enhances the bitumen absorption.

The results further indicated that for a fixed fiber content, increasing the fiber length negatively affected the drain-down performance. As the fiber length increased, the fiber dispersion within the mixture decreased, limiting the fiber's ability to act as an absorbing membrane. These findings are consistent with those reported in [25, 47].

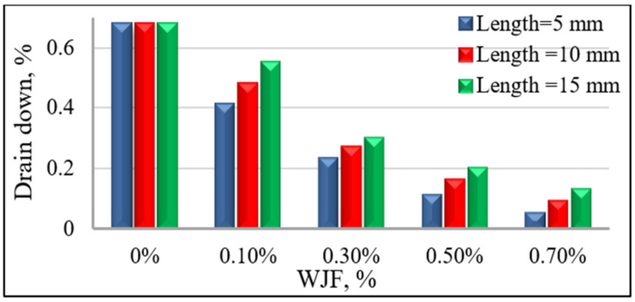

Fig. 7. Drain down test.

C. Indirect Tensile Strength Test Results

The ITS test estimates a mixture's sensitivity to moisture. The TSR is then utilized to distinguish between mixtures susceptible to moisture and those resistant, with 80% being the minimum proposed threshold, according to [44]. A high TSR value indicates that the mixture effectively halts moisture-related deterioration. It is clear from the data shown in Figures

8-13 that, compared to the control mixture, WJF mixtures under unaged, ST, and LT aging conditions had greater ITS values for both the conditioned and unconditioned samples. The addition of WJF resulted in a rise in ITS up to a dose of 0.5% for all fiber lengths after which the values started to decrease when WJF increased to 0.7%. The ITS values were higher for 10 mm than for 5 mm and 15 mm fibers. The fibers' coarse and fibrous texture promotes the mechanical interlocking with the asphalt binder and aggregate matrix. At the same time, the elevated surface area of WJF enhances the bitumen absorption and bonding efficacy, resulting in a more cohesive internal structure and, therefore, improved ITS values of the fiber-reinforced mixture. Additionally, more fiber was observed on the fractured surface with less adhesion when the fiber concentration increased, leading to a decrease in the ITS values. These findings are in line with those reported in [27, 28]. The aging process increased ITS, attributable to the heightened stiffness of the asphalt mixtures, as oxidation and volatile loss augment the mixture hardness. The increased ITS value in SMA can be ascribed to the augmented binder content and binder type. The results are consistent with those in [10, 29]. The highest improvement rate was at 0.5% WJF with a length of 10 mm, as illustrated in Table VII.

TABLE VII. HIGHEST IMPROVEMENT RATE IN ITS TEST RESULTS

Conditions	**Dry ITS**	**Wet ITS**	**TSR%**
Unaged	19.24%	36.1%	14.12%
ST aging	25.19%	46.1%	16.69%
LT aging	37.12%	63.7%	19.39%

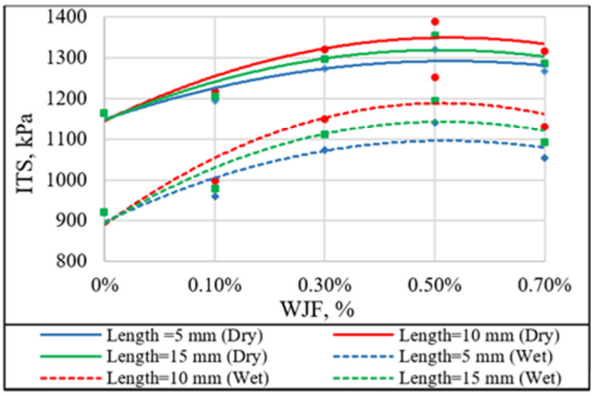

Fig. 8. The effect of WJF on dry and wet ITS for unaged conditions.

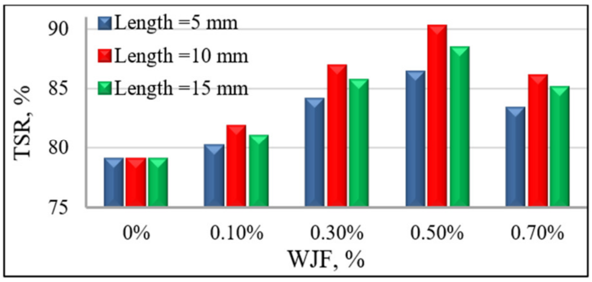

Fig. 9. The effect of WJF on TSR% for unaged conditions.

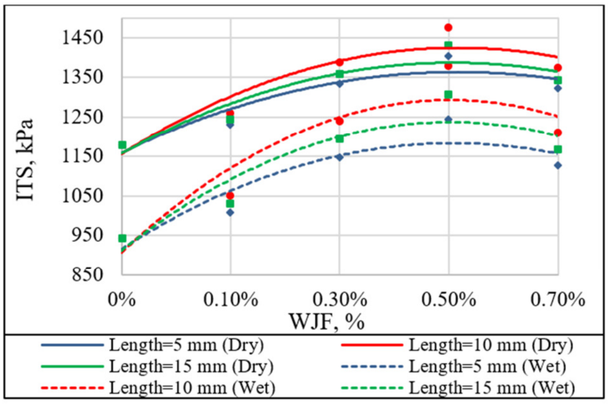

Fig. 10. The effect of WJF on dry and wet ITS for ST aging conditions.

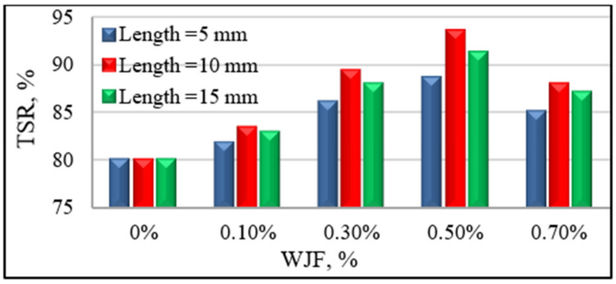

Fig. 11. The effect of WJF on TSR% for ST aging conditions.

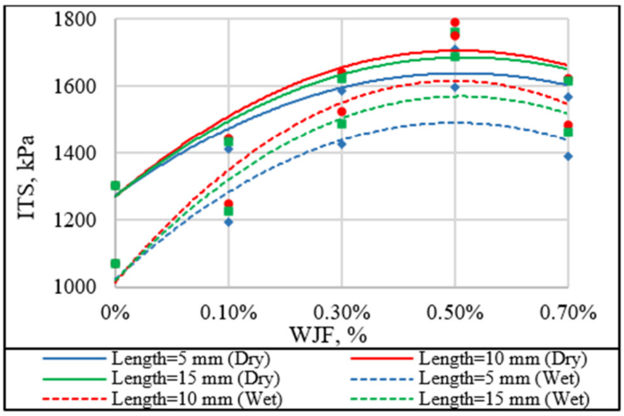

Fig. 12. The effect of WJF on dry and wet ITS for LT aging conditions.

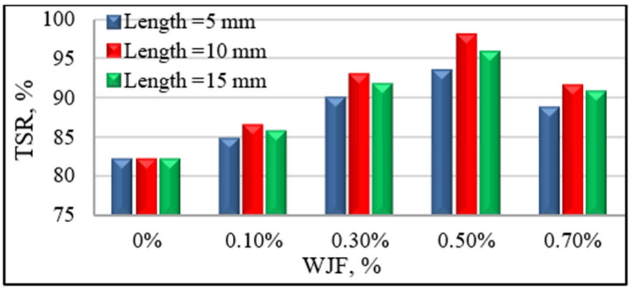

Fig. 13. The effect of WJF on TSR% for LT aging conditions.

D. Compressive Strength Test Results

The Iraqi specification estimates the moisture-induced damage to asphaltic mixes using the IRS parameter. According to SCRB/R9 [34], IRS is restricted to a minimum value of 70%. The data shown in Figures 14-19 indicate that in comparison to the control mixture, the WJF mixtures under unaged, ST, and LT aging conditions exhibited higher compressive strength values for both the conditioned and unconditioned samples. The incorporation of WJF increased the compressive strength up to a concentration of 0.5% for all fiber lengths after which a decline was observed when the WJF content was increased to 0.7%. The compressive strength values were higher for 10 mm fibers compared to both the 5 mm and 15 mm lengths.

The coarse and fibrous structure of the fibers facilitates the mechanical interlocking with the asphalt binder and aggregate matrix. The increased surface area of WJF enhances the bitumen absorption and bonding effectiveness, leading to a more cohesive internal structure and, consequently, improved compressive strength in the fiber-reinforced mixtures. Moreover, an increase in fiber concentration resulted in more fragmented surfaces with reduced adhesion, which led to a decrease in compressive strength.

The aging process also led to an increase in compressive strength, a result attributed to the enhanced stiffness of asphalt mixtures caused by oxidative hardening and the loss of volatile components. This stiffening effect contributed to higher mixture hardness over time. Among the tested configurations, the most notable improvement was observed at 0.5% WJF with a fiber length of 10 mm, showing the highest gain compared to the control mixture, as exhibited in Table VIII.

TABLE VIII. HIGHEST IMPROVEMENT RATE IN COMPRESSIVE STRENGTH TEST RESULTS

Conditions	Dry compressive strength	Wet compressive strength	IRS%
Unaged	21.37%	44.37%	18.95%
ST aging	26.71%	54.29%	21.77%
LT aging	38.1%	75.25%	26.44%

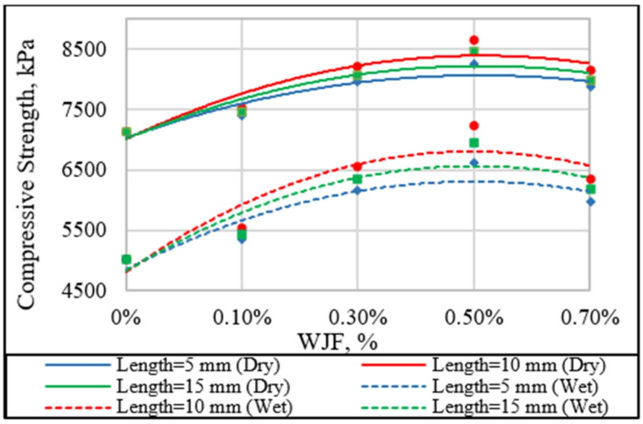

Fig. 14. The effect of WJF on dry and wet compressive strength for unaged conditions.

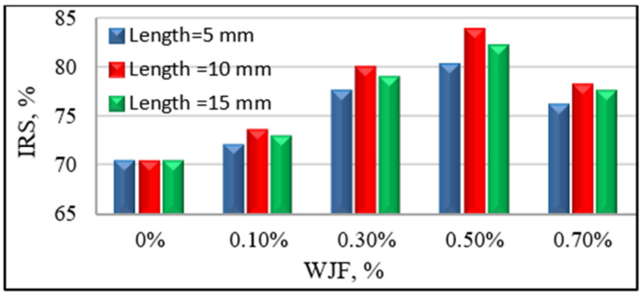

Fig. 15. The effect of WJF on IRS% for unaged conditions.

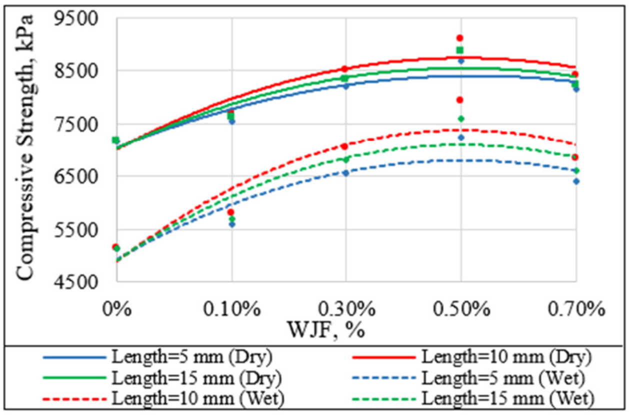

Fig. 16. The effect of WJF on dry and wet compressive strength for ST aging conditions.

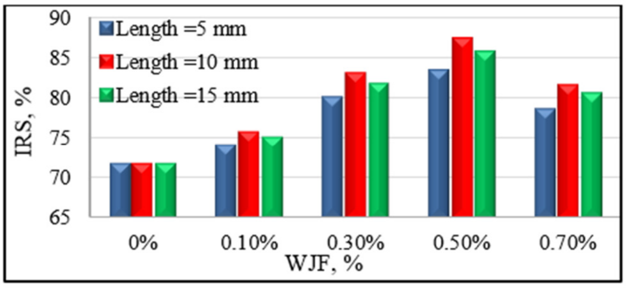

Fig. 17. The effect of WJF on IRS% for ST aging conditions.

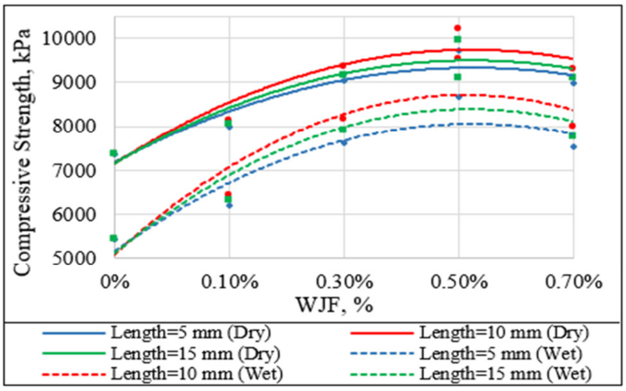

Fig. 18. The effect of WJF on dry and wet compressive strength for LT aging conditions.

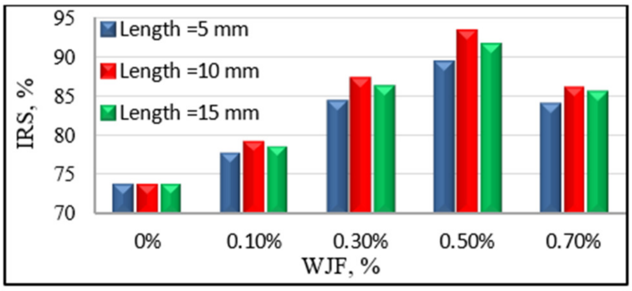

Fig. 19. The effect of WJF on IRS% for LT aging conditions.

V. CONCLUSIONS

This study evaluated the effect of Waste Jute Fiber (WJF) of varying lengths and contents on the moisture damage resistance and mechanical properties of Stone Matrix Asphalt (SMA) mixtures. The mixtures were prepared using asphalt cement with a 40/50 penetration grade and crushed aggregate under three aging conditions: unaged, Short-Term (ST), and Long-Term (LT) aging.

The addition of WJF enhanced the Marshall characteristics of the SMA mixtures. The stability values increased with a fiber length and content up to a certain threshold after which they declined. The highest increase in Marshall stability was 19.1%, achieved at a WJF content of 0.5% and a fiber length of 10 mm. The flow values decreased with the incorporation of WJF, with the maximum reduction observed at 15.36% for 0.7% WJF content and 15 mm fiber length. WJF also increased the air voids and Voids in Mineral Aggregate (VMA), resulting in lower bulk-specific gravity.

Higher fiber dosages led to reduced drain-down, and shorter fibers proved more effective. The lowest drain-down value recorded was 0.05%, corresponding to 0.7% WJF content with 5 mm fiber length. The use of WJF also had a positive effect on the moisture sensitivity, offering both mechanical benefits and environmental advantages through the reuse of waste material.

WJF-reinforced mixtures exhibited higher Indirect Tensile Strength (ITS) than those without fiber. Aged specimens showed greater ITS values due to binder hardening, with the most significant increase occurring under LT aging. The optimal combination of 0.5% WJF content and 10 mm length yielded the highest Tensile Strength Ratio (TSR) improvements of 14.12%, 16.69%, and 19.39% for unaged, ST, and LT aging conditions, respectively.

Similarly, the compressive strength of the WJF mixtures was superior to that of the control mixtures. Aging contributed to enhanced compressive strength due to the increased binder stiffness. The combination of 0.5% WJF content and 10 mm fiber length resulted in the highest Index of Retained Strength (IRS) improvements of 18.95%, 21.77%, and 26.44% under unaged, ST, and LT aging, respectively.

Overall, based on the results of this study, incorporating 0.5% WJF with a length of 10 mm significantly improves the durability and moisture resistance of the SMA mixtures.

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