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Research Article

Utilisation of Sawdust and Charcoal Ash as Sustainable Modified Bitumen

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Abstract

Bitumen pavements play a critical role in modern transportation infrastructure, providing durable and reliable surfaces for roads and highways. However, traditional bitumen modifiers often rely on non-renewable resources and may contribute to environmental degradation. In response to the need for sustainable alternatives, this study explores the potential of utilizing sawdust (SD) and charcoal ash (CA) as bitumen modifiers. SD and CA were blended with bitumen grade 60/70 with 0% (control) and varied amounts of proportion using combination of SD and CA. Moreover, the sustainable modified bitumen mixture was assessed using the Marshall stability, indirect tensile strength and loss abrasion test. Specifically, adding 7SD0.5CA performs the best in stability as a sustainable modified bitumen mixture. The correlation between stability, tensile strength and loss abrasion for SD and CA modified bitumen mixture was significant, with a strong Coefficient of Determination (R2) of average 0.96 for all testing parameters. According to this study's findings, the correlation of SD and CA content may improve the performance and engineering characteristics with respect to sustainable modified bitumen.

Keywords: Sawdust, Charcoal Ash, Bitumen Modifiers, Marshall Stability, Indirect Tensile Strength, Loss Abrasion

Introduction

Bitumen, a crucial component in bitumen mixtures, is susceptible to various forms of distress under traffic loading and environmental conditions. To enhance its performance and durability, researchers and engineers have long explored the concept of bitumen modification [1]. Bitumen modification involves altering the rheological properties and performance characteristics of bitumen through the addition of various additives or modifiers. These modifiers can include polymers [2], crumb rubber [3], natural additives [4], and industrial byproducts [5], among others. The primary objectives of bitumen modification are to improve the resistance to rutting, fatigue cracking, thermal cracking, and moisture damage, ultimately prolonging the service life of bitumen pavements [6,7,8]. This introduction sets the stage for understanding the importance and multifaceted nature of bitumen modification in the realm of bitumen engineering.

Utilising waste materials such as sawdust and charcoal ash in bitumen modification has gained significant attention as a sustainable modified bitumen. Sawdust, a byproduct of wood processing industries, and charcoal ash, a residue from biomass combustion, offer promising opportunities for enhancing bitumen performance while mitigating environmental impacts [9]. Despite their potential benefits, the utilization of sawdust and charcoal ash as bitumen modifiers is relatively underexplored. This finely powdered material is obtained through the combustion or incineration of sawdust, typically in industrial settings. Sawdust ash is rich in silica, potassium, calcium, and other minerals, which can impart beneficial properties when incorporated into bituminous materials [10,11]. Its high silica content offers potential for enhancing the stiffness and durability of bitumen mixtures, contributing to improved rutting resistance and overall pavement performance [12,13]. Additionally, the presence of potassium and calcium may facilitate adhesion between bitumen and aggregate particles, leading to better cohesion and reduced moisture susceptibility. Moreover, the utilization of sawdust ash in bitumen mixtures presents an opportunity for sustainable waste management, as it repurposes a waste product that would otherwise require disposal. However, challenges such as variability in the composition and potential environmental concerns must be carefully addressed to ensure the successful implementation of sawdust ash as a bitumen modifier in bitumen pavement applications.

Charcoal ash, a residue generated from the combustion of charcoal, holds promise as a potential additive in bitumen engineering [14]. Produced through the controlled burning of organic materials, such as wood, coconut shells, or agricultural residues, charcoal ash is rich in carbon and various mineral components. Its composition may vary depending on the feedstock and combustion conditions, but commonly includes silica, potassium, calcium, and other trace elements [15]. In bitumen mixtures, charcoal ash has the potential to enhance performance characteristics such as stiffness, rutting resistance, and moisture susceptibility. The presence of silica can improve the binding properties of bitumen, leading to better adhesion between bitumen binder and aggregate particles. Additionally, potassium and calcium may contribute to the formation of stable mineral aggregates within the bitumen matrix, enhancing overall pavement durability.

The Marshall test, a widely employed method for evaluating bitumen mixtures, was utilized to investigate SD and CA modified mixture characteristics. Previous research has reported improved stability, increased rutting resistance, and enhanced durability of SD and CA modified mixtures compared with conventional

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mixtures [16]. A laboratory evaluation conducted by Osuya and Mohammed [13] reported that 15% of sawdust ash (SDA) had the highest stability at 18.2 kN and increased stability. This strong potential was predicted since an increased of up to 15% SDA positively affected the stability. Fayissa et al. [12] investigated SDA as a filler materials in asphalt concrete production and found that optimum SDA replacement was 12%. The SDA findings can improved the stability, stiffness and deformation resistance of bitumen. Furthermore, Guesmi et al. [17] study the partial substitution of asphalt concrete filler of burnt sawdust. The findings indicated an optimal burnt sawdust content of 15%, showcasing improved properties when burnt sawdust was added to asphaltic concrete. Meanwhile, Oba et al. [18] also study the saw dust ash from quarry dust and evaluates usefulness of quarry dust and saw dust ashes mineral fillers in a bituminous concrete in order to reduce cost and encourage reuse of waste materials in the environment and it reaches the conclusion that cost of aggregate is reduced. Recently, Ing et al [9] presented the influence of sawdust ash as filler in asphalt mixture and it can be seen that the different percentage of sawdust ash had noticeably different effects on the performance of modified mixture.

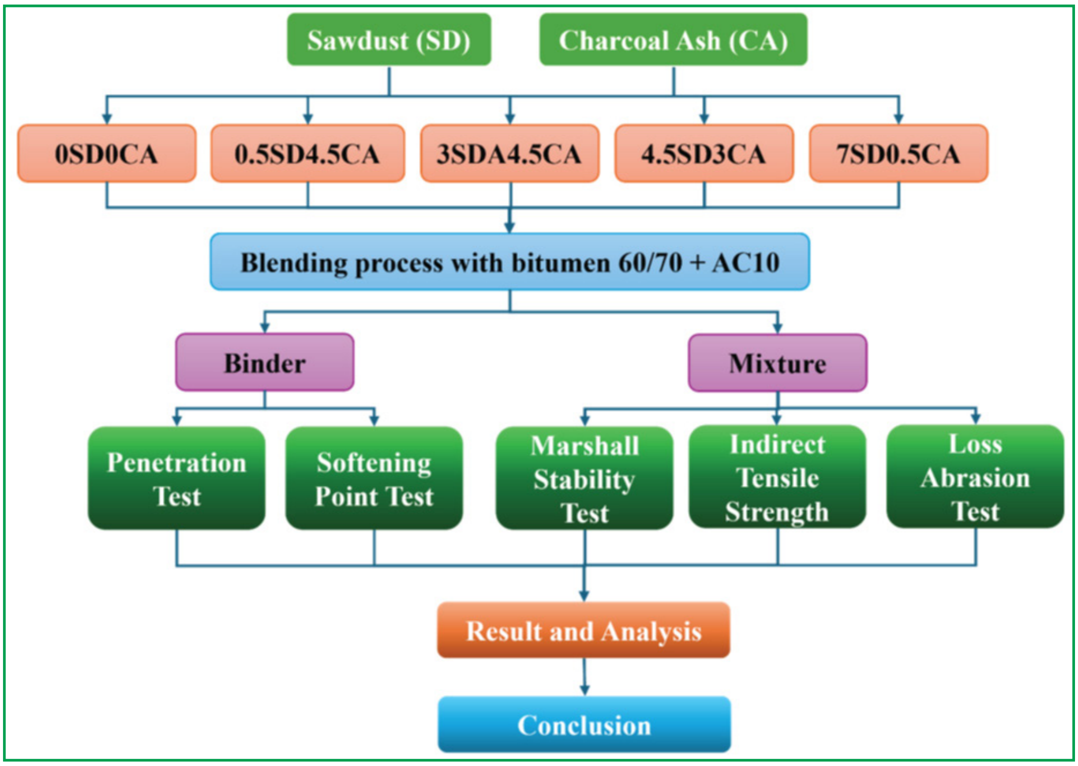

Figure 1. The various metholodolgy stages in this study

Previously, Putra Jaya et al. [14] performed a non-traditional bitumen modifier from a coconut shell which was the charcoal coconut shell ash (CCSA) and used to investigate the stimulation of aging. The results of samples with CCSA which underwent aging showed some improvement in terms of the stability and permanent deformation characteristics where the recommended value for durable asphalt concrete and high serviceability is 2% to 4% of CCSA. Furthermore, Jeffry et al. [19] studied the nano-charcoal coconut shell ash (NCA)

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in asphalt mixture and findings showed that the Marshall stability, indirect tensile strength (ITS), resilient modulus and dynamic creep of the asphalt mixture were significantly improved with the addition of 6% NCA. Moreover, Abdullah et al. [20] also study about the effect charcoal ash coconut shell, where they conclude that finer charcoal ash particles enhance bitumen properties and also high charcoal ash content improves resistance to low-temperature cracking.

These studies have provided valuable insights into the potential of waste materials, including sawdust and charcoal ash, as modifiers of bitumen mixtures. This research aims to address this gap by investigating the effects of incorporating sawdust ash and charcoal ash on key bitumen properties, including Marshall stability, indirect tensile strength, and resistance to loss abrasion. Figure 1 depict the various methodology stages in this study.

Materials and Methodology

Bitumen

This research used bitumen 60/70 PEN, with the characteristics of bitumen binders presented in Table 1. All the mixes consisted of a conventional mix (0%) and four modified bitumen mixes with different proportions of SD and CA starting from 0.5%, 3%, 4.5% and 7% for combination followed the proportion mention in Table 2. The waste materials were added to the bitumen before mixing with the aggregate in a process known as wet mixing.

Table 1. Bitumen binders' characteristics

Test	Method	Requirement	Outcomes
Penetration at 25°C (dmm)	ASTM D5	60-70	62
Softening point (°C)	ASTM D36	49-56	49.5
Specific gravity	ASTM D70	1.01-1.06	1.03
Viscocity at 135°C (Pa.s)	ASTM D4402	< 3 Pa.s	0.5

Table 2. Proportion of the study

Mixture	Proportion
Control (0% SD + 0% CA)	0SD0CA
0.5% SD + 7% CA	0.5SD7CA
3% SD + 4.5% CA	3SD4.5CA
4.5% SD + 3% CA	4.5SD3CA
7% SD + 0.5% CA	7SD0.5CA

Sawdust and Charcoal Ash

Sawdust was produced after the sawing process from Lubok Batu Sawmill Enterprise, Terengganu, Malaysia while charcoal obtain from the Eng Part Supply (M) Sdn Bhd, Pahang, Malaysia. Subsequently, SD and CA was fed into the Los Angeles Abrasion Machine for 30 minutes and 500 revolutions with 11 steel ball. Both waste materials was ground to form a nanoparticle size. The SD and CA particles were sieved to a size less than 75 µm, oven dried for 24 hours and stored in a vacuum desiccator, to keep it dry during analysis [15]. The particle size distributions of SD and CA used in the study were determined by gradation using standard sieves. The characteristics of SD and CA are outlined in Table 3. Figure 2 shows that SD is light brown and CA is absolute black in colour.

Table 3. Characteristic of SD and CA

Items	Sawdust	Charcoal Ash
Bulk density (g/cm^3)	0.18	0.87
Specific gravity	0.065	0.053
Ash Content (%)	2.5	24.7
Colour	Light brown	Black

(a) (b)

Figure 2. Raw materials (a) SD and (b) CA

Experimental Works

Sample Preparation

The modified binder was prepared by heating bitumen 60/70 to 160°C in a steel container until liquefied. Subsequently, SD and CA were added to the bitumen in proportions of 0SD0CA, 0.5SD7CA, 3SD4.5CA, 4.5SD3CA and 7SD0.5CA by weight of the original bitumen. A high-speed shear mixer operating at 1500 rpm for 60 minutes was used to mix the materials. This speed was chosen to ensure efficient dispersion of the waste elements in the bitumen. The blending process was performed at 160°C to avoid bitumen aging at high temperatures. To achieve a full mixing time with regard to the waste materials and bitumen, approximately 60 minutes was used to produce a homogeneous binder. Here, the Malaysian Public Works Department's standards [21] were used to establish the optimum amount of bitumen. Three specimens were constructed under each experimental condition and sample type. The optimal amount of bitumen was determined to be 5%. Figure 3 shows the graphical representation methodology involved in this study of modified bitumen binders and mixtures.

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Figure 3. Graphical representation of methodology

Physical Test

Penetration Test

A penetration test was conducted following the standard ASTM D5 determine the consistency and hardness of bitumen. The bitumen's hardness is indicated by a low penetration value. The penetration value is based on the grade of bitumen used for the sample testing. Bitumen 60/70 was used in this test, so the penetration value of the bitumen is in the range of 60 to 70 at standard test conditions. The bitumen is well mixed until it reaches a pourable consistency before being put into the test containers. The sample containers was then kept at a temperature of 25 °C in a temperature-controlled water bath for 1 hour. After 1 hour, the sample was taken out from the water bath, and the needle was brought into contact with the bitumen sample's surface. At this point, the dial's reading was set to zero when the needle contacts the sample's surface. After releasing the needle, the needle was allowed to penetrate for 5 seconds, and then final reading was taken. The factors affecting the accuracy of the test were the pouring temperature, needle size, weight applied to the needle, and test temperature. The test was conducted using the penetration equipment with a total applied load of 100 g for 5 seconds at a temperature of 25 °C.

Softening Point Test

The softening point test procedure followed the guidelines outlined in ASTM D36 [22]. This test is used to determine the temperature at which a given bitumen reaches a certain degree of softness. The softening point test of bitumen is important for result comparisons because bitumen does not have a definite melting point. The bitumen was melted and then poured into two rings that were set on a plate for 30 minutes. The thermometer was positioned level with the bottom of the ring in the middle of the ring holder. Each sample was given 3.5 g of steel balls, stirred, and then heated. The temperature of the sample was recorded up point after the ball was passed and dropped into the base plate.

Penetration Index (PI)

Using Eq. (1), which uses the penetration and temperature values acquired from the softening point test, the Penetration Index (PI) was established. Note that PI values between -3 and +7, according to Read and Whiteoak [23], denote strongly blown low-temperature susceptible bitumen and high-temperature susceptible bitumen, respectively.

$$PI = \frac{1952 - 500 \log pen - 20\, softening\ point}{50 \log pen - softening\ point - 120} \quad (1)$$

Mechanical Test

Marshall Stability Test

The Marshall stability test was conducted with respect to the ASTM D6927 specifications [24]. The samples were heated to 60 °C in a water bath for 20 minutes. The samples were then removed from the water bath and placed in the lower segment of the broken head. The upper segment of the breaking head of the specimen was placed in position, and the complete assembly is placed in position on the testing machine. The flow meter was placed over one of the posts and is adjusted to read zero. Subsequently, load was applied at a rate of 50 mm/min until the maximum load reading was obtained. The maximum load reading was recorded in Newtons, and the flow measured by the flow meter was recorded in millimeters. In this research, additional criteria were utilized to examine the overall effectiveness of the specimens, including stiffness, flow, bulk density, voids in total mix (VTM), voids filled with bitumen (VFB) as well as voids in mineral aggregates (VMA).

Indirect Tensile Strength

The indirect tensile strength (ITS) test characterises the stiffness of a bituminous mixture. This test was performed according to ASTM D6931 [25]. The cylindrical samples were loaded diametrically in the direction of the cylinder axis with a constant speed of displacement until they broke in the compression testing machine (MATTA machine) between the loading strips. The indirect tensile strength was at the maximum tensile stress calculated from the peak load applied at break and the dimensions of the samples using the Eq. (2). Where the F denotes peak load (kN), D denotes diameter of specimen (mm) and H denotes height of specimen (mm).

$$ITS = \frac{2F}{\pi DH} \quad (2)$$

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Loss Abrasion Test

The loss abrasion test was conducted with respect to the ASTM C131 specifications [26]. The goals of the loss abrasion test was to determine abrasion resistance using the loss Angeles abrasion machine. Before the samples were subjected to the loss Angeles machine, they were first weighed to determine their weight before abrasion (Mo). Moreover, the loss Angeles machine was used to test the samples with a steel ball at speeds between 30 and 40 rpm for 500 revolutions. After completion, the samples were taken out and weighed to recorded the weight after abrasion (Mi) using Eq. (3) where Mo represents the weight before abrasion and Mi represents weight after abrasion.

$$Loss\ Abrasion = \frac{Mo - Mi}{Mo} \tag{3}$$

Results and Discussions

Physical Properties

The findings with respect to the penetration test, softening point test, as well as PI for different percentages of SD and CA content are shown in Figure 4. Result shows the penetration value is decreasing from conventional bitumen of 62 dmm to 3% with 0.5SD7CA content and further decreasing to 3%, 19% and 4% with 3SD4.5CA, 4.5SD3CA and 7SD0.5CA, respectively. The penetration value indicating its consistency or hardness. A higher penetration value suggests a softer or more fluid bitumen, while a lower penetration value indicates a harder or more viscous bitumen. Bitumen with higher penetration values tends to be more susceptible to temperature variations and can experience softening and hardening in hot weather or cold weather, respectively. As Similar findings with other researchers studied SD and CA in bitumen modifications [9,18]. On the other hand, the softening point with regard to the modified binder increases with the increment in SD content. Moreover, the conventional binder's softening point increases by 3% with a 0.5SD7CA content and by an additional 5% with a 3SD4.5CA content. The highest softening point value of 60°C was achieved with 7SD0.5CA content. Modified bitumen binder's temperature, as well as flexibility susceptibility, are calculated utilizing the penetration index (PI). The influence of SD and CA regarding the modified bitumen binder's PI was illustrated in Figure 4. As stated, after adding 0.5SD7CA, the modified bitumen binder's PI increased slightly. Furthermore, the PI value substantially rises to 74% for a 3SD4.5CA content. This finding proposes that SD and CA may improve the bitumen's temperature as well as temperature susceptibility. Consequently, this established how adding SD and CA content to the control bitumen enhanced its temperature susceptibility. Overall, the findings suggest that adding waste materials, SD and CA able to modify the bitumen characteristics and enhance its performance in terms of temperature susceptibility, softening point, and penetration.

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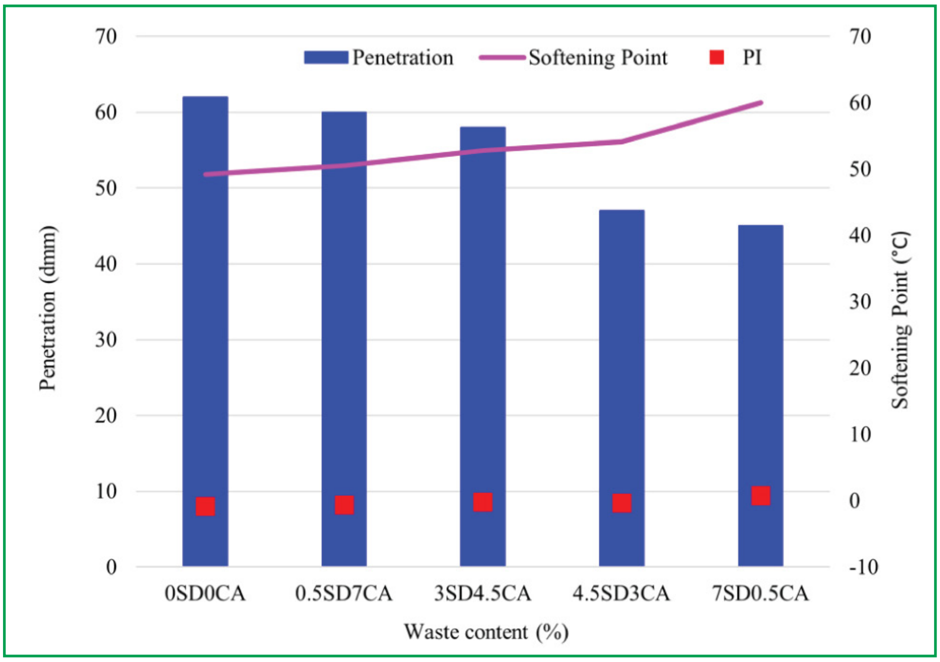

Figure 4. The penetration value of SD and CA modified bitumen binders

Marshall Stability Properties

Stability and Flow

The Marshall stability test results indicated the impact of adding SD and CA on the stability with regard to the modified bitumen mixture. Hence, the modified bitumen mixture showed more predictable behavior compared to conventional bitumen mixtures. The minimum stability requirement, as per the Malaysian Standard Specification for Road Works [21], is 8000 N. The stability with respect to the modified bitumen mixture exceeded this standard (Figure 5). Adding SD and CA significantly influenced the stability of the modified bitumen mixture. Among the different percentages of SD and CA added, the modified bitumen binder with 7SA0.5CA demonstrated the highest stability at 58381 N. However, the stability concerning the modified bitumen mixture decreases when the SD and CA content was reduced to 3SA4.5CA, resulting in a stability and flow value of 15220 N and 2.35 mm, respectively. Regarding control of 0SD0CA, the stability and flow values were found to be 11187 N and 2.03 mm, respectively, indicating that they provided the lowest stability among the tested waste materials. These results suggest that the addition of 7SD0.5CA may enhance the stability of the modified bitumen mixture. By improving the ability of the mixture to resist deformation under applied forces, these waste materials can potentially contribute to the establishment of more durable and resilient bitumen pavement.

According to the Malaysian Standard Specification for Road Works [21], the flow of bitumen mixture should fall within the range of 2.0 mm to 4.0 mm. Figure 4 portrayed that the modified bitumen mixture, by adding SD and CA, exhibited higher flow values compared to the conventional bitumen mixture. This suggests that the flow of the bitumen mixture increased by incorporating these two waste materials. The modified bitumen mixture generated a consistent flow value when exposed to raw waste materials conditions, having the sample flow in the range of relatively 2.03 mm to 2.99 mm. Among the different waste materials, the modified bitumen mixture containing 7SD0.5CA exhibited the highest flow rates. The best flow performance was achieved when 7SD0.5CA were added to the modified bitumen mixture where the flow values recorded were 2.99 mm. Subsequently, the performance of all waste materials looks promising as in the range of the JKR specification. These findings suggest that adding SD and CA to the bitumen mixture can enhance flow characteristics. Therefore, it is important to establish that the flow values remain within the acceptable range stated in the standard.

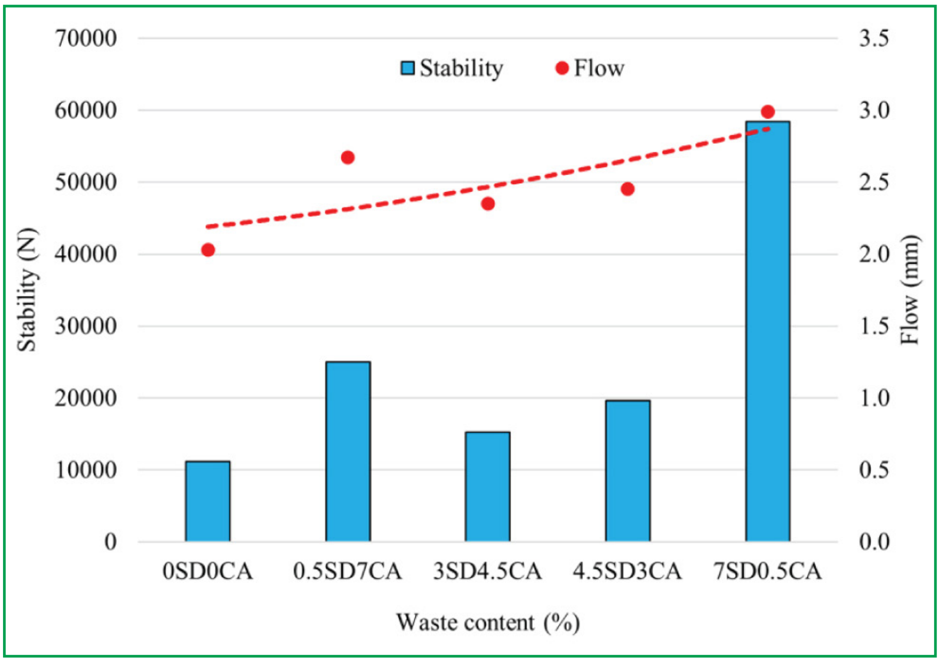

Figure 5. Stability vs flow of SD and CA modified bitumen mixtures

Stiffness and Flow

Figure 6 shows the stiffness and flow of an bitumen mixture with a combination of SD and CA at different percentages. The stiffness values of the bitumen mixtures are of primary interest as they indicate the resistance to deformation and the ability to withstand applied loads. The stiffness was highest at bitumen mixtures with a combination of 7SD0.5CA (19525 N/mm), compared to control mixtures, 0SD0CA with 5511 N/mm. This combination surpassed the control mixtures, highlighting the positive effect of incorporating SD and CA in the bitumen mixture. Bitumen mixtures with 3SD4.5CA recorded the lowest stiffness at 6477 N/mm with a flow of 2.35. A high flow value suggests increased susceptibility to deformation under traffic loads. Even though the minimum value of stiffness in this research is considered acceptable since the value is not less than the JKR standard [21], by referring to the JKR standard, the stiffness value must not be less than 2000 N/mm.

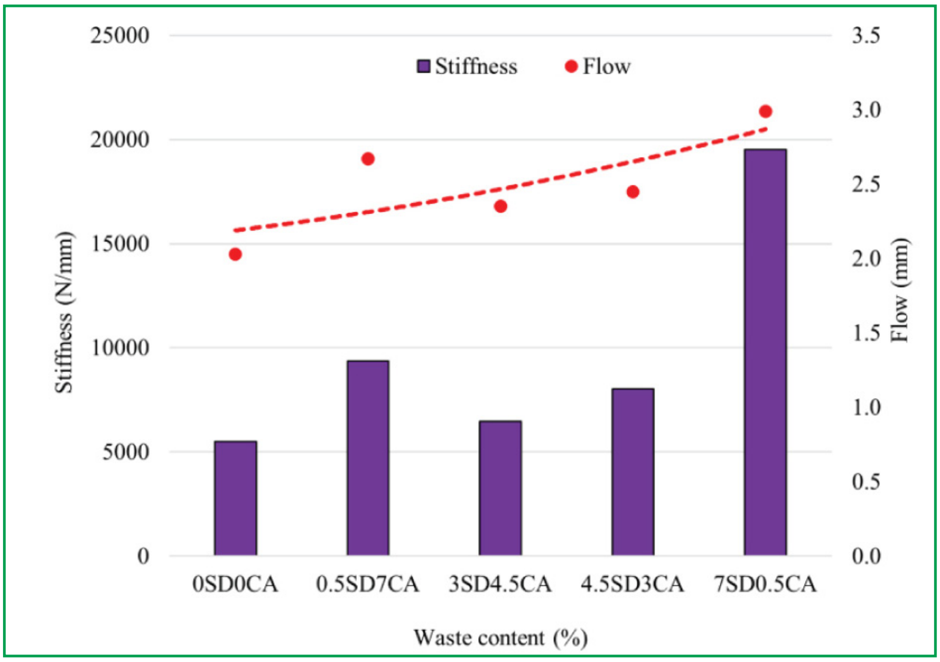

Figure 6. Stiffness vs flow of SD and CA modified bitumen mixtures

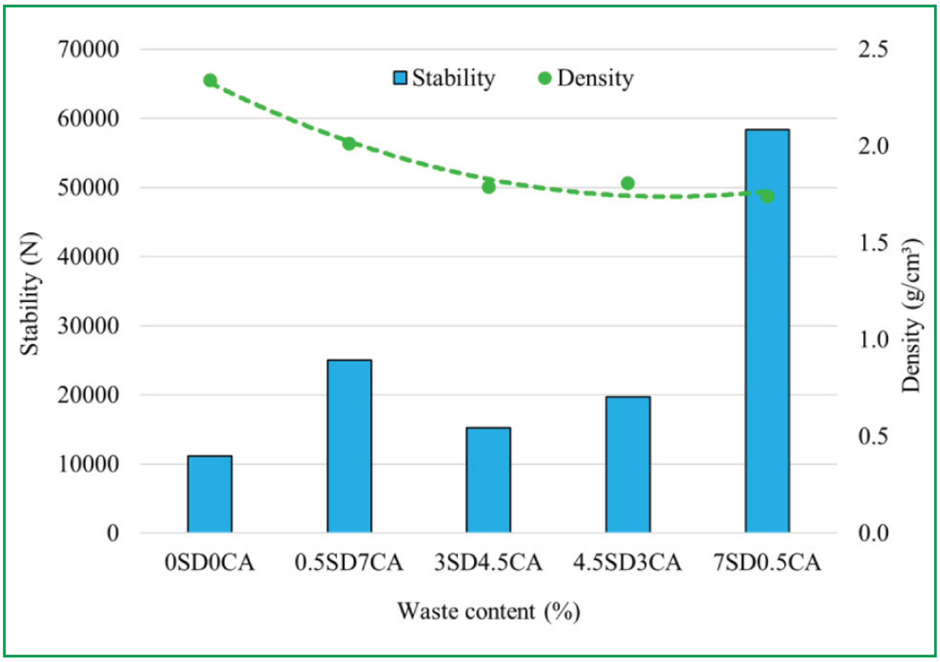

Figure 7. Stability vs density of SD and CA modified bitumen mixtures

Stability and Density

Figure 7 presents the relationship between the stability and density of modfied bitumen mixtures. The findings offer valuable insights into the interplay between these two properties and their implications for the performance of the mixture. As can be seen, the percentage of SD increased and the percentage of CA decreased, the density of the bitumen mixture decreased. This implies that a higher SD content and lower CA content result in a less compact mixture. Conversely, the stability of the bitumen mixture exhibits an increasing trend with increasing SD percentage and decreasing CA percentage. The bitumen mixture with 7SA0.5CA shows the highest stability at 58381N, while the control mixture exhibits the highest density at 2.338 g/cm^3. The contrasting trends between density and stability suggest that other factors, beyond density alone, contributed to the stability of the bitumen mixture. These factors may include the properties of the SD and CA and the resulting binder characteristics. Referring to the JKR standard, the stability of the mixture must not be less than 8000N, while the typical density for bitumen mixtures is approximately 2.322 g/cm^3. Based on the presented data, the bitumen mixture with 7SA0.5CA meets the stability requirement and exhibits the lowest density. Although the Malaysian Standard Specification for Road Works does not provide specific limitations for bulk density for bituminous mixture with waste materials, achieving higher bulk density values is generally desirable. A higher bulk density indicates a more compact and dense mixture, improving performance and durability.

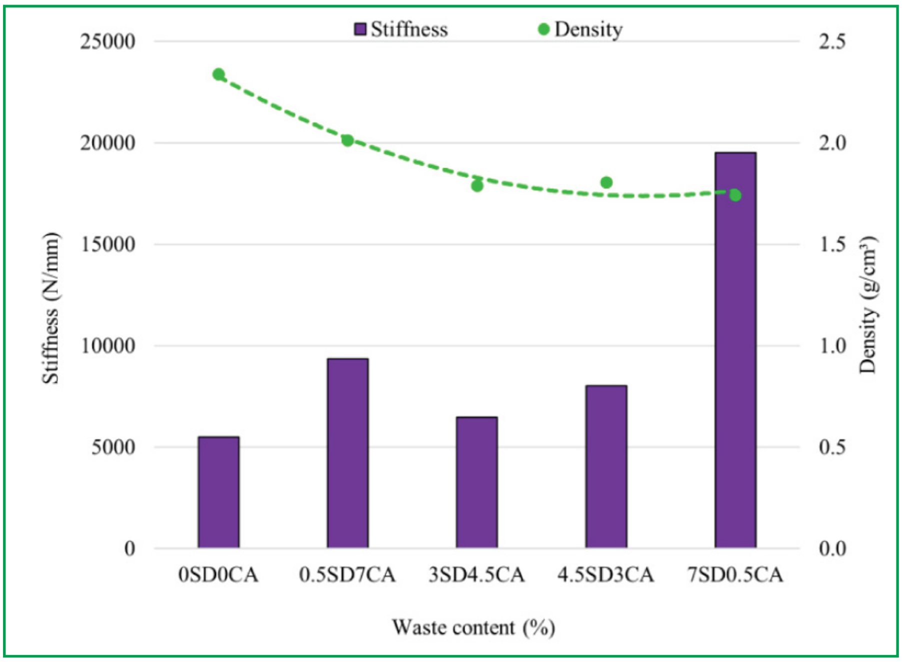

Figure 8. Stiffness vs density of SD and CA modified bitumen mixtures

Stiffness and Density

Figure 8 depicts the influence of different combinations of SD and CA on the stiffness and density of modified bitumen mixtures. The findings provide valuable insights into the performance of these mixtures and their compliance with JKR standards. As can be seen, the combination of 7SD0.5CA in the bitumen mixture yields the highest stiffness and lower density compared to the other combinations. Specifically, the stiffness of the bitumen mixture with this combination depicts 19525 N, while the control mixture of 0SD0CA exhibits a stiffness of 5511 N. Hence, the graph showed that the modified bitumen mixture, which included all two waste components, exceeded the minimum requirement value set in the Malaysian Standard Specification for Road Works (>2 kN) [21]. All the samples in the study, including the mixture with the 7SA0.5CA combination, meet this requirement, indicating that they are acceptable in terms of stiffness. These stiffness values fulfil the requirements for both modified as well as conventional bitumen mixtures. It can be said that the use of 7SD0.5CA as the percentage of the contents in the modified bitumen mixture was more efficient in improving stiffness.

Void in Total Mix (VTM)

The VTM represents the percentage of voids within the total volume of the bitumen mixture. It is an important parameter as it affects the durability and performance of the pavement. Figure 9 illustrates the VTM values for various SD and CA combinations are presented. Hence, the graph showed that the air voids with respect to the modified bitumen mixture with varying percentages of waste materials fall within the range of 3-5% as specified by the Malaysian Standard Specification for Road Works [21]. Maintaining air voids within this range is crucial for the modified bitumen mixture to prevent flushing, shoving, and rutting on the pavement surface. Among the waste materials, the modified bitumen mixture having 7SD0.5CA exhibited the lowest air void value of 2.63%. In contrast, the modified bitumen mixture with 3SD4.5CA possesses the highest air void value of 3.67%. For other waste addition, the 0.5SD7CA and 4.5SD3CA contents shows an increasing value of VTM of 2.99% and 3.33%, respectively. The lowest value of VTM indicates less air void space within the mixture, which can lead to increased strength and durability. Note that all percentage content of waste materials depicts a value of VTM in the range of JKR specifications.

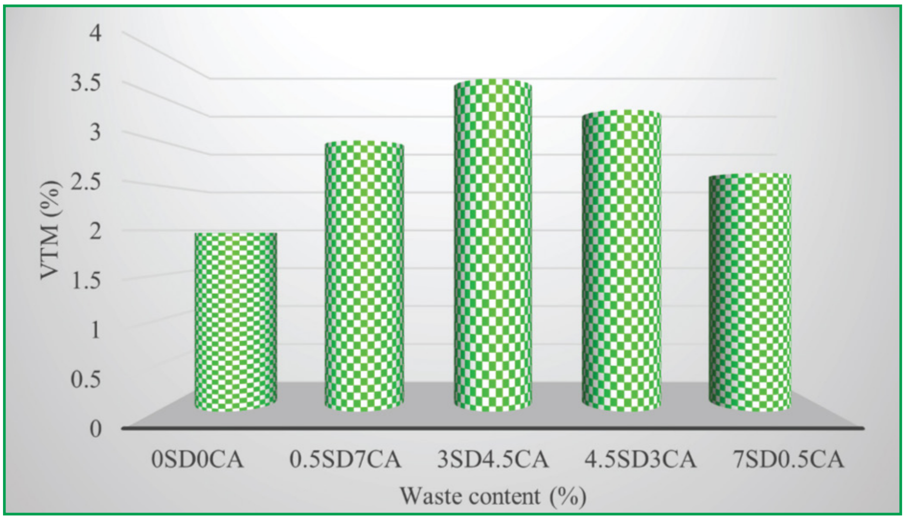

Figure 9. VTM of SD and CA modified bitumen mixtures

Correlation Analysis of SD and CA Modified Bitumen Mixtures

The correlation between stability, flow, density and stiffness for SD and CA modified bitumen mixture was significant, with a strong Coefficient of Determination (R^2) of average 0.96 for all testing parameters (Table 4) . According to this study's findings, the correlation of SD and CA content may improve the performance and engineering characteristics with respect to sustanaible modified bitumen.

Table 4. SD and CA modified bitumen mxitures's equations and R^2

Parameteres	Equation	R^2
Stability (N)	$y = 0.0457x^2 - 0.1853x + 3.119$	0.9588
Flow (mm)	$y = 0.0157x^2 - 0.0757x + 2.098$	0.9656
Density (g/cm³)	$y = 0.0545x^2 - 0.4671x + 2.739$	0.9734
Stiffness (N/mm)	$y = 0.0141x^2 - 0.5787x + 1.164$	0.9611

Voids Filled with Bitumen (VFB)

The VFB represents the percentage of voids in the bitumen mixture that are filled with bitumen. It is an important parameter as it influences the durability, strength, and performance of the pavement. Figure 10 displays the VFB values for various SD and CA combinations. The figure reveals that as the SD percentage increases and the CA percentage decreases, the VFB values generally increased. This indicates that higher SD content and lower CA content resulted in a increased proportion of voids filled with bitumen within the bitumen mixture. The VFB value at 4.5SD3CA increased up to 6% than 3SD4.5CA. The 7SD0.5CA mixture exhibits the highest VFB value at 76.76%. Having a higher VFB value within the range of 70-80% is desirable, as it indicates better resistance to deformations such as rutting. The recommended VFB range for bitumen mixture specifications by the JKR standard is 70% to 80%. Based on this specification, all of the samples meet the VFB requirements. The VFB values reported for all the combinations fall below the lower limit of the recommended range. It is important to note that inadequate bitumen filling of voids can negatively impact the performance and durability of the bitumen mixture. Based on the analysis, results indicate that modified bitumen mixtures with waste materials meet the VFB requirements and help lower the binder's susceptibility [28].

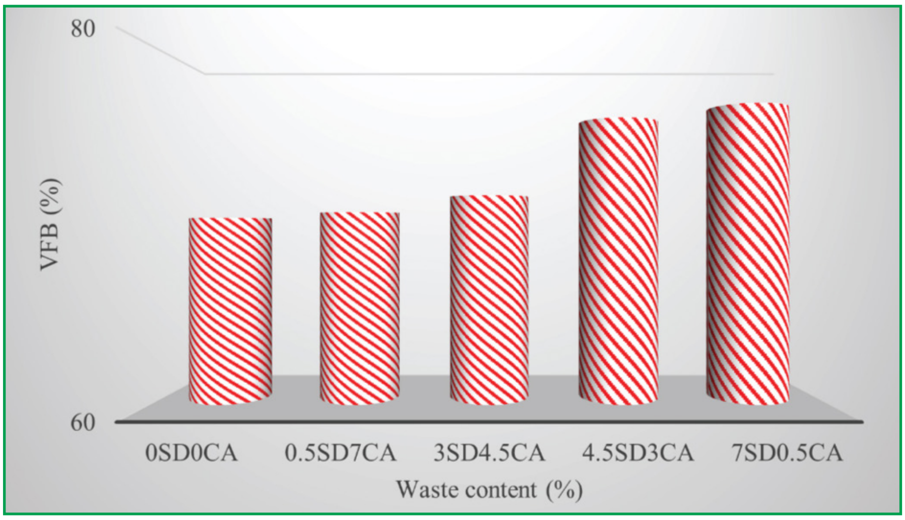

Figure 10. VFB of SD and CA modified bitumen mixtures

Voids in Mineral Aggregate (VMA)

The VMA represents the percentage of voids within the mineral aggregate in an bitumen mixture. It is a crucial parameter as it affects the overall performance

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and durability of the pavement. Figure 11 presents the VMA values for various SD and CA combinations. Notably, all the samples yield higher VMA values compared to the control mixture, which measures 15.59%. The lowest value of VMA percentage at 7SD0.5CA was 22.3% which indicates a limited amount of available space to accommodate sufficient bitumen binder. Insufficient VMA can hinder the ability to adequately coat each aggregate particle with the binder. Consequently, this condition makes the modified bitumen mixture more sensitive to changes in bitumen binder content, potentially affecting its performance and stability. It is crucial to establish both a minimum and potentially a maximum VMA limit in bitumen mixture specifications. Insufficient VMA may impede proper binder coating, while excessive VMA can lead to unacceptably low mixture stability. While the figure does not provide explicit information regarding the maximum VMA specification, it emphasizes the challenges associated with a low VMA percentage.

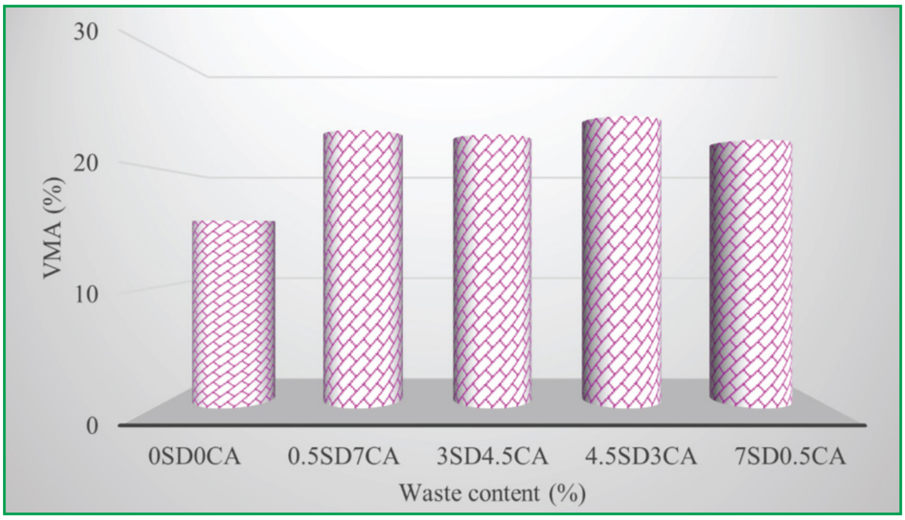

Figure 11. VMA of SD and CA modified bitumen mixtures

Indirect Tensile Strength (ITS)

The JKR has classified the rutting resistance of bitumen mixtures into different categories based on the ITS range [21]. These categories include very poor, poor, minimal, fair, good, very good, and excellent, corresponding to specification ITS ranges. Figure 12 provides the ITS results for different SD and CA combinations. The bitumen mixture containing 7SD0.5CA demonstrates the highest ITS at 551.46 kPa, falling into the very good rutting resistance category. The modified bitumen mixture containing 3SD4.5CA records an ITS of 231.32 kPa (fair), while the modified bitumen mixture containing 4.5SD3CA has an ITS of 135.86 kPa (minimal). The results indicated a clear relationship between the ITS and the percentages of SD and CA in the bitumen mixtures. The ITS increased with increasing SD content and decreasing CA content. This suggests that a higher proportion of SD and a lower proportion of CA have a detriment ITS strength and falls within the very good rutting resistance category. This combination exhibits optimum performance in terms of rutting resistance. The high calcium oxide content in SD contributes the enhanced rutting resistance and reduces the temperature susceptibility of the bitumen mixture, resulting in improved performance [10].

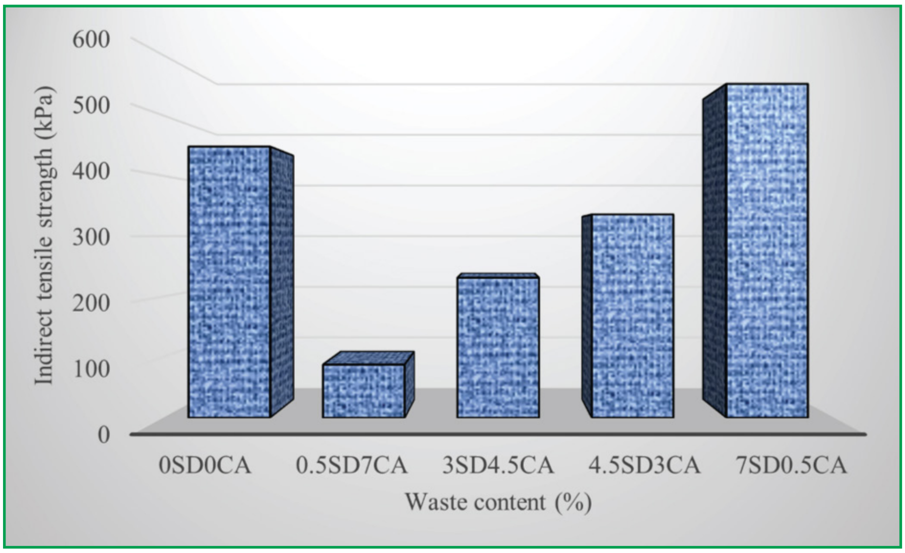

Figure 12. ITS of SD and CA modified bitumen mixtures

Loss Abrasion

The abrasion resistance of bitumen mixtures is a critical factor in evaluating their durability and ability to withstand wear and tear. In this study, the abrasion loss of different bitumen mixtures with varying combinations of SD and CA was examined using the loss Angeles Abrasion machine. Figure 13 shows the average percentage of abrasion loss for the bitumen mixtures with different SD and CA combinations. It is evident that the bitumen mixtures containing SD and CA exhibit significantly higher average abrasion loss values compared to the control mixture. The highest percentage of abrasion loss was observed in the sample with 7SD0.5CA, reaching 43.7%. This is followed by the sample with 4.5SD3CA, 3SD4.5CA and 0.5SD7CA, with the value of ITS of 40.65%, 36.78% and 11.04%, respectively. In contrast, the control mixture had the lowest abrasion loss percentage of only 1.93%.

The results clearly indicated that the modified bitumen mixtures with a combination of SD and CA have much higher average abrasion loss values compared to the control mixture. It is important to note that the maximum allowable percentage of abrasion loss typically falls between 35% and 45% according to JKR standards. All of the modified bitumen mixtures in this study met the specification, and the modified bitumen mixture containing 7SD0.5CA the combination of SD and CA in the bitumen mixtures results in a higher volume of voids compared to the control mixture. This increased void content performed that the bitumen mixture more susceptible to abrasion loss. The presence of voids provides spaces where the aggregate particles can detach and break away more easily during the abrasion process.

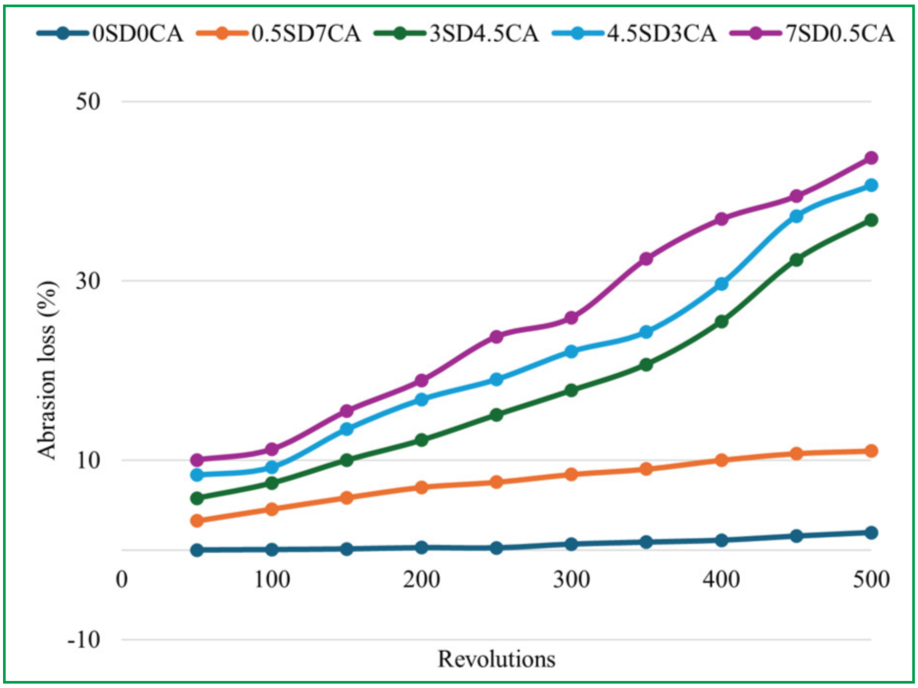

Figure 13. Abrasion loss of SD and CA modified bitumen mixtures

Conclusions

In summary, this study successfully investigated the potential of utilising waste materials, namely SD and CA, as modified bitumen binders as well as a mixtures in the performance of physical and mechanical properties. From the findings of the study, the performance of the modified bitumen mixtures was significantly improved through the modified bitumen mixture containing 7SD0.5CA. The AC10 containing SD and CA of higher SD than CA can improved the engineering properties of the modified bitumen mixtures. Due to its optimum density and stability, it achieved the highest tensile strength of 551.46 kPa which increased the internal resistance of the mixture to cracking. Moreover, consistent findings with abrasion loss values significantly increased as the SD contents increased, and for AC10 containing 7SD0.5CA, the abrasion loss 43.7% are within the JKR specification. The abrasion loss were increased after aging process due to the mixtures became stiffer. Based on the findings of the study, the use of 7SD0.5CA modified bitumen mixture for road construction applications needs to be studied in more detail. This composition shows favourable characteristics such as optimal density, better stability, and a significant increased in tensile strength, thereby increasing the mixture's resistance to cracking. Although a higher SD content leads to increased abrasion loss and aging effect, the AC10 mixture with 7SD0.5CA achieves a reasonable balance between performance and durability. However, additional research and field testing is advised to confirm the performance of the mixture under real-world conditions. These findings of analysis between SD and CA bitumen mixture suggest a promising potential for optimizing the use of waste materials to improve the characteristics with regard to the modified bitumen mixture and constituents' strategy for sustainable road pavement.

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Conflicts of Interest

The authors declare no competing interest.

Author Contributions

Wan Noor Hin Mior Sani: writing, original draft preparation. **Nurul Fatihah Allias:** writing, reviewing and editing. **Haryati Yaacob:** reviewing and editing. **Zaid Hazim Al-Saffar:** reviewing and editing. **Mohd Hazree Hashim:** reviewing and editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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