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Development of Sustainable Cold Asphalt Mixture by Using Biomass Ashes

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Abstract

Cold asphalt mixtures (CAM) have many economic and environmental benefits compared to traditional hot mix asphalt (HMA). However, because such a CAM has weak strength and high air voids, it receives little attention. The main objective of this research is to enhance traditional CAM by integrating two types of biomass ash: palm leaf ash (PLA) and reed ash (RA). The improvement in the mechanical properties of CMA was accomplished by replacing ordinary Portland cement (OPC) with PLA at proportions of 0%, 1.75%, 3.5%, 5.25%, and 7% by dry aggregate weight. RA was added later at concentrations of 0.25%, 0.5%, and 1% based on the dry aggregate weight. The mechanical characteristics and durability were evaluated by the Marshall stability, indirect tensile stress test, and water sensitivity test. The results indicated that 1.5% PLA, 5.5% OPC and 0.45% RA significantly enhanced the Marshall stability, where 15.9 kN were obtained after 3 days and 21.1 kN after 28 days, and this is due to the combined action of both PLA and RA, in addition to OPC activating the production of hydration products.

Keywords: Cold asphalt mix; Marshall test; Palm leaf ash; Reed ash; Water damage.

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1. Introduction

Cold asphalt mixtures (CAM) have gained international interest recently due to their benefits of reduction of emissions and usage of lower energy, in addition to the utilisation of reclaimed asphalt pavement [1]. Such CAM is considered inferior to the traditional hot mix asphalt (HMA) because of the long curing time, elevated air void content, and inadequate early strength necessary for optimal performance [2, 3]. However, limitations such as inadequate early strength and weak adhesion hinder the application of the CAM [4]. It was reported that HMA exhibits greater strength in comparison to CAM [5]; however, HMA significantly affects the environment due to the high temperatures necessary for heating aggregate and bitumen [3]. On the other hand, significant economic and environmental benefits can be achieved by eliminating aggregate heating when using CAM [5]. But using CAM is limited due to its inadequate early-age strength, high air void content, and elevated water damage [3, 6].

Filler, as an essential component in asphalt mixtures, primarily fills air gaps and reduces the interstitial space between particles [3]. This significantly affects the effectiveness of the mixture [7]. It was reported that waste filler materials possessing cementitious qualities can be utilised in CAM. The trapped water can be mitigated through the use of such hydraulic fillers [8, 9]. The incorporation of lime or cement can enhance the initial strength, moisture sensitivity, and resistance to high-temperature deformation of CAM [10]. Furthermore, waste additives such as fly ash, silica fume, and coal waste are currently utilised in CAM to enhance the CAM performance and mitigate the adverse environmental effects [11]. Such additives that partially or entirely replace cement in CAM can substantially reduce carbon emissions [12]. The previous studies did not investigate the integration of local biomaterials into a CAM. Some research has concentrated on (PLA) as a standalone modifier, thereby excluding its integration with other materials [13]. Research demonstrates that the incorporation of fly ash improves temperature stability, density, indirect tensile strength, fracture resistance, and fatigue life under initial high-strain conditions in CAM. However, it results in diminished deformation resistance at high temperatures and exhibits less susceptibility to water damage relative to CAM containing cement [14, 15].

Waste additives can significantly enhance specific properties of CAM. However, the essential mechanisms by which waste additives influence these capabilities remain unclear, hence limiting their application. Studies indicate that the use of additives remains limited in mixtures, and the impact of these materials on the design and functional performance of the mixture has not been sufficiently clarified. Therefore, there is a need to conduct a comprehensive analysis of the mechanical properties.

In this research, a CAM was developed using OPC, PLA, and RA. The aim of this study is to improve the mechanical properties and durability of a CAM containing PLA and RA as filler materials. PLA and RA are produced as by-products from the burning of palm fronds and reeds, and they were implemented due to their environmental and economic benefits.

2. Materials characteristics

2.1- Aggregate

The coarse and fine aggregates employed in this study were obtained from local quarries in Kerbala. The Standard Specification for Roads and Bridges stipulates that coarse and fine aggregates meet the designated parameters [20]. The physical properties of the coarse and fine aggregates utilised in this study are specified in Tables 1 and 2, respectively. Figure 1 illustrates that the aggregates underwent sieving, segregation, and classification to meet the gradation requirements of the prescribed Iraqi standard for surface layer type IIIA [20].

Table 1. Coarse Aggregates' physical parameters.

Property	ASTM Designation	Crushed Coarse NAP.	GSRB Specification (surface course)
Bulk specific gravity, gm/cm^3	C127 [21]	2.62	_
Specific gravity that is apparent, gm/cm^3	C127 [21]	2.66	_
Bulk SSD specific gravity gm/cm^3	C127 [21]	2.62	_
Water absorption,%	127 [21]	0.61	_
The percentage of wear caused by the Los Angeles abrasion	131 [22]	20	35%

Table 2. Fine Aggregates' physical parameters.

Property	ASTM Designation	Fine Virgin aggregate
Bulk specific gravity, gm/cm^3	C128 [23]	2.55
Specific gravity that is apparent, gm/cm^3	C128 [23]	2.74
Water absorption,%	C128 [23]	2.67

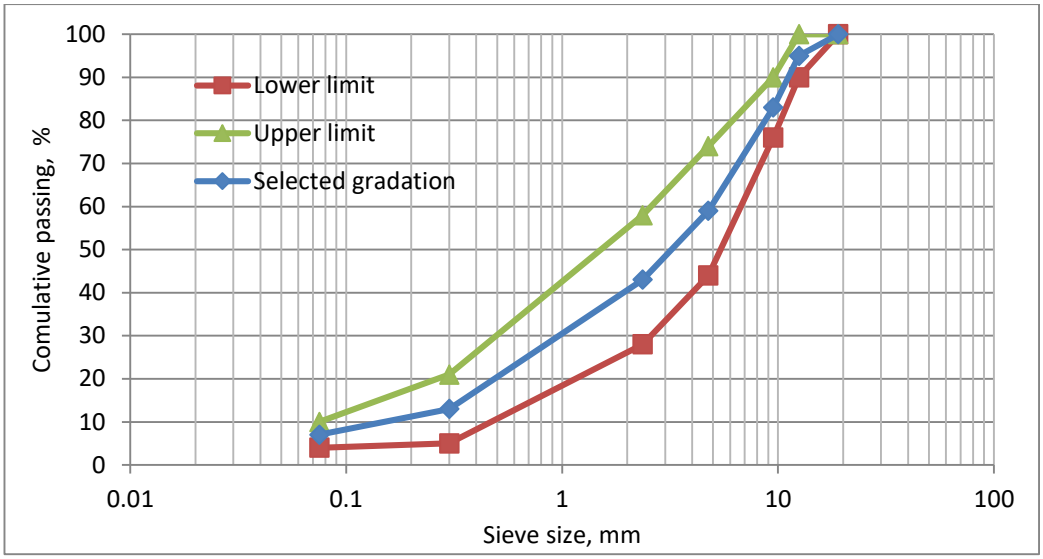

Figure 1. The dense graded worn course of type IIIA that was used and its particle size distribution [20].

2.2 Bitumen Emulsion and Bitumen Binders

The asphalt emulsion utilised in this investigation was Bituproof 12, manufactured by DCP, which was employed to formulate cold asphalt mixtures. The characteristics of the asphalt emulsion provided by the manufacturer are presented in Table 3. A 40/50-pen bitumen grade was utilised to manufacture the hot mix asphalt for comparative investigation, as illustrated in Table 4.

Table 3. Properties of Bituproof 12-bitumen emulsion.

Property	Results
Form	Thixotropic liquid
Colour/appearance	Dark brown liquid
Solid content	> 52
Overcoating time	3 hr @ 25 °C 2 hr @ 35 °C
Application temperature	5 to 45°C
Density	1 ± 0.02 gm/ cm³
Drying time: (for thickness < 0.4 mm)	2 - 3 hr @ 25 °C 1 - 2 hr @ 35 °C
Service temperature	-20 to 60oC
Chemical resistance	Resists to all water based salts, mild alkaline and acid solutions, detergents and most common aqueous minerals
Tensile strength: ASTM D412	0.2 MPa
VOC	< 40 gr/ ltr

Table 4. Properties of 40/50 bitumen binders.

Property	ASTM designation	Test results	GSRB requirements
Appearance		Dark	
Softening point, °C	D36 [24]	47	-
Specific Gravity, 25 °C, gm/cm^3	D70 [25]	1.03	-
Penetration,100gm., 25 °C, 5 sec (1/10 mm)	D5 [26]	45	40-50
Flash point, °C	D92 [27]	320	>232
Ductility, 25 °C, 5 cm/min, cm	D113 [28]	134	>100

2.3. Water

This experiment employed tap water as the prewetting agent for all types of CAM.

2.4. Fillers

Three categories of fillers were selected: ordinary OPC, PLA, and RA. The initial procedure involves reducing the volume by transforming burnt palm fronds and burnt reed into coarse ash; the succeeding step requires heating the material to 900 °C for two hours to achieve calcination [13, 29]. Thereafter, the ash was ground in a milling machine to yield a consistent fine powder. Tables 5 and 6 explain the characteristics of OPC, PLA, and RA according to ASTM C188-15 [30] and ASTM C430-17 [31].

Table 5. physical characteristics of filler.

Physical Properties	RA	PLA	OPC
Color	Light grey	Cream	Grey
Specific surface area (m^2/kg)	1340	930	340
Density (gm/cm^3)	2.4	2.014	2.56

Table 6. Chemical Analysis of RA, PLA, OPC.

Chemical Compositions, %	RA, %	PLA, %	OPC, %
SiO_2	75.9	66.6	19.07
Al_2O_3	8.47	8.55	3.40
Fe_2O_3	0.84	1.87	4.65
CaO	6.5	18.9	67.1
MgO	0.72	1.41	1.52
SO_3	2.2	3.19	2.33
Na_2O	1.6	2.1	

3. Design of CMA

The design process employed in Asphalt Institute MS-14 was used for developing the CAM [32]. The type IIIA surface layer has been selected [20], and the gradient is depicted in Figure 1. The total liquid content (TLC) includes the total prewetting water content, the moisture content of aggregates, and the asphalt emulsion content necessary for adequate coating in the mixture. The initial emulsion content (IEC) denotes the essential emulsion formulation for enduring stability and robustness. TLC was initially created for all mixes, afterwards, altering the emulsion content within the TLC was modified to determine the IEC. The initial residual bitumen content (IRBC) can be determined using the empirical formula shown in the equation below:

$$P = (0.05A + 0.1B + 0.5C) \times 0.7 \quad (1)$$

Where:

- P = The percentage of the initial residual asphalt content by weight of the total mixture.
- A = Content mineral aggregate coarse passing the No. 8 sieve.
- B = Content mineral aggregate finer than the No. 200 sieve retained after passage through the filter No. 8 sieve
- C = Content mineral aggregate finer passing the No. 200 sieve.

Determine the initial emulsion content (IEC) value, and divide P by the proportion of residual bitumen in the emulsion, established at 56%.

$$IEC = \frac{P}{X} \quad (2)$$

Where:

- IEC = Mass of dry aggregate relative to initial emulsion content, expressed as a percentage.
- X = Residual bitumen concentration of the bitumen

According to equation (1), the value of P was equal to 6.98%, and the value of IEC was equal to 12.5%, as determined by equation (2) based on the specified gradient.

The Asphalt Institute's specified method was employed to ascertain the asphalt emulsion concentration, which was 12.5% by weight [33]. OPC was added in the mixture at a ratio of 7% of the total aggregate weight. To determine the optimum water in the mixture, numerous mixtures were formulated with different concentrations varying between (3-5)% by weight of the aggregates. The optimal water amount for the CAM was established at 3%. The evaluation was performed visually. The optimum value for all CAM categories was determined as 12.5% by the Marshall stability test. The optimal total liquid content for CAM was 15.5%. The cold mix was created by combining palm leaf ash, reed ash, and OPC. PLA replaced OPC in increments of 0%, 1.75%, 3.5%, 5.25%, and 7% by dry aggregate weight. RA was subsequently added at concentrations of 0.25%, 0.5%, and 1%, based on the weight of the aggregate. The ratios of PLA and RA were selected based on a prior study [34]. Table 7 displays the ratios of the CAM .

All samples were prepared and compressed at ambient temperature. They were initially combined with the pre-hydrated aqueous mixture for 2 minutes. In the concluding mixing phase, the asphalt emulsion was mixed for an additional 2 minutes. The specimens for the Marshall and ITS tests were compacted using a Marshall hammer in molds with a diameter of 101.6 mm. Three samples were

evaluated for each percentage of every test. The CAM is compacted with a Marshall compactor with 75 blows applied to each side. The samples were processed. CAM samples were retained in the mold for 24 hours at room temperature, subsequently subjected to 24 hours in an oven at 40°C for an additional day of curing before being tested. This curing method requires a field curing period ranging from 7-14 days [35].

Table 7. Mixes designation for CAM.

Mix ID	Asphalt emulsion content, %	Water content %	Filler type and percentage	Aggregate , %
7% OPC	12.5	3	7%OPC	100
1.75% PLA	12.5	3	5.25% OPC +1.75% PLA	100
3.5% PLA	12.5	3	3.5%OPC + 3.5% PLA	100
5.52% PLA	12.5	3	1.75% OPC +5.25% PLA	100
7% PLA	12.5	3	7%PLA	100
1.5% PLA	12.5	3	5.5%OPC +1.5%PLA	100
0.25% RA	12.5	3	5.5%OPC+1.5%PLA +0.25%RA	100
0.5% RA	12.5	3	5.5%OPC+1.5%PLA +0.5%RA	100
1% RA	12.5	3	5.5%OPC+1.5%PLA+ 1%RA	100
HAM-OPC	4.9	0	7%OPC	100

4. Tests Methods

4.1.Marshall Test

A compacted cylindrical specimen of bituminous mixture was subjected to diametric loading to assess its strength and resistance to plastic deformation. The Marshall test configuration is explained in Table 8 in accordance with the specification [36]. The specimens were subjected to Stage 2 curing by being placed in an oven at 40°C for 24 hours, subsequently followed by the implementation of the testing technique detailed in Table 8.

Table 8. Marshall Test Conditions as per ASTM D6927

No. of samples		3	3
The rate of load application, mm/min		50 ± 5	50
Test temperature, ºC		60 ± 1	60
Measuring device accuracy		Min. 0.01 N	0.01 N
Conditioning duration prior to trial, min	In a water bath	30-40	30 min in a water bath
	In oven	120-130	
Sample thickness, mm		63.5 ± 2.5	63.5 ±2.5
Sample compaction		75 blows to each face	75 blows to each face
Sample diameters, mm		101.6-101.7	101.6

4.2. Indirect Tensile Strength Test

The ability of asphaltic mixtures to withstand tensile fracture failure was assessed using the ITS test. Two strips are placed along the diameter of the Marshall specimen to apply compressive force until failure, in accordance with ASTM D6931[37]. The test conditions are specified in Table 4. The Marshall specimen is subjected to diametric loading at a rate of 50.8 mm/min until failure occurs. This loading configuration generates a rather uniform tensile stress along the vertical diametrical plane, perpendicular to the direction of the applied force. The specimens in this experiment were kept in the laboratory at room temperature (25°C). During stage 2 curing, the materials were maintained at 40°C for 24 hours to replicate a duration of 7–14 days. This was conducted to ensure that the results were resilient and reliable. Equation 3 is used to determine the ITS value [37].

$$ITS = \frac{2000*P}{t*D*\pi} \quad (3)$$

where ITS = indirect Tensile Strength (MPa); P = Maximum load (N); D = specimen diameter (mm); and t = specimen height immediately before test (mm).

Table 9. Test conditions of the ITS test.

Parameter	Test Standard
No. of samples	3
Test temperature, °C	25 ± 2
Sample conditioning time before test, hr	2
Rate of load Application, mm/min	50 ± 5

4.3. Water sensitivity

According to MS-14 requirements, the water sensitivity index is used to evaluate the loss of Marshall stability of specimens when exposed to water [32]. The MS-14 stipulated that for CRAM specimens, the ratio of conditioned to unconditioned specimens must not be less than 50%.

Table 10. Conditioning Protocols For Preserved Marshall Stability Test.

Unsampled conditioning	sampled conditioning
The mould is incubated at laboratory temperature for 24 hours. 24 hours in the oven at 40°C	The mould is incubated at laboratory temperature for 24 hours. 24 hours in the oven at 40°C A water immersion at 60°C for 24 hours

The Water damage value can be determined by employing the following formula:

$$\text{Water sensitivity, \%} = \frac{\text{average of conditioned specimens}}{\text{average of unconditioned specimens}} * 100 \quad (4)$$

5. Results and Discussion

5.1. Marshall Test Results

The Marshall stability test was performed at 60℃ to assess the thermal stability of CAM. A mixture content of 25% PLA and 75% OPC demonstrates superior strength relative to OPC alone. A slight decrease. The results indicated a decrease in CAM strength with the increase in the percentage of PLA replacing OPC. The optimal mix showed 5.5% OPC and 1.5% PLA. The exclusive use of PLA resulted in diminished strength because of the inadequate calcium oxide content in SiO_2 compared to OPC, as calcium oxide is the principal component in the hydration process. This illustrates the role of the activator with pozzolanic materials; the hydration reaction can begin when water is added. Figure 3 shows the findings of the Marshall flow. The Marshall test performed at high temperatures (60°C) assesses the plastic deformation of asphalt mixtures. In contrast, various mixtures exhibit distinct characteristics; the makeup comprised exclusively of PLA is related to a notable rate of plastic deformation. Figure 4 shows that CAM became stronger when OPC was replaced with PLA and RA was added compared to CAM-OPC.

The MS increases with the addition of 0.25% RA, then rises with 0.5%, and then declines when RA is increased to 1%. At 0.25%, the influence of the MS is negligible, and the pozzolanic activity is both restricted and incomplete. The enhanced strength at 0.45% may be ascribed to the denser microstructure of the mortar due to the RA effect. Furthermore, the continuous formation of additional calcium silicate hydrate resulting from the interaction between reactive silica in pozzolan and calcium hydroxide produced from cement hydration might be attributed to the 0.45% RA. Previous studies confirmed that it offers strength, especially at later service stages [38]. Figure 5 shows the flow results; PLA initially increases the flow value of CAM, which then declines. Conversely, the trend associated with RA shows such behavior due to variations in air voids. The Marshall stability properties of CAM, incorporating fly ash, significantly surpass those of CAM with cement.

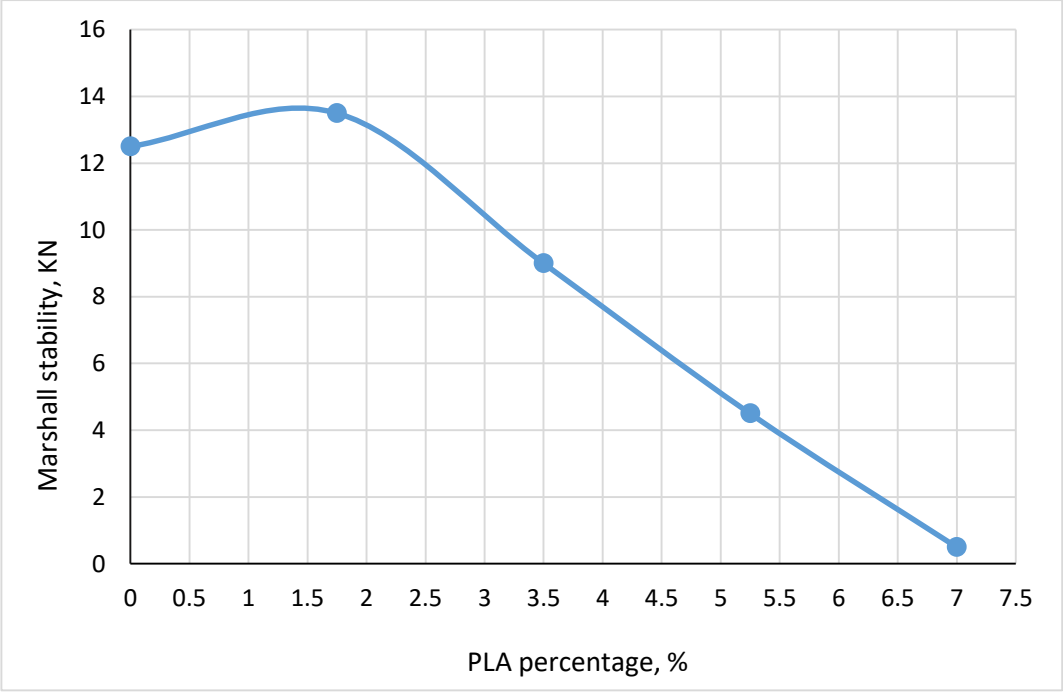

Figure 2. Marshall stability results for PLA incorporation after 7 days.

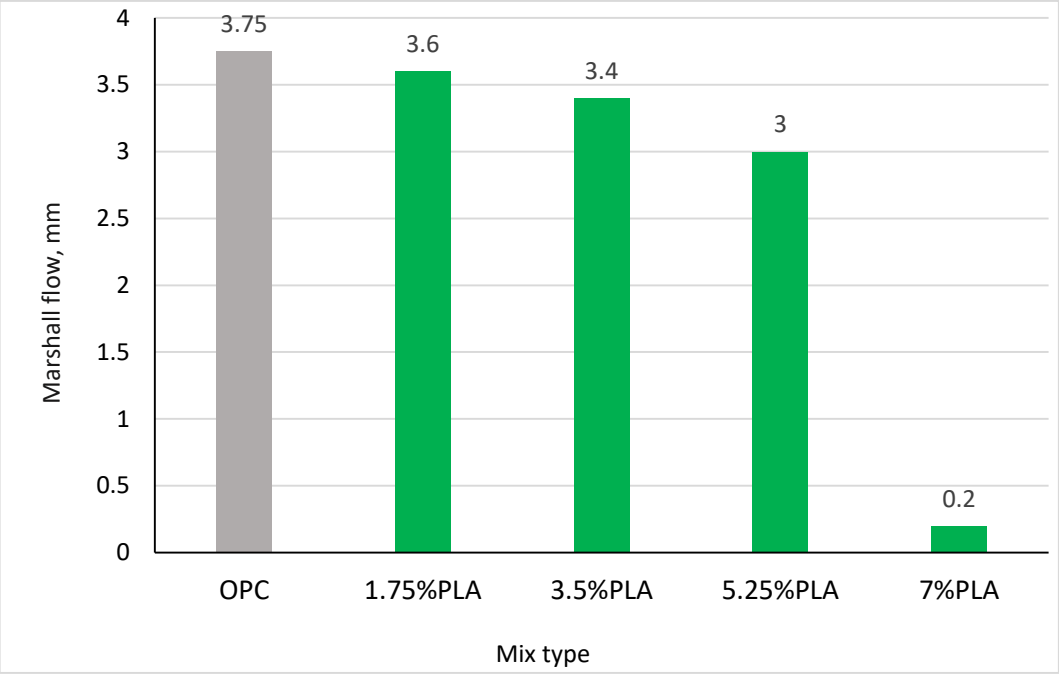

Figure 3. Marshall flow results for PLA incorporation after 7 days.

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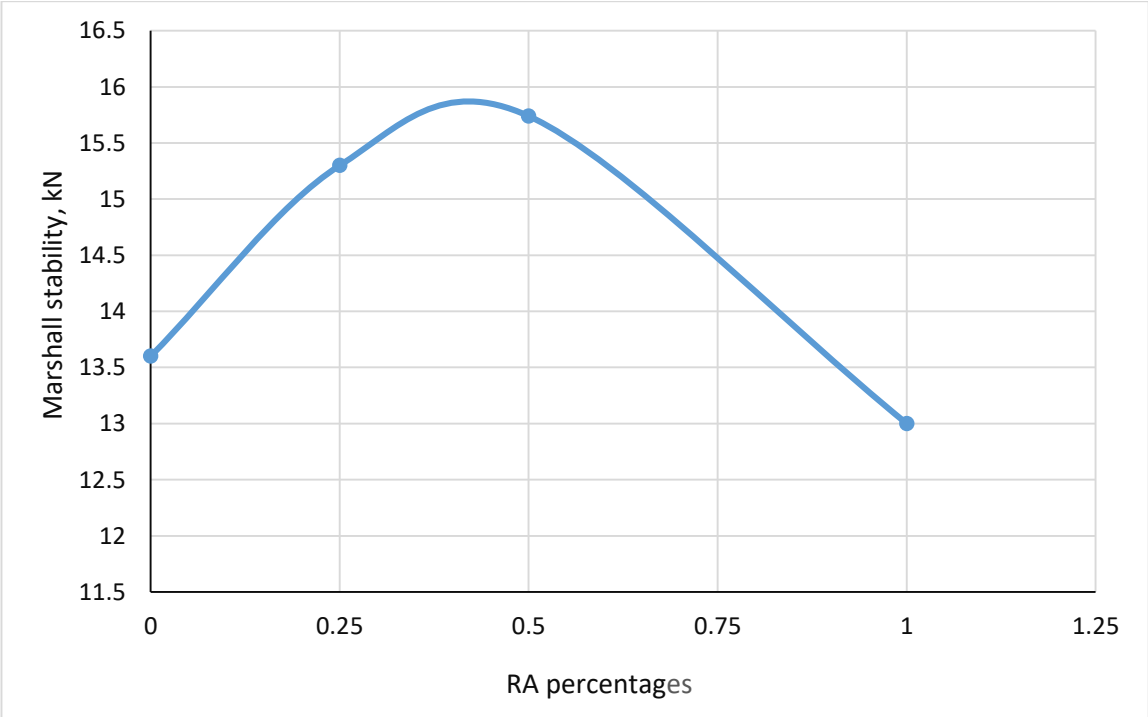

Figure 4. Marshall stability results for RA incorporation after 7 days.

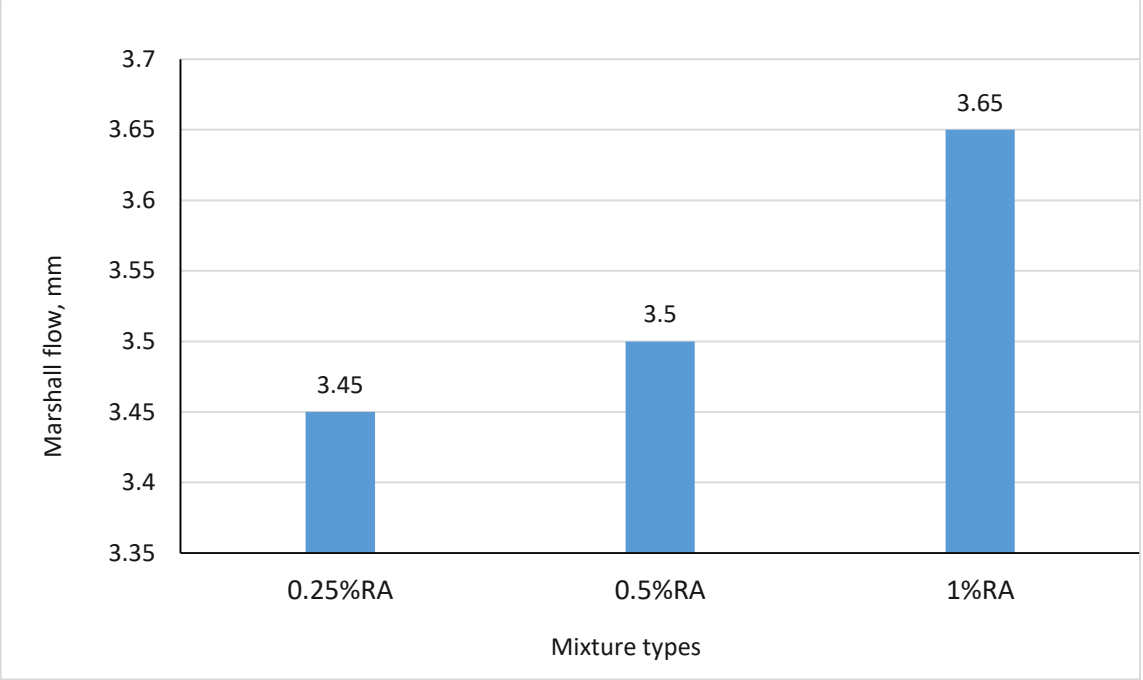

Figure 5. Marshall flow results for PLA incorporation after 7 days.

Figures 6 and 7 compared the Marshall stability of the modified CAM, reference CAM, and surface course HMA after 7 and 28 days of curing. The Marshall stability of the reference CAM attained 11 kPa after 7 days and 18 kPa after 28 days. The Marshall stability of the modified CAM improved to 15.9 kPa after 7 days and 21.1 kPa after 28 days of curing. An increase in the Marshall stability value of fly ash-modified CAM by curing period, reflects improvement in durability.

The addition of OPC significantly improves the performance of CAM in the early performance stage. The observed increased stability may be due to improved particle adhesion within the mixture, as the incorporation of OPC accelerates the hardening process. The early weakness in CAM may be due to hydration products; however, this can be mitigated by the action of OPC as a secondary binder. Water is essential for both the initiation and continuation of the hydration process. The water confined between the bitumen and the aggregate within the CAM influences its behavior and performance. The Marshall stability properties of cement asphalt mixtures containing fly ash far exceed those of cement asphalt mixtures containing cement. This means that asphalt materials containing fly ash have an improved to bear loads. This analysis explains the behavior of CAM with OPC where a network is formed as a result of hydration products resulting from interaction between bitumen and OPC, thereby enhancing the internal structure and mechanical performance of the mixture [39].

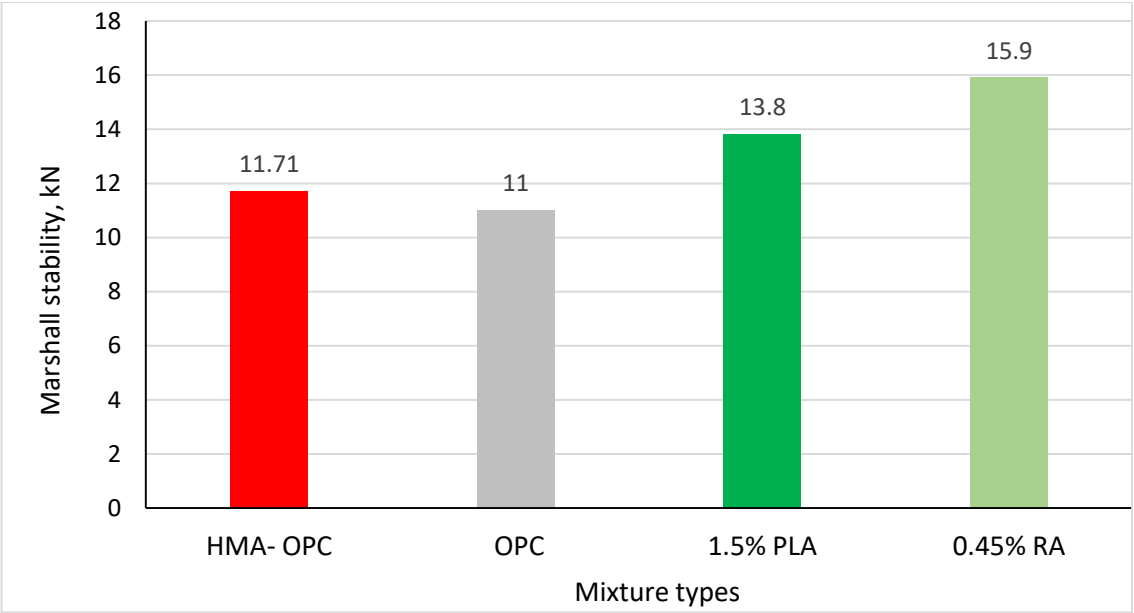

Figure 6. Marshall Stability results after 7 days.

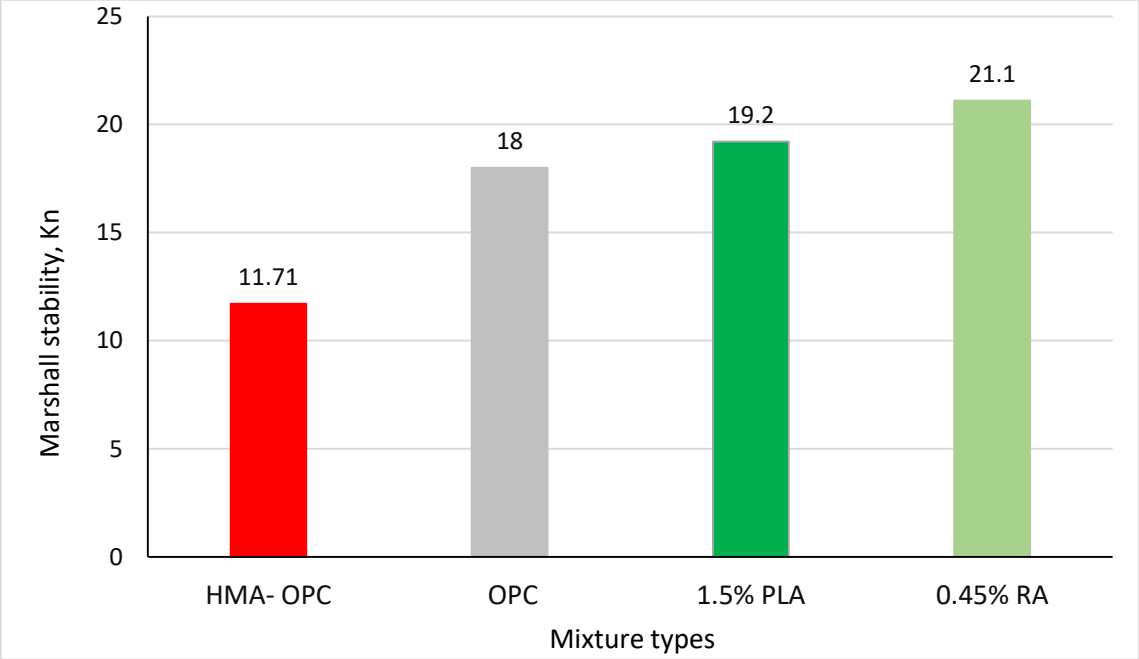

Figure 7. Marshall Stability results after 28 days.

5.2. Indirect Tensile Strength test (ITS)

According to the Marshall test methodology, ITST test samples were also prepared. It is important to note that the obtained ITS is comparable to HMA. Figure 8 shows the results for CAM samples: OPC, 5.5%OPC+1.5%PLA, and 5.5%OPC+1.5%PLA+0.45%RA. In the ITST test for CAM OPC samples, two prominent aspects are observed: OPC providing additional bonding and enhancing adhesion to the aggregate through hydration products. This can be explained by the expulsion of trapped water and the gradual development of hydraulic products over time. A decrease in ITS in

CAM with PLA and RA was observed. ITS is not significantly affected by the pozzolanic properties of PLA when combined with OPC.

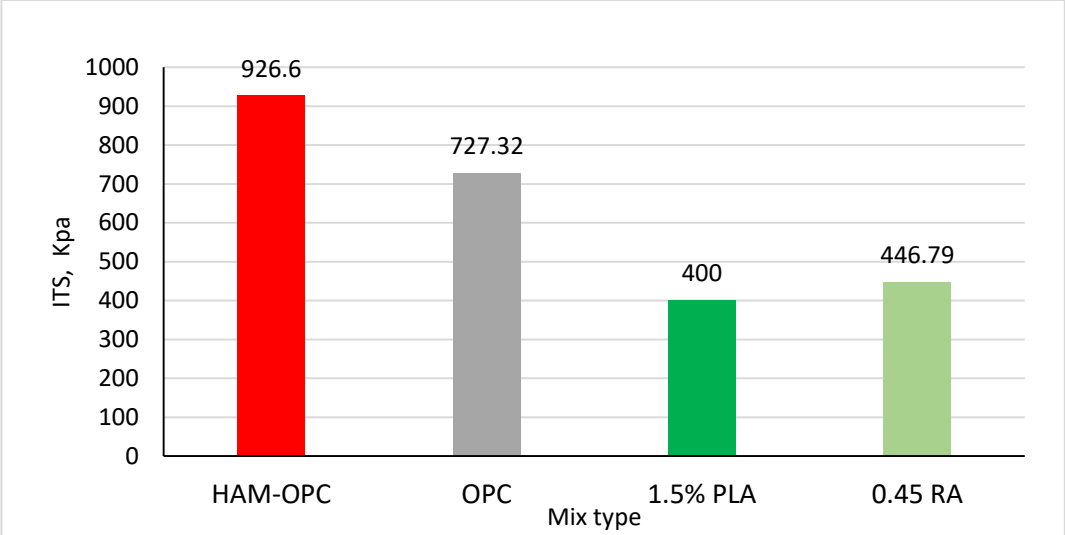

Figure 8. Indirect tensile strength properties.

5.3. Water sensitivity

The test results shown in Figure 9 indicate that the treated CAM exhibits better resistance to moisture-induced damage compared to HMA. Comparing CAM with a 7% OPC addition to CAM with 1.5% PLA, 0.45% RA waste, and 5.5% cement indicates that the latter exhibits increased water damage. The mechanism can be analyzed as follows: cement hydration products formed in CAM at the interface with VA and emulsion mortar, enhane interfacial adhesion and reduce water presence, leading to lower moisture susceptibility in CAM [40]. The CAM with OPC, PLA, and RA shows the greatest increase in capacity. This is due to the additional pozzolanic reaction between fly ash and calcium hydroxide, resulting in an increase in the amount of hydration products.

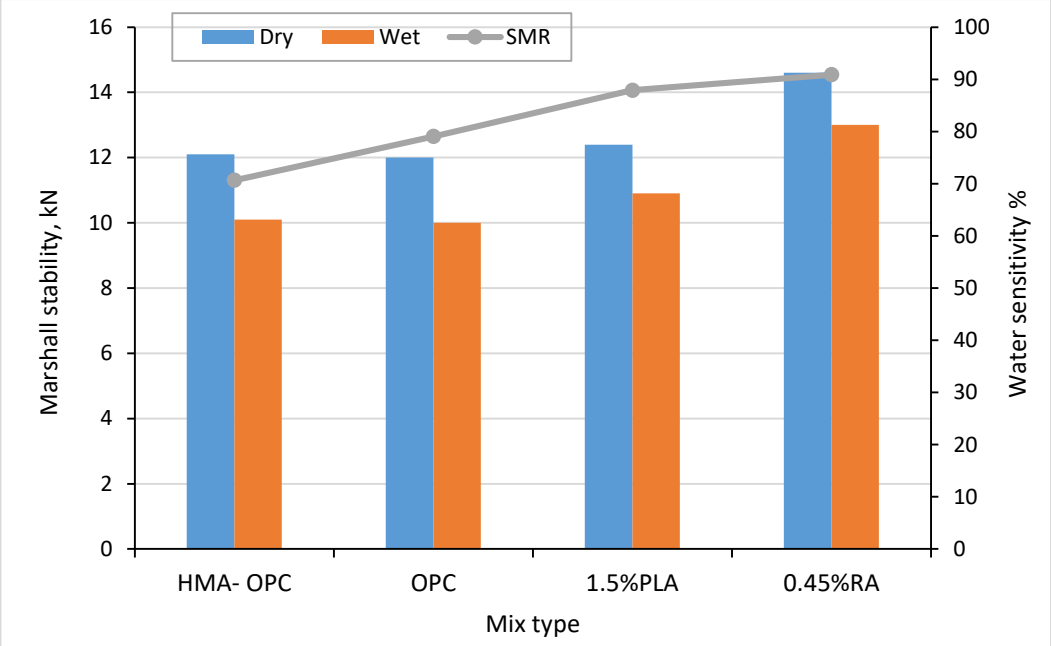

Figure 9. Water damages results

5. Conclusions

The mechanical properties of CAM have been investigated by a sustainable approach that entailed substituting a portion of PLA with OPC and including RA. The following conclusion can be drawn:

1. Due to the pozzolanic nature of RA and PLA, a significant portion of OPC can be substituted with PLA; the addition of RA further improved the Marshall stability. This significantly enhances the characteristics of CAM.
2. The Marshall stability test revealed that 1.5% of PLA can substitute OPC and provide improved performance. The addition of 0.45% of RA further improved the performance.
3. The combined application of 5.5% OPC and 1.5% PLA markedly improves water sensitivity. 0.45% of RA makes the CAM less sensitive to water damage.
4. The results of the ITS reveal that the performance of the 1.5% PLA mix is comparable to that of the mix with 0.45% RA. However, both have less ITS than the HMA.

Declaration of generative AI and AI-assisted technologies in the writing process

-None

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تطوير خلطة اسفلتية باردة مستدامة باستخدام الكتلة الحيوية

الخلاصة: تُعدّ الخلطات الأسفلتية الباردة من التقنيات المستدامة الواعدة لما تتمتع به من مزايا اقتصادية وبيئية مقارنةً بالخلطات الأسفلتية الحارة التقليدية، إلا أن ضعف مقاومتها الميكانيكية وارتفاع نسبة الفراغات الهوائية فيها قلل من استخدامها على نطاق واسع. يهدف هذا البحث إلى تحسين أداء الخلطة تم تحسين الخصائص الميكانيكية للخلطة من خلال الاستبدال الجزئي الأسفلتية الباردة من خلال دمج نوعي رماد وهما رماد سعف النخيل ورماد القصب. للسمنت البورتلاندي الاعتيادي برماد سعف النخيل بنسب مدروسة، مع إضافة رماد القصب بتراكيز مختلفة محسوبة من وزن الركام الجاف. جرى تقييم الأداء الميكانيكي والمتانة باستخدام اختبار ثباتية مارشال، واختبار الشد غير المباشر، واختبار الحساسية للماء. أظهرت النتائج أن الخلطة المثلى، المحتوية على 1.5% من رماد سعف النخيل، و5.5% من السمنت البورتلاندي الاعتيادي، و0.45% من رماد القصب، حققت تحسنًا ملحوظًا في قيمة ثباتية مارشال، إذ بلغت 15.9 كيلو نيوتن بعد 3 أيام و21.1 كيلو نيوتن بعد 28 يومًا. ويُعزى هذا التحسن إلى التأثير التكاملي للرماد مع السمنت، مما أسهم في تنشيط تكوّن نواتج الإماهة وتحسين تماسك الخلطة ومقاومتها الميكانيكية.

الكلمات المفتاحية: خليط الأسفلت البارد؛ مقاومة الشد غير المباشرة؛ اختبار مارشال؛ رماد أوراق النخيل؛ رماد القصب؛ اختبار حساسية الماء.