Research Article

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Evaluation of mechanical and performance characteristics of bitumen mixture using waste septage ash as partial substitute

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Abstract: The aim of this research is to investigate the potential application of septage ash (SA) as a partial substitute for conventional fillers in Bitumen mixes. The study's purpose was to evaluate the mechanical and performance characteristics of Bitumen mixes by incorporating varying amounts of SA into the filler. To achieve this, bitumen mix samples were prepared with different concentrations of SA (5, 10, 15, and 20% of the filler weight). The study's initial focus was on analyzing the physical properties of the samples and determining the fundamental parameters of tiny crystallites using X-ray diffraction and specific surface area. Additionally, the strength, stiffness, resistance to velocity, temperature effects, and impact of water on the mixture were carefully evaluated by conducting Marshall stability tests, indirect tensile strength, Cantabro tests, Freezing and Thawing (F&T) tests, and Moisture susceptibility tests to determine their durability in the presence of water. The findings of this study indicate that incorporating SA improved the strength by 32%, reduced fine loss by 23% at an optimal 5.35% bitumen content, and increased moisture sensitivity by 15%. Overall, the experimental results suggest that waste SA can be used as a sustainable solution to improve the mechanical performance of the surface.

Keywords: waste septage ash, filler, bitumen mix, sustainability, moisture sensitivity, ANOVA single factor analysis

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1 Introduction

The incorporation of waste products in the bituminous mixes has attracted the interest of experts in the past few years because of modern environmental issues and advances in road construction technology. Recycled concrete aggregate, fly ash, and industrial waste-based artificial aggregates have been studied to replace part of the conventional materials in the bituminous mixtures [1,2]. Results of these studies were considered encouraging since they demonstrate positive shifts in mechanical properties and, at the same time, increases durability yet decreasing effect on the environment. For instance, interaction between fly ash and recycled concrete aggregate used in porous asphalt mixtures have shown the capability of offsetting negative impacts on mechanical properties [1]. Similarly, the use of industrial waste-based artificial aggregates processed under accelerated carbonation has shown improvements in anti-rutting properties, moisture damage resistance, and skid resistance of bituminous mixtures [2]. Furthermore, the application of waste materials such as paper sludge ash and re-refined acidic sludge in cold bitumen emulsion mixes and warm mix asphalt, respectively, has yielded favorable results in terms of mechanical performance and durability [3,4]. Given the success of these waste materials in bituminous mixtures, it is worthwhile to explore the potential of waste septage ash (SA) as a partial substitute in bitumen mixtures. This approach aligns with the growing trend of incorporating alternative materials in road construction to enhance sustainability and reduce environmental impact while maintaining or improving the performance characteristics of the resulting mixtures [5,6].

In the fields of road construction and pavement engineering, this trend has manifested in the exploration of waste materials as potential fillers in bitumen mixtures. Bitumen, a crucial component in road construction, traditionally relies on mineral fillers to enhance its performance. However, the extraction and processing of these conventional fillers often incur significant environmental and economic costs. Consequently, researchers and engineers have focused on waste materials as alternative fillers to lessen the environmental effect of road building while possibly increasing the mechanical qualities of bitumen pavements [7–9]. This approach addresses the challenge of waste management and aligns with the principles of a circular economy, in which waste is viewed as a valuable resource rather than a disposal problem [10].

The use of waste products as fillers in bitumen mixes provides a multitude of potential benefits. From an environmental perspective, it reduces the demand for virgin materials, minimizes landfill usage, and decreases the carbon footprint associated with filler production and transportation [11]. Economically, this can lead to cost savings in road construction projects by reducing material costs and potentially improving pavement longevity. Moreover, certain waste materials were discovered to boost the performance of bitumen mixes, thereby improving rutting, moisture susceptibility, and thermal cracking resistance [12]. The spectrum of waste materials studied was large and varied, including fly ash from coal burning, waste plastic, recycled glass, steel slag, and various forms of construction and demolition waste. Each of these materials imparts unique properties to Bitumen mixtures, necessitating thorough research to understand their impact on both short-term performance and long-term durability of pavements [13].

However, the incorporation of waste materials as fillers into bitumen mixtures is challenging. The variation in the content and qualities of waste materials can lead to inconsistencies in bitumen performance, requiring rigorous quality control measures [14]. There are also worries about possible leaching of harmful substances from certain waste materials, which necessitates comprehensive environmental impact assessments. Additionally, the long-term behavior of pavements containing waste materials requires field trials and monitoring programs [15]. Despite these challenges, the potential benefits of using waste materials as fillers in bitumen mixtures have sparked significant research interest. As environmental restrictions grow increasingly rigorous and the push for sustainable construction practices intensifies, the development of effective strategies for incorporating waste materials into bitumen mixtures is likely to become increasingly important in pavement engineering [16].

1.1 Research objectives

1. The primary objective of using waste SA in bitumen mixtures is to enhance sustainability by repurposing waste material as a partial substitute for traditional fillers.
2. This reduces dependency on virgin materials, minimizes environmental impact, and addresses waste management issues.
3. The research aims to improve bitumen mixtures' mechanical and performance properties while promoting a circular economy approach.
4. By integrating SA, the study explores the potential for cost savings, enhanced durability, and environmental benefits, aligning with sustainable development goals in pavement engineering.

Initially, the SA sample was tested for X-ray diffraction (XRD) to identify the structure and components inside the molecules. Based on the XRD results, the sample consists of dominant phase accounting for 60–70% of the sample, the secondary phase accounting for 20–30%, and the minor phase accounting for 10–20%. The estimated size of the crystallites in the sample is 30–50 nm based on the SEM image of the SA. The highest point had an angle of approximately 25.5° and a relative intensity of 100%. Additional notable peaks are observed at approximately 31.5°, 55.5°, and 67.5°. The crystal symmetry was probably reduced, possibly to monoclinic or orthorhombic, exhibiting uneven spacings and peak intensities. As illustrated in Figure 1, XRD is a flexible nondestructive technique for characterizing the physical properties of materials such as powder, solid, and liquid samples. This makes possible examination of formation features like phase distribution, crystal structure, and orientation. As shown in Figure 1, various substances consist of small crystalline particles [39].

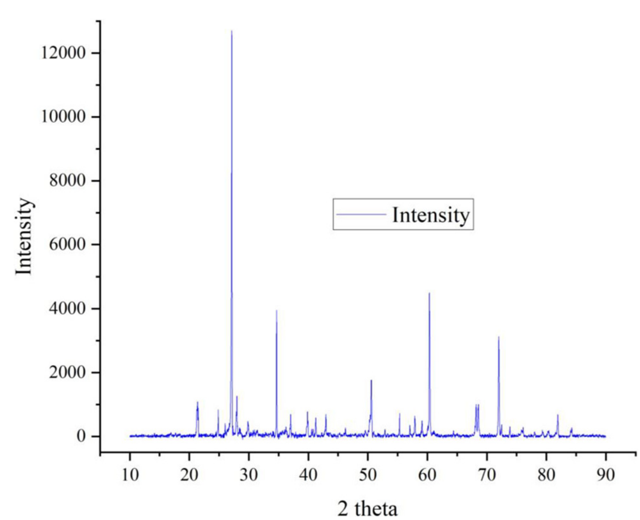

Figure 1: X-ray diffraction (XRD) of the septage ash.

1.2 Research methodology

In this experimental work, waste SA was a partial replacement of the filler with respect to the weight of the filler. An XRD test was conducted for the SA properties and intensity concerning 2 theta. Prior to sample preparation, the specific surface area (SSA) of the particle size distribution was evaluated to determine the feasibility of incorporating fillers into the bitumen mixture, ensuring a comprehensive understanding of the material's properties for optimal mix design. Samples were prepared by varying the SA to 0, 5, 10, 15, and 20% in the bitumen mix. The study evaluates critical mechanical properties such as Marshall stability (MS), tensile strength, compressive strength, stiffness, and moisture resistance. These properties assess the load-bearing capacity, deformation, and durability of bitumen mixtures with SA. The Cantabro and F&T tests analyze abrasion resistance and resilience under environmental stress. By examining these parameters, the research aims to validate SA's potential to improve the structural and performance characteristics of bitumen mixtures, ensuring they meet industry standards for strength, durability, and stability.

2 Materials

2.1 Aggregate

Aggregates were acquired from a nearby crusher and were subsequently examined to determine their size and form, both of which are crucial factors for their suitability for pavement applications. There were certain constraints to this investigation. The results of the combined data with limitations are presented in Table 1, highlighting the necessary characteristics for pavement construction: ASTM C 131, ASTM C535, ASTM D 5821, ASTM C127, and ASTM C127.

Table 1: Test results for aggregates according to ASTM methods with limitations

Name of experiment	Result Values	Limitations	ASTM designation
Los Angeles abrasion test	42%	Max. 45%	ASTM C 131
Aggregate impact test	19.46%	Max. 24%	ASTM C535
Crushing strength test	28.07	Max 30%	ASTM D 5821
Specific gravity Test	2.65	2.5–3.0	ASTM C127
Water absorption Test	0.165	0.1 to 2%	ASTM C127

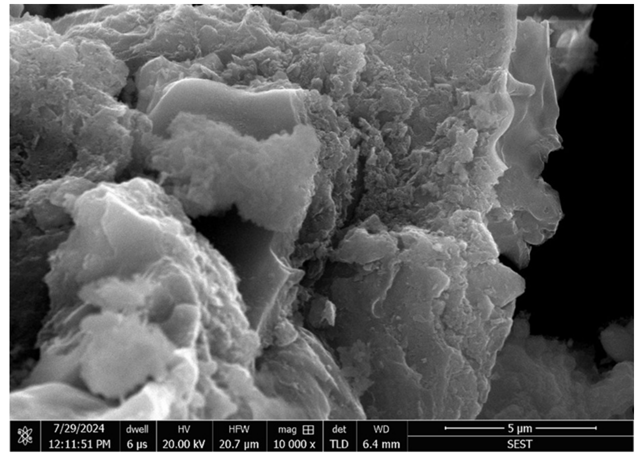

Figure 2: SEM image of septage ash.

2.2 Sampling of aggregate

The ingredients were selected using the job mix formula from Figure 2 gradation chart of ingredients with limits. As shown in Figure 3, the particle percentage was determined for bitumen grade [17–19]. The middle limit (red color) was considered for the mix. The mean value was used to calculate the percentage of aggregates utilized in the combination, and the median value in Table 2 was used to pick the aggregate gradation, as shown in Figure 6.

2.3 Bitumen

The research work utilized VG 30 grade bitumen. To verify compliance with ASTM standards, essential testing was done

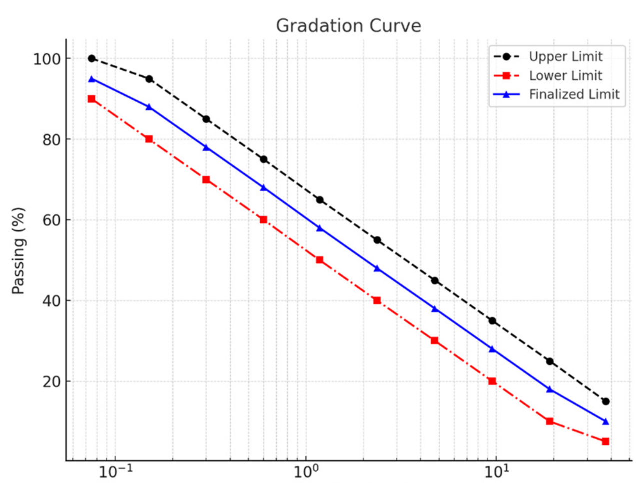

Figure 3: Gradation chart of the mix.

Table 2: Gradation of constituents for bitumen concrete

Sieve size (mm)	Upper limit (%)	Lower limit (%)	Finalized passing (%)
19	100	95	98
13.2	95	85	90
9.5	90	78	85
4.75	75	60	68
2.36	60	45	52
1.18	45	30	38
0.6	30	18	25
0.3	20	10	15
0.15	12	5	10
0.075	8	2	5

Table 3: Test results for the bitumen according to ASTM testing with limitations

Test name	Value	Limitation	ASTM designation
Ductility test	42.5 cm	Min 40 cm	ASTM D113-17
Flash and fire point test	280° and 320°C	Min 220°C	ASTM D8254-19
Penetration test	67 mm	50–70 mm	ASTM D5/D5M-13
Softening point test	54°C	Min 47°C	ASTM D36/ D36M-12
Specific gravity test	1.01	0.9–1.02	ASTM D2726
Viscosity test	2,500	2,400–3,600	ASTM D4402

on the product, and the relevant findings, together with their associated limitations, are shown in the accompanying table. Table 3 displays the bitumen testing results following ASTM standards, including any restrictions or limits [20–22].

2.4 Filler (SA)

SA, which is leftover material from septic tanks, is used in bitumen mixtures to provide rigidity and reduce empty spaces, thereby resulting in denser pavement structures [23–26]. Local authorities incinerate this ash at temperatures between 1,400 and 1,500°C, resulting in black-colored ash that is disposed in landfills. Figure 3 shows SA collected from the treatment plant. The basic properties of the SA are listed in Table 4. The elements and characterization of the filler were calculated using the SSA measured by the Blaine air permeability apparatus (IS5516) (Figures 4 and 5).

3 Experimental study

3.1 Marshal stability test

The MS test apparatus, which is illustrated in Figure 6, is used in determining the durability of the bitumen mixtures. These are the specimen mold assembly, the specimen extractor, the compaction hammer, the compaction pedestal, the breaking head, the loading machine, and the flow meter as shown in Figure 4 (ASTM D6927-15, 2015).

3.2 Preparation and testing of sample

The process involved the fusion of 1,200 g of aggregates and exposing them to heat in an oven until the required mixing temperature was achieved. Bitumen was added to achieve a viscosity of 170°C. The heated mixtures were transferred to a mold, subjected to 50 hammer strokes for compression, and subsequently removed. The sample was then allowed to cool and its mass was measured to determine its density, thus facilitating the calculation of void properties [27,28]. The specimens were heated to 60 ± 1°C using a water bath or oven. The lower half of the breaking head was positioned and the upper part was mounted. Subsequently, the assembly was placed in a test apparatus. The flow meter was adjusted to a zero reading and the load was systematically increased at a consistent rate of 50 mm/min until it reached its highest possible value. The maximum load measurements in Newtons were concurrently recorded [29,30]. The ingredients and prepared samples are shown in Figure 6(a) and (b).

3.3 Volumetric properties

Voids in the Mineral Aggregate (VMA), air voids (AV), dry bulk density, and voids filled with bitumen (VFB) were

Table 4: The basic properties of SA

Component	CaO	Al_2O_3	SiO_2	Fe_2O_3	P_2O_5	Specific gravity	SSA (cm^2/g)
Weight (%)	5–15	10–20	40–60	5–15	01–5	3.58	5981.89

Figure 4: Waste septage ash.

measured using ASTM D2726 (for VMA) and ASTM D3203 (for AV, dry bulk density, and VFA). Consequently, they were acquired using Eqs. (1) and (2) [27,28].

$$\text{Dry density} = \frac{\text{Weight in air}}{\text{SSD weight} - \text{Weight in water}}. \quad (1)$$

The saturated surface dry (SSD) reflects the weight of dry samples when they are completely wetted on the surface (g).

$$\text{Air Voids} = \left(1 - \frac{\text{Dry density}}{SG_{max}}\right) \times 100. \quad (2)$$

SG_{max} refers to the highest specific gravity of a combination as established following the ASTM D2041 standard.

Figure 5: Blaine air permeability apparatus for specific surface area.

Figure 6: Marshall stability apparatus.

Where CA, FA, F, and B are the coarse aggregate, fine aggregate, filler, and bitumen, respectively, by the weight of the mix.

$$\text{VMA} = 100\% - \frac{\text{Gmb} \times \text{Ps}}{\text{Gsb}}. \quad (3)$$

Ps represents the overall percentage of the aggregate in the complete mix, whereas Gsb represents the bulk-specific gravity of the aggregate.

3.4 Indirect tensile strength (ITS) test

The ITS tests used ASTM D 4123 methodology to evaluate the tensile strength of a cylindrical specimen. The specimen was subjected to diametric compression at a consistent rate of 50.8 mm/min, which caused tension along its diameter. The equation representing the greatest tensile strength is formulated as follows [29]:

$$\text{ITS} = \frac{2P_{max}}{\pi DH}. \quad (4)$$

In this context, "ITS" represents the indirect tensile test, measured in kilopascals (kPa). "Pmax" denotes the highest force applied during the test, expressed in kilonewtons (KN). "*H*" refers to the height of the specimen, measured in meters (m), whereas "*D*" denotes the specimen's diameter also measured in meters (m) (Figure 7).

A popular way for material testing is to evaluate its tensile strength. The ITS tests were conducted using the

(a) (b)

Figure 7: (a) Ingredient used for the mix and (b) prepared samples.

(a) (b)

Figure 8: (a) Indirect tensile strength test and (b) cracking pattern of sample after loading.

methods outlined in ASTM D 4123. The experimental approach utilized to determine the tensile strength of the cylindrical specimen involved subjecting it to diametrical compression at a consistent rate of 50.8 mm/min (2 in/min), as shown in Figure 8(a). This process induced a state of tension along the specimen diameter that was subjected to a load. The equation representing the highest tensile strength can be expressed using Eq. (4). To determine the weight of the blends, the specimens were allowed to reach ambient temperature after molding. The density can be calculated using bulk-specific gravity or saturated-surface dry-weight techniques. Moisture-removal techniques have also been used. Maintaining the temperature between 25 and 3°C is crucial. The test results and cracking pattern of the sample after loading are shown in Figure 8(b), respectively.

3.5 Cantabro test

This procedure measures the abrasion loss in compacted Hot-Mix Asphalt (HMA) specimens using a Los Angeles abrasion machine shown in Figure 9(a). Cantabro loss, a percentage of weight loss, indicates the durability of the low-rutting bitumen, porous friction course, and hot-mix cold laid. The test can be conducted on other HMA mixtures and the results are reported as the average percentage loss [41].

$$\mathrm{CL} = \frac{A - B}{A} \times 100, \tag{5}$$

where CL is the Cantabro loss, %, A is the initial weight of the test specimen; and B is the final test specimen weight.

Following the molding process, the specimens are let to cool down to the surrounding temperature before being weighed. The density of the porous friction course mixes was determined by using either the bulk-specific gravity or the weight of the mixture when it is saturated and surface dry. The specimens were dehydrated using dimensional analysis. Ensure that temperature levels are maintained

(a) (b)

Figure 9: (a) Los Angeles abrasion test machine and (b) samples after testing.

within the range of 60–3°C to achieve precision and reliability. Prior to testing, the samples are subjected to a 24 h period of heat conditioning in a chamber or oven. The specimens are positioned inside a testing apparatus located in Los Angeles, as seen in Figure 9(a), and undergo rotation at a speed of 30–33 rpm for a total of 300 revolutions. Discard loose samples after 300 revolutions [41]. The total deterioration of the sample after 300 revolutions provided resistance to raveling, as shown in Figure 8(b).

3.6 F&T test

Pavement degradation can be caused by traffic loads and cyclic climatic activities, leading to thermal fractures and low-temperature distress. In cold places, bitumen pavements face issues due to repeated thermal stresses and moisture-related consequences. This test, F&T cycles used to assess the performance of rubberized bitumen concrete under severe conditions. Samples were generated for a 5-day aging technique to analyze the impact of cyclic temperatures, ice, and moisture on the deterioration of rubberized materials. The volumetric, mechanical, and durability tests were conducted at specified intervals (0, 1, 5, and 10 cycles). The results suggest that rubberized bitumen concrete may be more resilient under severe conditions. Based on ASTM C666/C666-M, each sample was soaked in water at the temperature of 23 ± 2°C (room temperature) for 48 h after the curing time and before the F&T cycles. Following the conditioning phase, the F&T cycles commenced with a freezing phase programmed to achieve a temperature of −18 ± 2°C and held for a duration of 3 h (180 min). It was followed by a thawing phase conducted in cold water to reach a temperature of +4 ± 2°C and maintained for 1.5 h (90 min) [24].

3.7 Marshall quotient (MQ)

The MQ or rigidity ratio was used to evaluate the resistance of the bituminous mixes to rutting. The relationship between the flow value and MS values was observed in compacted Marshall specimens after failure. Higher MQ values indicated enhanced rigidity and load dispersion, leading to superior resistance to deformation and rutting. The Indian specification mandates a MQ range of 2–5 kN/mm to create bitumen mixtures resistant to rutting and prevent excessively brittle bituminous concrete mixtures [31–33].

Table 5: RMS for conditioned and unconditioned samples

Bitumen %	Conditioned in Pascals	Unconditioned in Pascals	RMS (%)
4	2238.08	2109.61	94.26
4.5	2478.50	2315.16	93.41
5	2639.45	2416.68	91.56
5.5	2839.79	2538.48	89.39
6	2741.21	2416.92	88.17

3.8 Retained Marshall stability (RMS) tests

The water resistance of the bituminous mixes was assessed using the RMS test and modified Lottman test. This test, which is not included in the current Indian specification, is simpler and requires less time and resources than other tests. Six Marshall specimens were created for each combination and divided into two groups. The samples in Group I underwent water conditioning, whereas those in Group II were unconditioned. Table 5 represents the results. The mean stability calculations were performed for each group, and the MS was represented as a percentage using standard equations [34–36].

$$\text{RMS} = \frac{\text{MS}_{\text{Cond}}}{\text{MS}_{\text{Uncond}}} \times 100, \quad (6)$$

where RMS is the retained Marshall stability (%), MS_{cond} is the MS of conditioned specimen (kPa), $\text{MS}_{\text{uncond}}$ is the MS of unconditioned specimen (kPa).

According to MoRTH (2001), bituminous mixes should have a minimum RMS value of 75% to ensure satisfactory moisture resistance.

3.9 Moisture sensitivity analysis

The table shows the RMS and tensile strength ratio (TSR) of various bituminous mixtures. Higher TSR and RMS levels are thought to improve the moisture resistance. The TSR (RMS) values declined as the filler content increased, indicating an increased moisture sensitivity. The visible bitumen coating acts as a protective barrier, ensuring durability and moisture resistance. A reduction in oxidative stress leads to a decrease in the process of aging F&T,

resulting in decreased moisture resistance. This pattern aligns with the findings of previous studies [16,37–40].

4 Results and discussion

4.1 Effect of SA on flow and MS

The MS rating of a bitumen mixture is the maximum load that it can bear during testing, whereas Marshall flow is the deformation of the specimen when the load decreases. Marshall stiffness was determined by dividing the MS by the flow, resulting in kN/mm. The ideal percentage of bitumen increased by 5.5% when SA was substituted into the MS, indicating that these materials improved the rigidity and adhesiveness of the mixtures.

Figure 10(a) proves the correlation between bitumen content in the absolute and the flow value in the case of the application of asphalt mixes with the addition of SA in different proportions. The mix that contains no SA is considered the control mix; as indicated earlier, it contains all the conventional material. The flow value improves when the blends contain a higher proportion of bitumen as is expected in view of the fact that it serves as both a binder to the aggregate and a lubricant to the mix. In fact, mixes with 5, 10, 15, and 20% SA content prove to provide slightly better flow values than the conventional 5% bitumen content. This means that SA, which has filler properties, may improve mix fluidity at a lower content of bitumen. But this influence reduces as the bitumen content rises and the flow values of all the mixes are generally approached. The flow behavior of asphalt mixes has therefore been established with varying bitumen contents and SA contents in this analysis.

In Figure 10(b), the graph relates MS values measured in kg to various percentages of bitumen, namely, 4.0, 4.5, 5.0, 5.5, and 6.0% of the mix as well as to the mix proportion of SA. The conventional mix presents the lowest stability value ranging from 700 to 840 kg at 5.5% bitumen. As the percentage of SA increases, the stability values tend to increase with small fluctuations (5%, 10%, 15%, and 20%). The blend with 15% of SA shows the highest density is 997 kg and consumed at 5.5% of the bitumen content. All mixtures have facilities in this aspect as they follow a trend similar to each other where stability rises with an increase in bitumen content and reaches its optimum at 5.5% bitumen, though at the top level of 6.0% bitumen, the value declines. For the 10% SA, the slump is between 750 and 920 kg while for the 15% SA mix and 20% SA mix, the slump is slightly higher than the normal mix but not as high as that of 15% SA.

4.2 Effect of SA on volumetric properties

The volumetric mechanical qualities of bitumen concrete mixtures are greatly influenced by their properties' durability, and performance in real-world applications. Techniques such as specific gravity determination, AV study, mineral aggregate void assessment, and bitumen void-filling void analysis are used to evaluate these

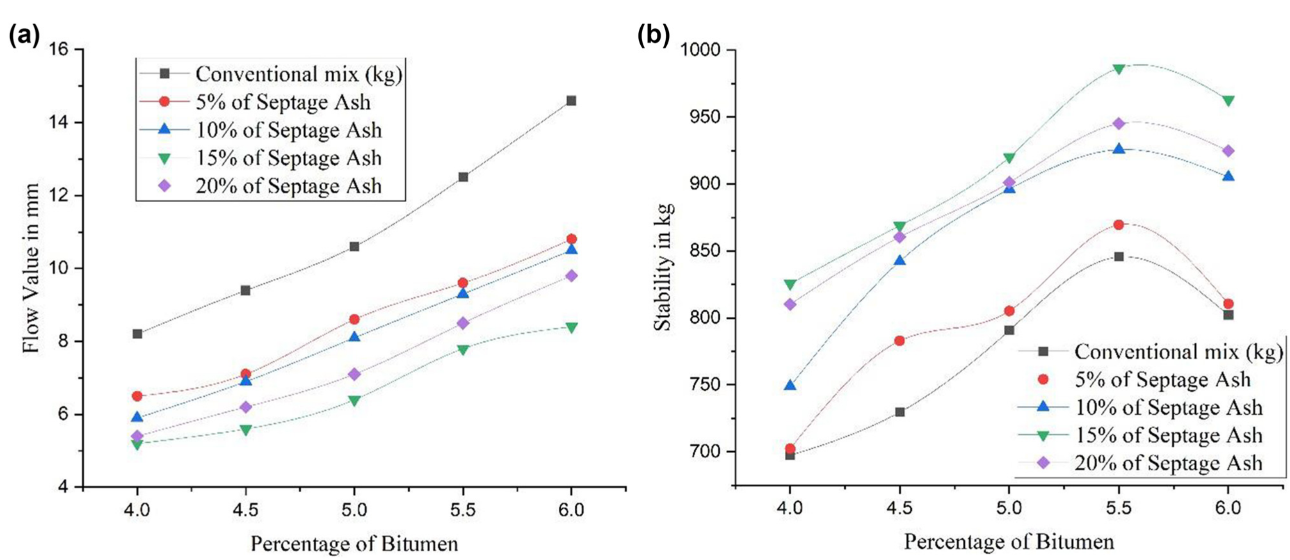

Figure 10: (a) Flow value and (b) Marshall stability.

characteristics and can calculated using Eqs. (1)–(3). The volumetric parameters are shown in Figure 11.

Figure 11(a) shows the percentage of bitumen on the volume of voids/AV with the SA substitution level in an ascending scale: 0, 5, 10, 15, and 20%. The outcomes further confirm that there is increased reduction in the voids as the quantity of bitumen as well as SA is increased. For the conventional mix, when SA content is 0%, voids reduce from 4.5% at 4% of bitumen to 3.0% at 6% of bitumen, making a gradual compacting curve of the material. At 5% SA, the voids decrease from 4.4 to 2.9%, which shows slightly better condition than conventional concrete mix. Similarly, voids decrease from 10% SA to 8% with 15% substitution, and 6% with 20% substitution and with 6% bitumen, 2.7 and 2.6% were obtained, respectively. This trend indicates that SA improves the compactness of the mix.

In Figure 11(b), the graph depicts the interaction between the percentage of bitumen and, the VFB based on the SA replacement of the following: 0, 5, 10, 15, and 20%. The traditional blend (0% SA) results in VFB accumulation of about 70% at 4% of bitumen, rising to 80% at 6% of the same; a clear implication that improved bitumen filling is obtained with higher content. Starting at 5% SA, the VFB is at approximately 68% for 4% bitumen and rises to 78% for 6% bitumen and exhibits a trend somewhat lower than that of the VFA. The 10% SA mix has the following VFB: 66% at 4% bitumen, up to 77% at 6% bitumen, showing only a slightly poorer filling efficiency. However, while it rises to both 15% and 20% ash content, the VFB reduced greatly. For 20% ash, it is 55% at 4% bitumen and rises to only 65% at 6% bitumen, implying diminished bitumen contact and bonding capacity at higher ash content.

Figure 12 represents the ITS with different asphalt content (4–6%) and different replacement of SA 0, 5, 10, 15, and 20%. ITS values for the base mix (0% SA) ranges from approximately 2,200 kPa at 4% by bitumen up to about 3,500 kPa at 5.5% by bitumen and slightly decreases at 6%. For 5% SA, the ITS values are a little higher, starting from 2,300 kPa at 4% bitumen to a maximum of 3,600 kPa at 5.5% bitumen and a minimum of 3,400 kPa at 6%. The average ITS values increases up to the 5.5% bitumen and then slightly reduces, the value lies around 2,100 at 4% SA mix and 3,500 KPa at 5.5%. However, ITS values decrease with an increase in SA content in the mixes (15 and 20%). When 20% SA is specified, the ITS values reduce drastically, starting at 1,800 kPa at 4% of bitumen and jumping to 3,000 KPA at 5.5% of the bitumen. This trend suggests that about 5–10% replacement SA improves ITS while excessive SA (15–20%) compromises the tensile strength because of poor interfacial adhesion and poor aggregate bitumen interaction.

4.3 Effect of SA on hardness

Hardness refers to the ability of a substance to withstand the frictional forces generated by vehicle motion. The Cantabro test measures the hardness, and the fine loss percentage is calculated using different ratios of SA loss, based on the interlock and stiffness characteristics of the nominal mix.

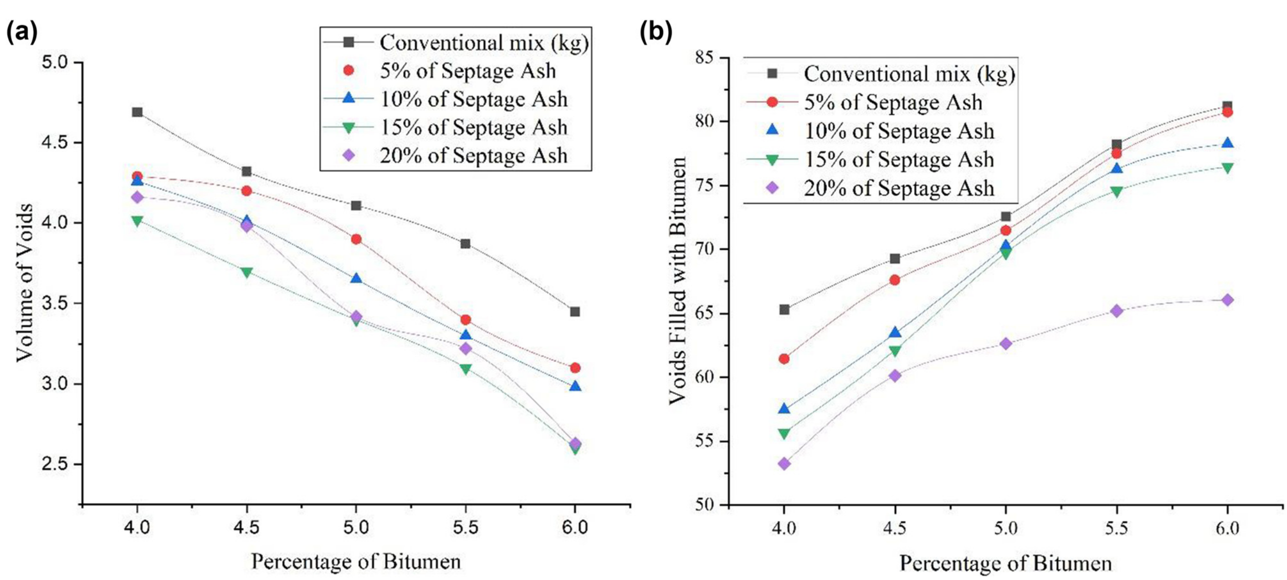

Figure 11: (a) Volume of voids/air voids and (b) voids filled with bitumen.

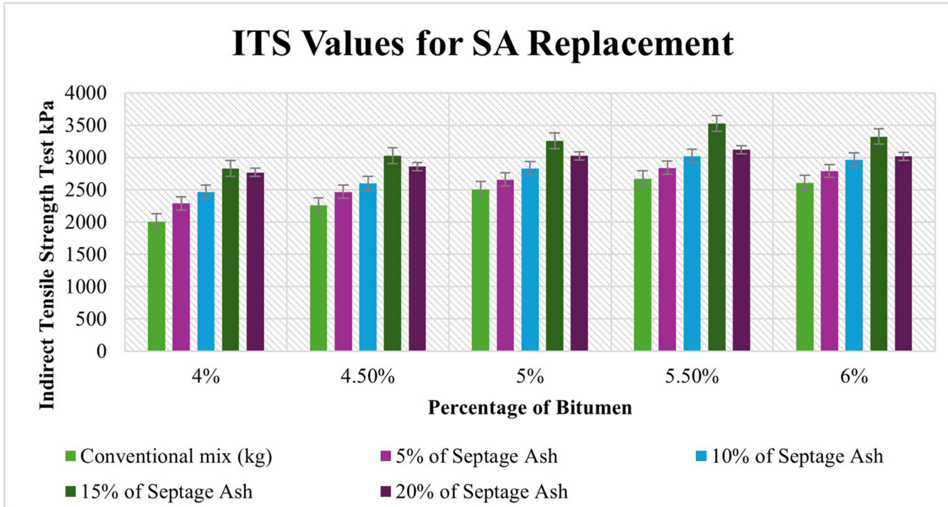

Figure 12: Indirect tensile strength values.

The Cantabro fine loss test results are presented in the form of a pie chart in order to show the proportion of fine particles lost for various kinds of asphalt mix formulations. The result revealed that the nominal mix had the highest percentage of fine loss at 24%, which implies that this mix is more prone to loss of fine materials. This is accompanied by the 20% Stone Mastic Asphalt (SMA) mix with 26% loss indicating that even though SA increases the content of mix stability a particular formulation of this mix has registered more loss of fines. However, the 15 and 10% SA mixes demonstrated a significantly improved fine loss of 16%. This may mean that the intermediate SA percentages offered by the mixes above might have offered the right balance between stability and resistance to fine loss than the nominal mix and the 20% SA mix. The 5% SA mix on the other hand recorded a fine loss of 18%, which was slightly higher than the 15 and 10% SA mixes. These results demonstrate how fine loss works in concrete with varying factors to affect fine aggregates in asphalt mixes. The distribution of SA is another important figure, though other factors such as aggregate gradations, amount of binder and level of compaction also have an impact. Knowledge of these interactions is a powerful tool to create and produce high-strength and long-service asphalt pavements that can cope with traffic and climate loads as shown in Figure 13.

4.4 Test results of volumetrical changes in F&T test

The density fluctuations for each cycle are determined in Figure 14. Before transitioning to subsequent cycles, density calculations were used to assess volumetric changes. Figure 14 shows the density variations after F&T tests for SA mixes. According to Figure 14, the density fluctuations were greater in the nominal mix. The density variations

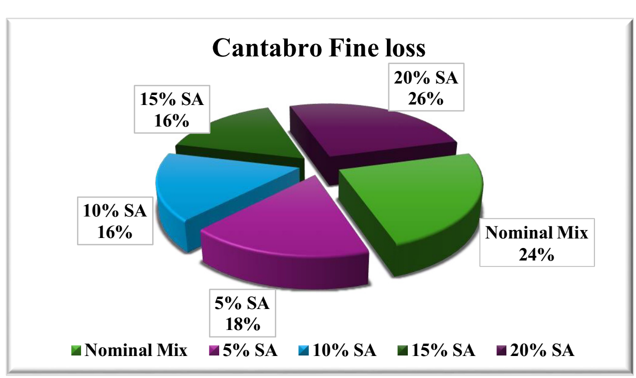

Figure 13: Cantabro fine loss.

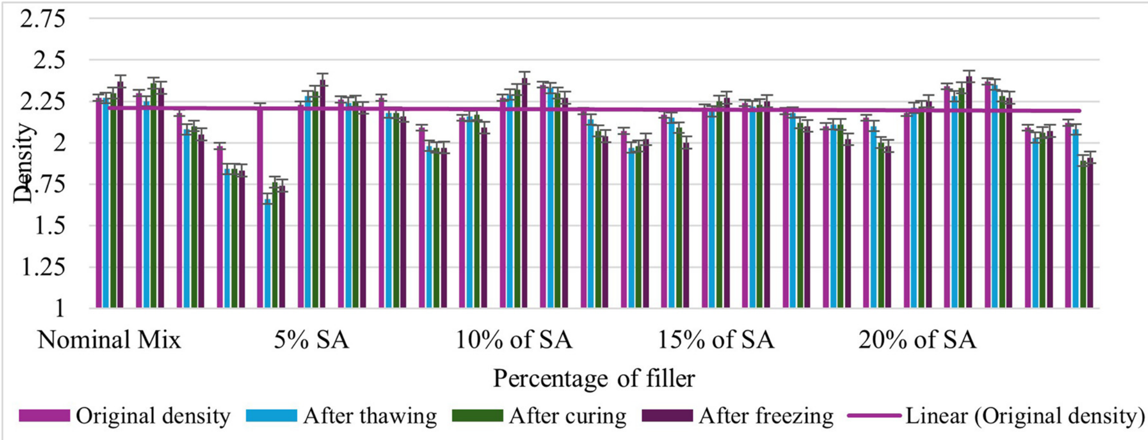

Figure 14: Density variations after freezing and thawing test for SA mixes.

were compared with the original sample. The volume and density of the bitumen decreased by 5.5% when 15% SA was added, mostly because the voids were filled with ash, resulting in increased compatibility. According to ASTM C666/C666-M, each sample was soaked in water at a temperature of 23 ± 2°C (room temperature) for 48 h after the curing time and before the F&T cycles. The F&T cycles commenced after the conditioning phase. The freezing phase was adjusted to achieve a temperature of −18 ± 2°C and lasted for 3 h (180 min). This was then followed by the thawing phase, which was conducted in cold water to reach a temperature of +4 ± 2°C and lasted for 1.5 h (90 min).

4.5 Test results on MQ

MS quotient value is the ratio of the stability to the flow value, which quantifies the load-bearing capacity and deformation per unit loading and represents the strength value of the mix. The results show a higher strength than that of the original mix, as shown in Figure 15.

4.6 Effects of SA on moisture sensitivity

The moisture sensitivity impact was determined by calculating the ratios of the RMS and TSR of the conditioned and unconditioned samples while altering the proportion of bitumen. Figure 16 illustrates the correlation between the RMS and the TSR. Enhancements were made to the mechanical and durability characteristics. Figure 16 demonstrates that the presence of extra particles hindered the entry of moisture into the mix, hence diminishing the strength and impact of moisture. According to the results, bitumen mixtures containing up to 15% SA exhibit improved resistance to moisture-induced deterioration, suggesting that this material may increase pavement longevity in damp environments [37,38,41–43].

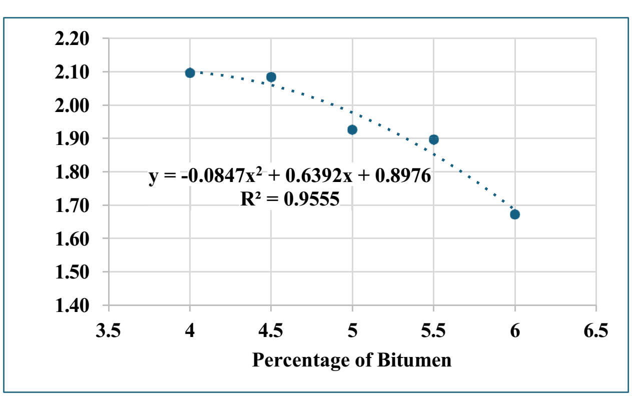

Figure 15: Marshall stability.

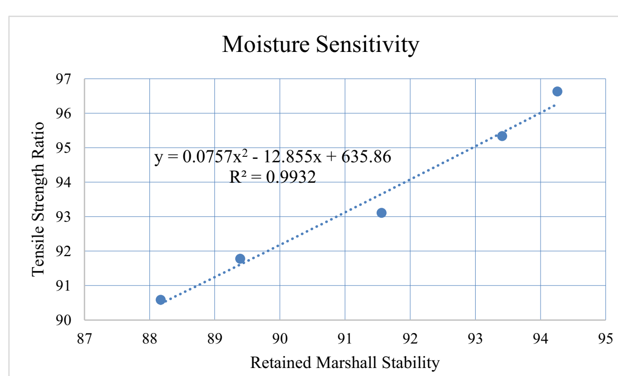

Figure 16: Retained Marshall stability and tensile strength ratio.

Table 6: Single-factor ANOVA results for normal and SA replaced mix

Test	Source of variation	SS	df	MS	*F*	*P*-value	F crit
Retained Marshall stability	Between groups	16234612.7	2	8,117,306	757.3071	9.36×10^{-11}	**4.256495**
	Within groups	96467.808	9	10718.65			
	Total	16331080.5	11				
Marshall stability	Between groups	3022801.71	5	604560.3	185.9347	2.26×10^{-18}	**2.620654**
	Within groups	78035.1862	24	3251.466			
	Total	3100836.9	29				
ITS Test	Between groups	1410074.72	4	352518.7	11.78087	0.000157	**3.055568**
	Within groups	448844.737	15	29922.98			
	Total	1858919.46	19				
Cantabro test results	Between groups	276.292136	4	69.07303	3.389378	0.036459	**3.055568**
	Within groups	305.688967	15	20.37926			
	Total	581.981103	19				
Moisture sensitivity	Between groups	0.04205	1	0.04205	0.006109	0.940244	**5.987378**
	Within groups	41.30235	6	6.883725			
	Total	41.3444	7				
Flow value	Between groups	50.973	4	12.74325	4.497089	0.013793	**3.055568**
	Within groups	42.505	15	2.833667			
	Total	93.478	19				
VFB	Between groups	385.86945	4	96.46736	2.742651	0.067923	**3.055568**
	Within groups	527.59555	15	35.17304			
	Total	913.465	19				
The volume of voids Vv	Between groups	1.35137	4	0.337843	1.520968	0.246216	**3.055568**
	Within groups	3.33185	15	0.222123			
	Total	4.68322	19				

SS–Sum of squares; df–degrees of freedom; MS–mean square; F–F-ratio; P-value–probability value; F crit–critical F-value.

5 Validation of Anova test results for different test results

Single-factor ANOVA (Analysis of Variance) is a statistical technique used to compare the means of three or more groups based on a single independent variable. It determines whether significant differences exist between group means, assuming normal distribution and homogeneity of variance.

The primary objective of the single-factor ANOVA in Table 6 was to assess the impact of the filler SA and nominal mix with bitumen concentration (B) on the properties of the mixes. The significance level was set at $p < 0.05$. Statistical analysis showed that the type of filler and the amount of bitumen have an impact on various properties of the bitumen mixture, including the MS, flow value, ITS, and Cantabro test, and volumetric parameters such as volume of voids and voids filled with bitumen, RMS, and moisture sensitivity. The findings suggest that an F-crit value larger than 1 validates the practical importance of these findings. The results of this test showed that the interaction between the two independent variables ($A \times B$, filler type, and bitumen concentration) had a significant effect ($p < 0.05$) on all the dependent variables. The above F crit (0.05 < specific value) values of all results mention the adhesion between the filler SA and other ingredients in the mix shown in Figure 7(c). Considering this, according to the data of the single-factor ANOVA statistical analysis, the result values are $p < 0.05$ with the exception of moisture susceptibility and the other elements meet the conditions for being a filler to the bitumen mix.

6 Conclusion

Within the scope of this research, the qualities of bitumen mix Grade 2 prepared with SA and normal fillers typically used in pavement manufacturing were investigated. The main findings are summarized as follows:

- Suitability of SA as filler: SA demonstrated properties comparable to conventional fillers such as fly ash, cement, and brick powder, making it a viable partial substitute in bitumen mixtures.
- Optimal replacement ratio: The study identified that a 15% replacement of traditional filler with SA yielded the best mechanical and performance characteristics, enhancing the overall quality of the bitumen pavement.
- Improved mechanical properties: Incorporating SA increased the strength of the bitumen mix by 32% and

reduced fine loss by 23%, indicating enhanced durability and resistance to deformation.
- Enhanced moisture resistance: Bitumen mixtures with up to 15% SA showed improved resistance to moisture-induced damage, suggesting better performance in wet environments.
- Reduced volumetric changes: The addition of SA minimized density fluctuations during F&T cycles, indicating better stability under environmental stress.
- Sustainable waste management: Utilizing SA as a filler aligns with sustainable practices by repurposing waste material, reducing landfill usage, and lowering the environmental impact of road construction.
- Cost-effective solution: The use of SA offers potential cost savings in road construction by reducing the reliance on virgin materials and improving pavement longevity.

The study findings indicate that SA possesses qualities that qualify it as a suitable filler material for Grade 2 mixes.

7 Recommendations/future scope

Subsequent research should prioritize an extended assessment of the effectiveness of bitumen mixtures containing SA in real-world scenarios. Furthermore, it is crucial to evaluate the ecological consequences of using SA for road construction to guarantee long-term viability.

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Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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