Investigating the Impact of Palm Leaf Fibers on the Crack Resistance of Hot Asphalt Mixtures

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ABSTRACT

Sustainability attracts high interest in various fields. Over 95% of roads are paved using Hot Mix Asphalt (HMA), consequently, employing one sustainable material adds significant value. In this work, modified dry methods are suggested to generate modified balls including Palm Leaf Fibers (PLFs). This study aims to evaluate the extent of improvement in HMA crack resistance using these balls. Measurements of volumetric characteristics, mixture sensitivity to moisture damage, and crack-related tests, namely, the Ideal-CT test, the Indirect Tensile Strength test (ITS), the fracture energy (G_f), the Cracking Resistance Index (CRI), the Flexibility Index (FI), and the Toughness Index (TI) were performed to assess the tensile strength of the mixtures. The results showed that the method deployed to create HMA using PLFs was effective in preventing cracks. Moreover, the results suggest that utilizing ITS test alone is insufficient in capturing all phases of mixture behavior since this test resistance to tensile cracking is largely dependent on the peak load whereas there are numerous characteristic indices, such as the CT-index, which provide a more accurate assessment. Therefore, this study offers a significant sustainable approach by modifying the mixing and improving the cracking resistance.

Keywords-crack resistance; cracking tolerance index; indirect tensile strength; modified balls; modified dry process; modified hot asphalt mixtures; palm leaf fiber; waste materials

I. INTRODUCTION

Pavements, a necessary part of most transportation infrastructures, are directly involved with economy, sustainability, and safety, all of which have prominent profiles in the field of transportation engineering these days. Hot Mix Asphalt (HMA) is the most commonly used type of asphalt, with most pavements worldwide being constructed with it [1, 2]. Fatigue behavior is one of the most significant factors reducing the life of road pavement; it begins with micron cracks on the bottom of the asphalt layers and gradually spreads to the upper layers. This is because pavements face a variety of simple and compound forces due to the increasing number of transportation vehicles in the world, and the resulting dimension increase of transportation vehicles [3, 4]. Wear and tear or alligator cracks, edge cracking, grade depressions, block cracking and slipping, potholing, revealing, shoving, stripping, and rutting are examples of pavement's degradation. Even within a single season, in cold climates [5, 6], significant fissures in the asphalt mixture might arise from groundwater freezing beneath the surface layer. The effective adhesive layer in the asphalt concrete is created by asphalt mastic, which is primarily made up of mineral filler and asphalt binder. It is usual for viscoelasticity to cause temperature-dependent susceptibility and weak tensile behavior [7, 8].

Using specific additives, like fibers or polymers, to alter and enhance the mix's characteristics is one method to extend the life of road surfaces. When it comes to designing flexible pavements, modifying the bituminous mixture with fibers or polymers seems to offer the greatest potential for success in terms of extending the pavement's service life or thinning out the pavement layer or base thickness [9-11]. Fibers have been utilized from ancient times to provide brittle materials with more durability, hardness, and tensile strength, all of which help to postpone the breaking process. Although asphalt mixes exhibit viscous elastic behavior, they behave like brittle materials at mid-to-high pavement temperatures [4, 12-14]. Bitumen modifiers have been grouped into many primary categories based on their composition through certain studies that have been carried out. These groups include polymers, fillers, fibers, hydrocarbons, anti-stripping compounds, and crumb rubber. Because of the large variations in these additives' physical and chemical characteristics, the performance of asphalt concrete pavements is affected in many ways. The mixture becomes less stiff in colder temperatures and stiffer in hotter ones according to the asphalt additions.

Under typical temperatures, they regulate the mixture's suppleness [15-17]. Thus, assessing the asphalt mix's cracking potential during the design stage can significantly reduce fatigue cracking and lengthen the flexible pavement's useful life. Therefore, it is imperative to utilize a straightforward, however, dependable performance test indicator. For many years, the Indirect Tensile Strength test (ITS) is the industry standard and most recognized method for determining mixture resistance to cracking. For a considerable amount of time, the ITS will be the standard for determining a mixture's durability, as well. It is worth noticing that only the highest tensile stress of a particular combination can be represented by the ITS. The relevant phases of crack propagation and initiation are not well identified. Some mixes get weaker when they reach their maximum loading, while others continue to withstand some force [18-20].

II. RESEARCH AIM AND SCOPE

This research aims to examine the cracking characteristics of dense-HMA by enhancing its qualities with green fibers. The work attempts to address the phenomenon of predicted pavement cracking failure, which will help to clarify the HMA. Currently, there is little discussion of this topic in the HMA literature and especially regarding their resistance to cracking. Thus, the parameters considered for comparison will include volumetric characteristics and susceptibility to moisture damage. The research shows how the added Palm Leaf Fibers (PLFs) might improve the cracking properties of a sustainable HMA. The scope of the research is provided below:

- Whenever feasible, the HMA's were prepared to meet national specifications. As a result, attention was drawn to factors such mixture particle sizes and gradation, mechanical property range, and durability restrictions.
- A new process is proposed for creating an HMA sample, utilizing a modified dry method, which entails generating improvement by using little balls to illustrate the impact of adding a different additive to the HMA by 2%, 4%, and 6% of aggregate weight.

III. EXPERIMENTAL PLAN AND SAMPLE PREPARATION

A. *Materials*

The aggregate materials (coarse and fine) with a Nominal Maximum Aggregate Size (NMAS) of 12.5 mm were provided from Karbala quarry. They were categorized in accordance with the Iraqi General Standard for Roads and Bridges (GSRB) R9 [21] (Figure 1). Tables I and II present the physical properties of the coarse and fine aggregates, respectively. Asphalt cement (grade type 40–50) was provided by the Al-Neisseria factory, and bitumen emulsion (Nitoproof 30) was produced by the FOSROC firm. Tables III and IV show the properties of asphalt and bitumen emulsion. Three different types of fillers were used: Conventional Mineral Filler (CMF), Hydrated Lime (HL), and Plaster Of Paris (POP). Table V lists the characteristics of them.

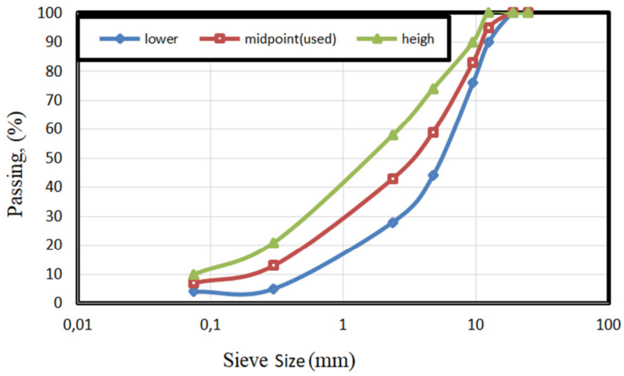

Fig. 1. Distribution of the chosen aggregates' size.

TABLE I. PHYSICAL PROPERTIES OF COARSE AGGREGATE

Coarse Aggregate			
Property	**Value**	**Standard**	**GSRB Specification**
Bulk Density, gm /cm^3	2.546	ASTM C127	-
Apparent Density, gm /cm^3	2.684	ASTM C127	-
Water Absorption, %	2.033	ASTM C127	-
Percent Wear, %	24.19	ASTM C131	30% Max
Clay Lumps, %	0.065	ASTM C142	3%, Max

TABLE II. PHYSICAL PROPERTIES OF FINE AGGREGATE

Fine Aggregate			
Property	**Value**	**Standard**	**GSRB Specification**
Bulk Density, gm /cm^3	2.559	ASTM C128	-
Apparent Density, gm/cm^3	2.65	ASTM C128	-
Water Absorption, %	3.175	ASTM C128	-
Clay Lumps, %	3.71	ASTM C142	3%, max
Material finer than #200%	3.842	ASTM C117	45% Max
Sand equivalent, %	48	ASTM D2419	Min.45

TABLE III. PROPERTIES OF ASPHALT

Property	Test Values	ASTM Designation	GSRB Requirements
Penetration, 100 gm, 25°C, 5 sec (1/10 mm)	48	D5	40-50
Specific Gravity, 25 °C (gm./cm^3)	1.03	D70	-
Ductility, 25°C, 5 cm/min (cm)	146	D113	>100
Flash Point, (°C)	344	D92	>232
Softening Point (°C)	47.8	D36	-
Rotational viscosity, Pa.s	@170 -165°C @280 -153°C		

TABLE IV. PROPERTIES OF BITUMEN EMULSION

Property	Value
Form	Dark brown liquid
Specific gravity	1.00
Solid's content	60 to 65%
Rubber content	Approx. 10 %
Drying time	30 minutes at 25°C
Over coating time	1 hour @ 25°C

Also, palm leaves were used to create cellulose fibers (PLF). Finally, a percent of solvent (Table VI) was utilized for reducing the viscosity of the emulsion.

TABLE V. PROPERTIES OF USED FILLERS

Physical Properties of Fillers			
Properties	**Filler Type**		
	CMF	**HL**	**POP**
Specific Surface Area (m^2/kg)	223	1241	900
Density (gm/cm^3)	2.652	2.301	0.73
Chemical Properties (XRF)			
SiO_2	81.891	0.892	0.68
$Al2O_3$	3.783	------	0.34
Fe_2O_3	1.922	2.255	0.07
CaO	7.370	90.585	33.48
MgO	3.454	3.604	0.69
K_2O	0.735	0.590	0.05

B. *Fiber Preparation*

In order to turn palm leaves into fiber, they were first dried and then cut. The selected fibers passed No. 16 sieve and were retained on No. 200.

C. *Additive Preparation*

Modified Dry Process (MDP) is a newly introduced process based on the dry process and is suggested to guarantee sufficient fiber dispersion in the mixture. During the process all the enhancing materials: fiber, hydrated lime, emulsion, solvent, and plaster of Paris, are mixed together in various proportions, as exhibited in Table VI, creating six groups of small balls P_1, P_2, P_3, P_4, P_5, and P_6 (Figure 2). Those balls will be added later to a standard hot mixture of asphalt, at laboratory temperature.

TABLE VI. THE PERCENTAGE OF HMA'S ADDITIVE MATERIALS

Mix type	Add. %	Add. type	Additive Ingredients				
			Palm fiber %	Paris plaster %	Hydrated Lime %	Emulsion %	Solvent %
HMA0	0	-	0	0	0	0	0
HMA-P_1	2%	P_1	13	2	20	65	10
	4%						
	6%						
HMA-P_2	2%	P_2	17	2	20	61	10
	4%						
	6%						
HMA-P_3	2%	P_3	21	2	20	57	10
	4%						
	6%						
HMA-P_4	2%	P_4	25	2	20	53	10
	4%						
	6%						
HMA-P_5	2%	P_5	29	2	20	49	10
	4%						
	6%						
HMA-P_6	2%	P_6	33	2	20	45	10
	4%						
	6%						

D. *Experimental and Sample Design*

In order to satisfy the requirements of the experiment design, the asphalt mixtures were created in two phases using two samples. The traditional mixture utilized in the first stage, known as the control mixture, includes aggregate graded in accordance with the Iraqi GSRB R9 [22]. Coarse and fine aggregates are included, along with three different types of filler, namely: 5% LimeStone Dust (LSD), 2% Hydrated Lime (HL) (used in the mixture and 20% of it was utilized for ball preparation), as well as five different concentrations of neat asphalt (4%–6%, with a 0.5% used in the increment step). The Optimum Bitumen Content (OBC) of the HMA-Control mixture was determined to be 5.5% of the sample's weight, in accordance with the Marshall design method D6927. Indexes of Marshall Test of Surface Coarse according to GSRB are illustrated in Table VII.

(a) (b)

Fig. 2. The enhancer materials: (a) final shape, (b) six different groups.

TABLE VII. INDEXES OF MARSHALL TEST

Index	GSRB limits
Stability Value, KN	> 8
Flow Value, mm	2- 4
Air Void (%)	3- 5
Void Mineral Aggregate (%)	>14

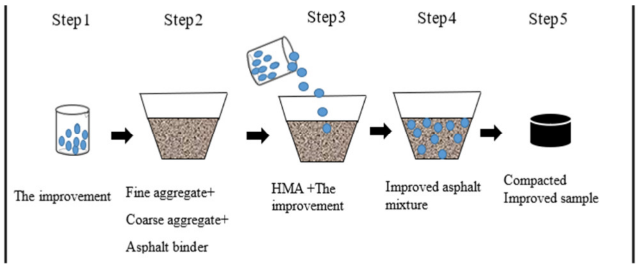

Fig. 3. Procedure steps.

The second phase is to evaluate the asphalt mixture's mechanical and volumetric qualities to determine the best modified mixture. The modified mixtures for which the OBC has been determined are enhanced in the second stage by adding the small balls of the improvements in percentages of 2%, 4%, and 6% of the aggregate weight (Table VI). The mixing time for the mixture with balls was extended to two minutes in comparison to that of the traditional mixture in order to guarantee that the balls spread evenly under the same conditions. Figure 3 depicts the steps of the procedure.

IV. EXPERIMENTAL TEST AND CONDITIONS

A. Volumetric Properties

The size and number of air voids are determined in accordance with D2041 / D2041M and the Marshall properties were utilized to determine the mixes OBC.

B. Cracking Resistance Test

1) Indirect Tensile Strength Test (ITS)

The tensile strength test is carried out to characterize the stiffness of a bituminous mixture. It is conducted in compliance with the American Society for Testing and Materials (ASTM) D4867/D4886M. Tensile strength is created along the test sample's diametrical axis. The toughness of the sample is determined by integrating the area under the ITS curve against horizontal deformation.

2) Cracking Tolerance Index (CT-Index)

Although the ITS test is frequently used to assess the cracking potential of asphalt paving mixtures, more advanced distinct cracking characteristics are needed to define the cracking stages. Many research works [22-24] suggested that the indices of the load (force) displacement curve from an ITS test have the capacity to describe the Cracking Tolerance (CT) index. It was discovered that the CT index is sensitive to important mixture components, including recycled asphalt mixtures, age levels, binder contents, and air voids with unmodified asphalt mixtures. Moreover, it is sought to incorporate a dependable, user-friendly, and efficient fatigue performance-based quality test into the mixture design phase. To assess the cracking potential of the mixes, the recently developed indirect tensile asphalt cracking test (IDEAL-CT) is gaining popularity. The ASTM D8225 describes the IDEAL-CT.

The CT-index is a simple substitute test indication for the indirect tensile strength test that can be used to evaluate how well mixtures resist breaking [25]. In 2017, the Texas A and M Transportation Institute developed this brand-new test [26]. The mixture's capacity to support loads decreases when micro-cracks start to form after it reaches the pinnacle of its load-bearing capacity. To effectively depict the stages of cracking resistance, multiple factors are required. The popular ITS test does not identify the breaking phases precisely. Without taking into account the crack propagation resistance, the maximum preserved tensile strength of a specimen determines the ITS index. Although a mixture's tensile strength or maximum load may be the same, its ability to absorb energy may vary. Accurate evaluation is not ensured by using the fracture energy parameter in a crack index formula. The breakdown of asphaltic pavement brought on by crack propagation (cracking velocity) is explained by post peak cracking resistance. The CT-index offers better reliability for assessing fracture resistance. Table VIII provides a summary of the ITS test and CT-Index conditions.

The CT_{index} measurement (1) [27] is a crucial performance metric for preventing cracking since it implicitly takes into account the crack propagation phase's performance (the post peak slope).

$$CT_{Index} = \frac{t}{62} \cdot \frac{G_f}{m_{75}} \cdot \frac{l_{75}}{D} \tag{1}$$

where t is the thickness (mm), D is the diameter (mm), and G_f is the fracture energy (Joules/m^2) [28], which is defined as the amount of energy absorbed to create a unit area of a crack and is measured by:

$$G_f = \frac{W_f}{D \cdot t} \cdot 10^6 \tag{2}$$

where W_f is the work of failure (the area under the load-displacement curve) in Joules.

Furthermore, m_{75} calculates the absolute value of the local slope (N/m) and is measured by:

$$m_{75} = \left| \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \right| \tag{3}$$

where P_{85} and P_{65} represent the peak load percentages (85% and 65% of the peak load (N)) during the breakdown stage, respectively, l_{85}, l_{65}, and l_{75} represent the displacement (mm) at P_{85}, P_{65}, and P_{75}, respectively.

TABLE VIII. ITS AND CT-INDEX CONDITIONS ACCORDING TO ASTM.

Parameter	Standard	Used Value
Number of Required Specimens	3	3
Rate of the Applied Load mm/min	50 ± 5	50
Measuring Device accuracy	Min. 0.01 N	0.01 N
Temperature of the Test, ºC	25 ± 2	25
Diameters of Specimen, mm	101.6, 150	101.6
Thickness of Specimen mm	50.8-65.5	63.5 ± 2.5
Compaction, Marshall Hammer	75x 2	75x2
Specimen Conditioning before Test	2 hr.	2 hr.
Measuring Device Accuracy	Min. 0.01 N	0.01 N

3) Cracking Resistance Index (CRI)

The CRI index was established by authors in [29]. It demonstrates the overall performance of crack resistance and does not provide specific details for the phases of fracture initiation or propagation [30]. It is measured using:

$$CRI = \frac{G_f}{P_{\max}} \tag{4}$$

where P_{max} is the maximum load (force) in N.

4) Toughness Index (TI)

The TI is simply determined using the post-peak G_f, which is indicative of the energy absorbed during the crack propagation, while it cannot provide information on the crack's beginning [25, 31]. The TI is a crucial component in analyzing the performance and cracking behavior of asphalt mixtures under various circumstances [32]. The *TI* value can be measured by:

$$TI = G_{f,post-peak} \cdot \left(\Delta mdp - \Delta P_{\max} \right) \cdot 10^{-3} \tag{5}$$

where $G_{f,post\text{-}peak}$ is the post-peak failure energy, ΔP_{max} indicates the displacement at the maximal load, and Δmdp is the displacement at 50% of the maximum load.

5) Strain Tolerance

The strain tolerance of the asphalt mix at a 75% load decrease is represented by the quotient: $\varepsilon = l_{75}/D$.

6) Illinois Flexibility Index Test (I-FIT)

This test suggests a testing temperature of 25°C and a loading rate of 50 mm/min. Equation (6) calculates Flexibility Index (FI), which is used by the I-FIT to characterize the resistance of asphalt mixtures to cracking. It has been demonstrated via studies that FI is sensitive to variations in mixture factors and aging circumstances [33-37]. In general, the *FI* values span from 1 to 30, representing the asphalt mixtures that perform the worst to the best.

$$FI = \frac{G_f}{m_{75}} \cdot 10^{-2} \quad (6)$$

7) Tensile Strength Ratio (TSR) - Durability Test

In order to calculate the water damage, ASTM D4867/D4886M states that the calculated Tensile Strength Ratio (TSR) is equal to the quotient of the unconditioned samples' average split tensile strength at 25°C and the conditioned samples' average split tensile strength at 60°C (7).

$$TSR\% = \frac{ITS\ of\ conditoned\ specimen}{ITS\ of\ unconditoned\ specimen} \cdot 100\% \quad (7)$$

V. RESULTS AND DISCUSSION

A. Volumetric Properties

The results (Figure 4) generally indicate that adding the additive reduces the modified HMA's density very slightly, when compared to the controlled HMA0. However, the samples with 2% additive of type P_1, P_2, and P_3 mixtures suggest an exception, with their densities seeing a limited rise. Conversely, a gradual but not very significant drop in densities is recognized upon raising the additive dosage from 2% to 6%.

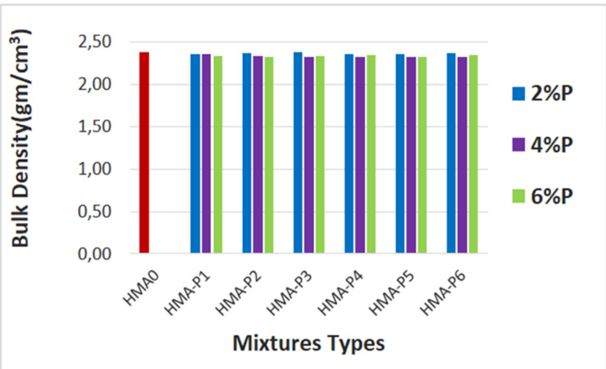

Fig. 4. Density results.

Increasing the proportion of bitumen emulsion, increases the proportion of asphalt and its viscosity because of the lubricating effect of the emulsion, which aids in the particles sliding over one another and slightly decrease air voids, as can be seen in Figure 5. When the improver's dosage is increased, the amount of bitumen emulsion decreases and the amount of PLF increases. This results in increasing the friction between the aggregate particles and the additive, while the air gaps are reduced because of the particles adhering to one another more firmly. Therefore, it is essential to carefully consider how these components affect air spaces while constructing asphalt mixtures for their best performance and longevity to be accomplished.

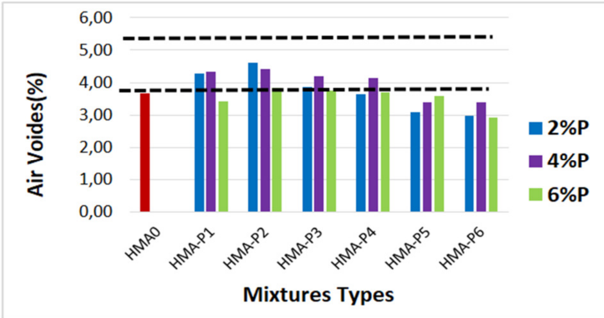

Fig. 5. Air Void results.

B. Indirect Tensile Strength

Figure 6 demonstrates that the modified HMAs have significantly changed in contrast to the controlled HMAs in terms of the ITS results. For example, the HMAs with the addition of 2% additive have higher ITS values than the controlled HMAs for all mixture types. As the fiber content of the palm leaves increased, the ITS of the combination containing 2% additions improved steadily, reaching 16.20% for P_5, and slightly decreased for P_6. This differentiation in P_6 might be a result of strengthening asphalt mixture resistance to cracking due to an increase in fiber over the emulsion. When the improver is added, the bitumen emulsion begins to diminish and the PLF begins to rise. This causes the asphalt mixture to become brittle, which in turn causes the indirect tensile strength to decrease. This increment is identical for all types of mixtures but with lower ITS values compared to the controlled HMA0. Based on the modified dry process method, the improved HMAs yielded the best combination for the mixture P_5.

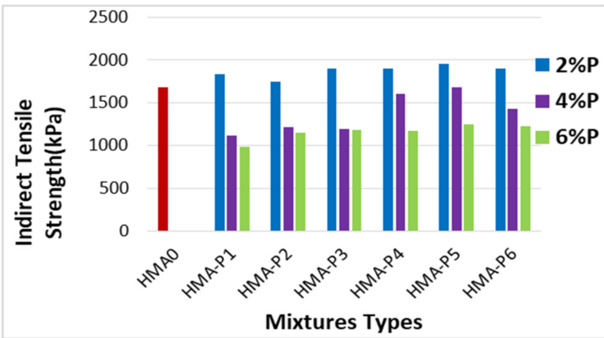

Fig. 6. ITS results.

C. Cracking Tolerance Index (CT-Index)

The modified HMAs' display a significant change in contrast to the controlled HMA0 in terms of the G_f results (Figure 7). For example, HMAs with 2% addition have higher G_f values than the HMA0 for all mixture types. As the fiber content of the palm leaves increased, the ITS of the combination containing 2% additions improved steadily, reaching 55.47% for P_3 and P_4, and slightly decreased for P_6. Conversely, the mixture containing 4% and 6% modified balls was inferior in G_f values compared with the HMA0 mixture.

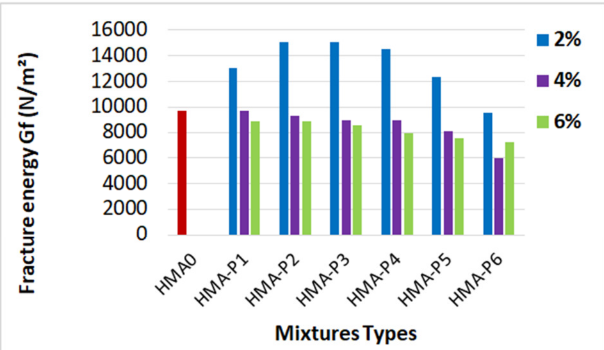

Fig. 7. Fracture energy results.

Figure 8 shows the results of failure energy (G_f-CI) (the energy required until the initiation of a crack) for all mixtures. All mixtures with 2% modified balls have higher G_f-CI than HMA0. The best value of G_f-CI is in HMA-P_2 so the optimum value of additives is the 87.83% of the P_2. As the fiber content of the palm leaves increased, the G_f-CI of the combination containing 4% additions improved steadily, reaching 58.31% for P_3, with a slight decrease for P_6. In the increased dosage of 6% modified balls, they all have a G_f-CI that is less than the G_f-CI of the HMA0, except HMA-P_3 and HMA-P_5, respectively as 12.5% and 0.47% from HMA0. Cracking is the first sign of future difficulty, usually caused by water intrusion, even though it is considered a form of distress. For a pavement to function properly and to be durable and preserved, crack initiation must be delayed.

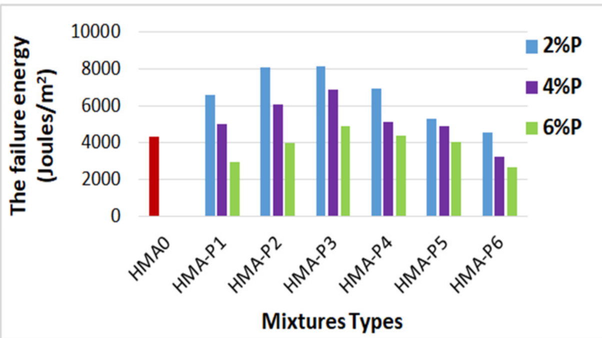

Fig. 8. Required failure energy.

Figures 9-11 depict the loading–displacement curves for all the research mixtures that were modified with PLF balls by 2%, 4%, and 6%, respectively. Adding PLF was found to be efficient in increasing the maximum indirect cracking load of all modified HMAs. The best mixtures, when compared to HMA0, are HMA-P_5 with 2% (Figure 10) and HMA-P_5 with 4% (Figure 11) of additives. Adding PLF in 6% certainly improved the HMAs response to loading although it made them be more brittle than the HMA0 connected to the P_{max} displacement position and relative to the HMA displacement position (Figure 12).

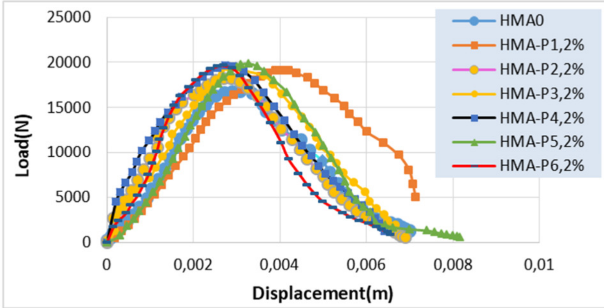

Fig. 9. Load-Displacement curve of HMA 2% mixtures.

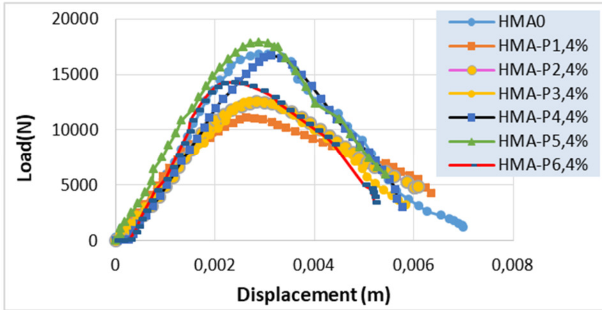

Fig. 10. Load-Displacement curve of HMA 4% mixtures.

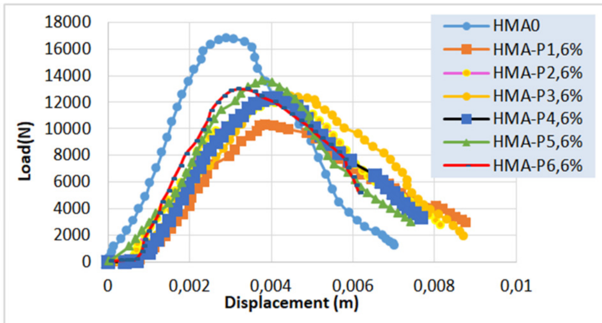

Fig. 11. Load-Displacement curve of HMA 6% mixtures.

The CT indices for the mixtures are presented in Figure 12. It can be assumed that the CT index for the modified HMAs exhibits more favorable characteristics than the HMA0. The CT index for asphalt mixtures ranges from 31 to 255 [30]. Furthermore, the modified HMAs show improvement after adding PLF of 2% for all combinations. The CT index improved steadily, reaching 175% for P_4. The CT index of the combination containing 4% additions improved steadily, reaching 70.54% for P_5 and slightly decreased for P_5 and P_6. However, adding 6% more PLF to the mixtures resulted in a continuous improvement in the CT index. The highest proportion is 181% for HMA-P_3. According to the literature, the failure energy, the slope of the post-peak inflection point, and the strain value at 75% of the peak load value are the three main elements that affect the CT index. The mixture's constituents and volumetric characteristics have a significant impact on these indexes, notably, for the HMA-P5 with higher ITS values in terms of mechanical features. Regarding the components, PLF used emulsion with the asphalt to improve adhesion and cohesion and, eventually, crack resistance. Conversely, the excess of PLF outweighed the binder components and impacted their function, having a lower impact on adhesion and cohesiveness.

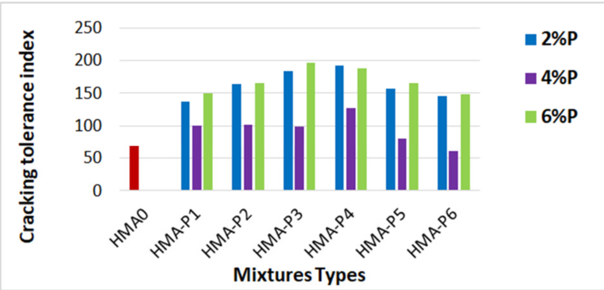

Fig. 12. CT Index results.

The results for m_{75} demonstrate higher magnitudes in all mixtures with 2% of modified balls. Moreover, all mixtures with 4% and 6% of modified balls have a lower m_{75} (Figure 13). When the improver's dosage increases, the amount of asphalt emulsion decreases and the amount of palm leaf fibers increases. This makes the mixtures more brittle than the HMA0, but indicates that the mixtures have better flexibility as a result of the ductility of bitumen emulsion. Therefore, a little slope value for the m_{75} parameter is preferred as it signifies a stronger cracking resistance of the asphalt mixture.

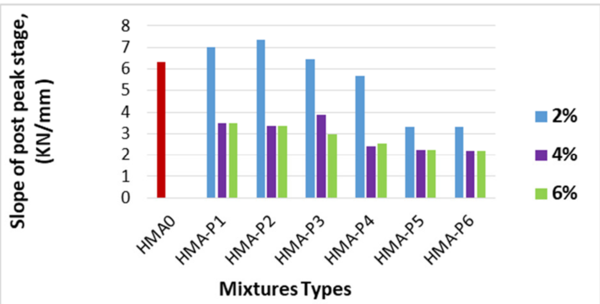

Fig. 13. m_{75} results.

D. Strain Tolerance

The results of strain ε, at 75% of the post-peak load are displayed in Figure 14. The larger value of ε is linked to the ductile material, whilst the lower value indicates the brittleness of the asphalt mixture and/or the beginning of cracks. The PLF's introduction caused ε to rise. As demonstrated in the previous figures, this is further supported by the value of P_{max} and/or ITS when comparing the modified HMAs with the HMA0 with 2% modified balls, in the mixtures HMA-P_1, P_2, P_3, and P_4 that have greater values of ε. This shows that the asphalt mixture resists breaking after peak occurrence and has a good bearing capacity. Mixtures containing 4% additions improved steadily even though a slightly decrease in P_6 was observed, while all combinations of mixtures containing 6% additions have a higher value of ε.

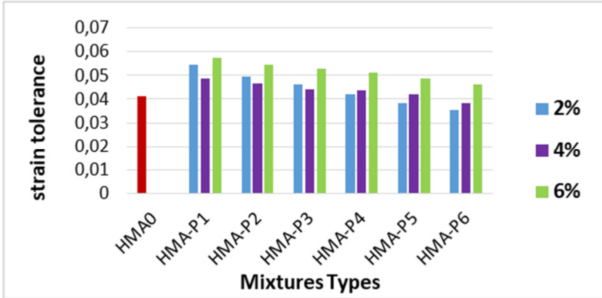

Fig. 14. ε results.

E. Cracking Resistance Index

The mixture with 2% addition has higher CRI values than the controlled HMA0 for all blend types with a slight decrease in P_6 (Figure 15). Conversely, half of the mixtures (P_4, P_5, P_6) with 4% and 6% of the modified balls have values less than HMA0. PLF can enhance the anti-cracking ability of the asphalt mixtures, with the increase in the fiber content resulting in improved cracking resistance up to a certain optimal level. For example, HMA-P_5, with 4% additives, and HMA-P_5, with 6% additives, have a higher value in terms of the ITS of the group P_4, P_5, and P_6, but have a lower value in CRI. A mixture may exhibit a lower CRI value despite having a high peak load resistance and weak energy absorption (area under the load–displacement curve).

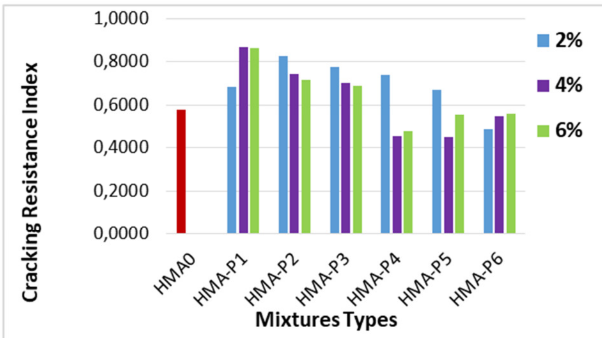

Fig. 15. CRI results.

F. Toughness Index

The TI illustrates the features of post-cracking, or how much post-cracking is related to the material's overall toughness, with the brittle material having a much lower value than that of the ductile material (Figure 16). When the improver's dosage is increases from 2% to 6%, the amount of bitumen emulsion decreases and the amount of palm leaf fibers increases resulting in higher TI values for all the controlled HMA0 for all blend types, with a slight decrease in P_5 and P_6.

Several factors can be attributed to this decline in TI. An excess of fibers can disrupt the asphalt matrix, lowering its ability to resist cracking and deformation and lowering the toughness index. Improper fiber alignment or distribution can result in reduced interlocking and reinforcement, which lowers the toughness index. Additionally, the fibbers' length and aspect ratio can affect the toughness.

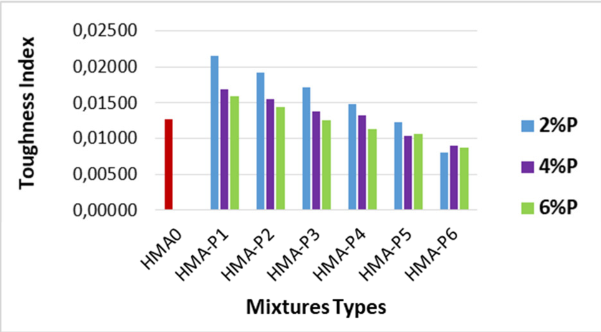

Fig. 16. TI results.

G. Flexibility Index (FI)

Figure 17 shows the results of FI. When the improver's dosage is increased from 2% to 6%, all mixtures have higher FI values than those of the controlled HMA0. The high value in 2% is 86.67% for P6, in 4% is 68.61% for P5, and in 6% is 117% for P6. Bitumen emulsion can improve the cohesion and adhesive properties of the asphalt mixture and the enhanced bonding between the aggregate particles and asphalt binder, which can lead to a more flexible and cohesive mixture, the combination of palm fibers and asphalt emulsion can boost the asphalt mixture's resilience against cracks. As a result, there was less chance of fracture forming and growing, which raised the asphalt mixture's flexibility index.

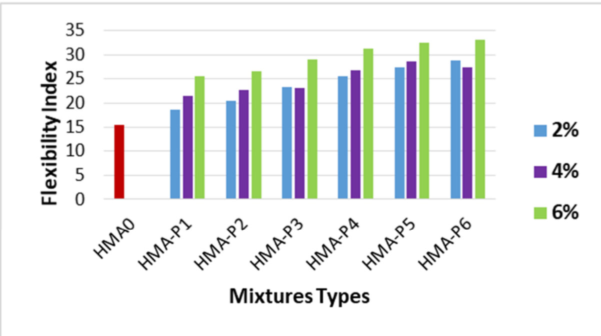

Fig. 17. FI results.

H. TSR Results as Moisture Damage

Figure 18 presents the results of the HMA-P_5 mixture for the TSR, which has a higher value of ITS, while increasing the PLF as modified balls were added. The result is the rising values of TSR in the following order: HMA-P_5, 2% followed by HMA-P_5, 4% and HMA-P_5, 6% with percentages of 1.33%, 9.3%, and 30.66%, respectively. The existence of PLF and bitumen emulsion are critical for creating and improving mixture strength because the specimens are always made by supplying and trapping water from their conditioning. Thus, under these circumstances, cellulose fibers are ready to form bonds with other particles in aggregates.

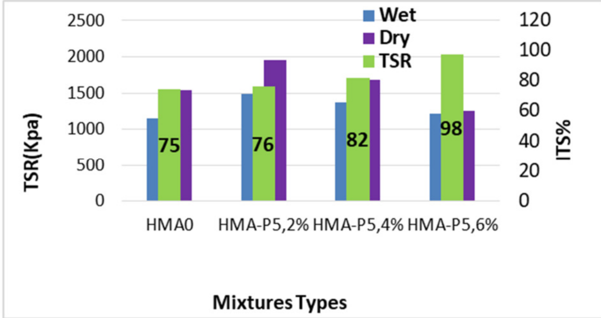

Fig. 18. TSR results of HMA-5, considering moisture.

VI. CONCLUSION

The goal of this study was to assess how well hot asphalt mixtures containing Palm Leaf Fibers (PLFs) cracked. It also looked at how the PLF's presence affected the asphalt mixtures' ability to resist cracking. Beyond the conventional Indirect Tensile Strength index (ITS), other cracking indices were also investigated. The key discovery emphasizes how several stages leading up to the final fracture have an impact on these asphalt combinations' ability to break. Taking into account that several indices provide a more thorough comprehension of material behavior and performance concerning cracking, the following conclusions can be made in light of the testing program and outcome analysis:

- Regarding the Hot Mix Asphalt (HMA), various percentages of PLF as/in the form of modified balls generated by the modified dry process have significantly affected its volumetric and mechanical characteristics.
- The modified dry method effectiveness was proven to enhance the hot mix asphalt in order for it to be used as a structural layer.
- The volumetric properties bulk density, Air Voids (AV), the sum of the volumes of the air voids (VMA), and the percentage of VMA containing asphalt binder (VFA) for the mixture P_2 in the modified HMA displayed the highest values for each of the modified balls, which were: 2%, 4%, and 6%.
- For all 2%, 4%, and 6% of the modified balls, the mixture with the best ITS indication was P_5.
- The study's use of cracking resistance indices shows how successful the proposed design process is at creating modified HMAs. When compared to hot mixtures, these mixes display a higher tensile strength, suggesting better resistance to cracking.
- Pavement cracking resistance can be described illusorily by solely using the ITS value as a criterion. This is because some combinations with high ITS values may have lower fracture energy (G_f) and Cracking Tolerance (CT) index values. The CT index test method is a useful technique, especially for combinations that are more brittle than the

typical hot mix asphalt. It assesses the cracking resistance of mixtures taking crack phases into account.

- When considering different cracking indices and given that each of them depicts a different process associated with cracking, both prior to and during fracture, it is best to think of them as a whole rather than as discrete components.
- A number of cracking performance indicators showed the effectiveness of the sustainable process in using green fibers, or waste fibers, for the creation of newly designed hot asphalt mixtures.
- Concerning the durability and mechanical performance in terms of various cracking indices, it is recommended that the best modified hot mix asphalt is HMA-P_5, as it reflected higher properties than those bof the control HMA0.

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