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Innovative Use of Crumb Rubber and Silica Fume in Hot Mix Asphalt: A Material Properties Study

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ABSTRACT

A significant percentage of road pavements suffer from cracking and rutting, primarily owing to poor asphalt mixture characteristics and heightened traffic loads. Subsequently, they acquire defects such as creep, fatigue, and rutting. To address these issues, this study explores the use of crumb rubber (recycled tyres) and silica fume (by-product of silicon alloy production) as modifiers for enhancing asphalt performance. Asphalt mixes were prepared with varying amounts of crumb rubber (5–10% by weight of bitumen) and silica fume (5–10% by weight of fine aggregate). Aggregate tests (Aggregate Impact Value Test, Aggregate Crushing Value Test, Los Angeles Abrasion Value Test, and water absorption), bitumen tests (penetration, softening point, and ductility), and mechanical performance tests (resilient modulus, dynamic creep, and Scanning Electron Microscopy analysis) were performed. Results revealed that the mixture containing 10% crumb rubber and 5% silica fume exhibited a 25% increase in resilient modulus and a 30% reduction in permanent strain compared to the conventional mixture. This combination modification method is unique in integrating both crumb rubber and silica fume at optimized levels to enhance the performance for both mechanical and morphological properties simultaneously. It can be concluded that the utilizing of these materials significantly improves pavement lifespan and reduces environmental impact while also improving sustainability and durability.

Keywords: Crumb rubber; silica fume; hot mix asphalt; modified asphalt; green pavement

INTRODUCTION

Pavements are the base of all current urban mobility and transport systems. They play an important role in economic growth and national integration. Flexible pavements are the most common type of road construction in Malaysia. They are cost-effective, strong, and can handle different traffic levels (Intan Jasmin Rosli and Abd Sukor Sarif, 2021). The flexible pavement is mostly made of conventional bitumen and aggregates. The flexible pavement has multiple structural layers, and the Hot Mix Asphalt (HMA) is the surface layer that resists vehicle loads and environmental damage (Liu et al. 2024).

Furthermore, the problems of rutting, fatigue cracking, and moisture-induced degradation with typical asphalt mixtures will occur due to rising traffic loads and environmental concerns. These pavement distresses compromise road safety and contribute significantly to maintenance costs, leading to premature pavement failure (Abdulaziz Alsaif and Abdulrahman Albidah 2024).

At the same time, the increase in waste products, such as waste tyres and industrial by-products such as silica fume, represent a serious problem for the environment. Recycling such wastes in asphalt mixes not only reduces landfill dependency and environmental pollution but also offers an opportunity to enhance asphalt mechanical performance (Li et al. 2024a). Hence, the use of crumb rubber and silica fume in asphalt mixture is in line with both performance enhancement and sustainable development principles and thus are potential option in contemporary pavement engineering.

Therefore, the recycling of waste materials into asphalt mixtures has been pursued in highway engineering as a means of achieving sustainability and enhancing performance (Saqib Gulzar et al. 2023). Earlier studies have looked at different industrial and post-consumer wastes, such as crumb rubber (CR), silica fume (SF), reclaimed asphalt pavement (RAP), recycled concrete aggregates (RCA), and waste plastics (Jamshidi and White, 2019). This study focuses on CR and SF as partial replacements in asphalt pavement, with subsequent sections detailing their individual and synergistic contributions to asphalt performance.

Around 8.2 million used tyres are collected annually in Malaysia with roughly 57,391 tonnes as quoted by Mamauod in 2024. Roughly 60% of waste tyres are dumped into untraceable disposal techniques. Since tyres will not decompose naturally, most individuals just take them to landfills, thereby spreading bad chemicals to the air, water, and earth, which end up reaching the local environment. CR is a recyclable material from old and used tyres. Road use and pavement damage have increased due to the number of vehicles worldwide has grown. Adding crumb rubber to pavement can improve its durability and performance. It also helps address environmental concerns (Khaled, Aboud and Al-Hamd, 2020). Due to the growing supply of scrap rubber, the adverse environmental consequences, and the need to reduce the use of natural resources in construction, crumb rubber is becoming increasingly popular in the industry (Mohajerani et al. 2022).

The previous researcher figured out that when adding 12% crumb rubber into the asphalt mixture would increase the Marshall Stability Values and enhance the durability of the pavement (Khaled, Aboud and Al-Hamd, 2020). The researchers Al-Rubaie and Joni also find that the asphalt mixture with 10% crumb rubber will have the highest Marshall Stability and small rut depth, which may enhance the lifespan of the road pavement (Al-Rubaie and Joni 2021).

SF is the production of elemental silicon or silicon alloys in electric arc furnaces (Panesar and Zhang, 2020). Silica fumes are also known as micro silica, condensed silica fumes, or silica dust. For instance, OM Materials (Sarawak) Sdn. Bhd. manufactured about 1369.96 metric tons daily of micro-silica and 308,000 of 75% Si ferrosilicon annually, which is harmful to the human body (Nugroho et al. 2025). It also has a high surface area and is known for its pozzolanic properties of approximately 120-200% of Ordinary Portland Cement. The silica fume added to the asphalt mixes has shown its efficacy in reducing the amount of asphalt concrete, reducing the stiffness modulus, and enhancing the longevity of fatigue (Naser et al. 2023).

Researcher Pinki Deb. states that the addition of silica fume to asphalt mixture will have a significant improvement in stability and fatigue life for higher temperatures (Deb and Singh 2022). The addition of silica fume as filler for the asphalt mixture could increase the indirect tensile strength of the asphalt mixture compared with the conventional asphalt mixture (Tiwari et al. 2023).

Therefore, using crumb rubber and silica fume in asphalt mixture can be a sustainable practice, as it uses recycled materials and reduces the need for landfilling or disposal. It aligns with broader efforts to promote eco-friendly construction practices (Aboelmagd et al. 2021; Intan Jasmin Rosli and Abd Sukor Sarif 2021). Investigating the impact of these materials on asphaltic mixture performance can lead to an understanding of cost-effectiveness as it can improve the lifespan of pavement, indirectly reducing maintenance and replacement costs (Milad et al. 2022).

Although previous researchers have investigated the effect of crumb rubber or silica fume individually to enhance the performance of asphalt pavement (Wang et al. 2022; Murali, 2023; Ragab et al. 2025). There is few research carried out the combination for both crumb rubber and silica fume as waste materials replacement in modified mixture of asphalt pavement. Therefore, this study systematically investigates the combination of the use of these waste materials as modifiers in asphalt mixtures.

Therefore, the objective of this study is to investigate the influence of crumb rubber and silica fume on the physical, mechanical, and morphological properties of asphalt mixtures. Various laboratory tests, including aggregate and bitumen characterization, Resilient Modulus, Dynamic Creep, and Scanning Electron Microscopy (SEM) analyses, were conducted to evaluate the effects of these modifiers. The research specifically examines how crumb rubber improves binder elasticity and how silica fume enhances mixture stiffness and durability. The findings contribute to developing more sustainable and high-performance pavement materials by demonstrating the effective co-utilization of waste-derived additives.

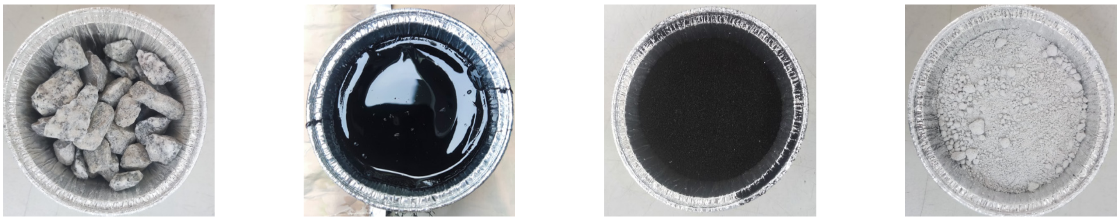
MATERIALS AND METHODS

MATERIALS

In this study, the materials used to produce the asphalt mixture are granite aggregate and bitumen, while CR is used as a partial replacement for bitumen, and SF as a partial replacement for fine aggregate. Granite aggregate was used as the main load-bearing material, while crumb rubber improved the elasticity and high-temperature performance of the bitumen. Silica fume enhanced the creep behaviour of the asphalt mixtures under high temperatures and stress. The description of the materials used for this study is shown in Table 1 and the image for the materials is shown in Figure 1.

TABLE 1. Physical properties of asphalt mixture materials

Materials	Description
Bitumen	- Penetration grade 60/70 - Manufactured by Fosxil Petroleum Sdn. Bhd.
Aggregate	- Type: Granite aggregate - Particle size: 14 mm – 75 µm - Manufactured by SEDC Premix Sdn. Bhd.
Crumb Rubber	- Particle size: < 595 µm - Manufactured by ZHA Environmental Sdn. Bhd.
Silica Fume	- Particle size: 0.1 – 0.3 µm - Manufactured by OM Materials (Sarawak) Sdn. Bhd.



Granite Bitumen Crumb rubber Silica Fume

FIGURE 1. Type of materials

MIX PROPORTION

Silica fume (SF) and crumb rubber (CR) were utilized as replacement materials in this work. In CR, bitumen was partially replaced, and in SF, fine granite aggregate was replaced. The used bitumen in this test is penetration for 60/70 grades. The granite aggregate utilized for this work was graded as per the AC14 specification, which is commonly used for asphalt concrete wearing courses. The aggregate gradation was designed to satisfy the specification limits for the AC14, outlined in Table 2.

Crumb rubber-modified bitumen (CRMB) was prepared by initially heating the base bitumen to a temperature of approximately 110-120***°C*** to ensure it reached a fluid state suitable for mixing. The required proportion of crumb rubber, based on the total bitumen weight, was then accurately weighed. Once the bitumen reached the desired temperature, the crumb rubber was gradually introduced into the bitumen while maintaining constant stirring to prevent clumping. The mixture was then placed on a hot plate and blended using a high-speed mechanical mixer for 20 to 30 minutes. Continuous mixing ensured the crumb rubber was uniformly dispersed, producing a consistent and homogenous modified binder.

The mix of asphalt was prepared according to the equal bitumen content of 5% by the weight of the total mix, for which 5% to 10% bitumen was being replaced by crumb rubber, and 5% and 10% of fine aggregate was being replaced by silica fume The process was initiated by preheating the bitumen and granite aggregates to a temperature of 110˚C for 1 hour for easy processing of the blending process. After the preheating process, the sample will be poured into a wok mixed with the bitumen and aggregates together until it reaches 180˚C.

After that, the blended asphalt mix was compacted to standard cylindrical moulds using a Marshall compactor machine for 50 compactions. The standard dimension for the mould sample is 101.6 mm in diameter and 65.9 mm in height. After compaction, the moulds were left to cool at room temperature for 24 hours to let the samples fully harden. Once cooled, the samples were carefully demoulded, and their dimensions were measured to ensure they met the strict size requirements for the Dynamic Creep and Resilient Modulus tests. These tests would then measure how well the samples resisted permanent deformation and recovered under repetitive loading. The procedure of the mixing process is shown in Figure 2.

Several physical tests were carried out on bitumen and aggregate in the field to ascertain its workability. Both conventional bitumen and crumb rubber modified bitumen will be experimentally tested for penetration test, softening point test, and ductility tests. Aggregate with a 14 mm size will be used to conduct the test of Aggregate Crushing Value (ACV) test, Aggregate Impact Value (AIV) test, Los Angeles Abrasion Value (LAAV) test and water absorption test. The sample required for these physical tests is in Table 3 and Table 4.

Moreover, the mechanical performances of the asphalt mixtures were examined by the Resilient Modulus test and Dynamic Creep test. Mix designs were performed using 5% bitumen by the total weight of the mixture. The tests were carried out on cylindrical samples (diameter of 101.6 mm and height of 65.9 mm) to evaluate the elastic characteristics and rutting resistance of the modified mixes. The research employed a comprehensive method involving laboratory testing and performance assessment of asphalt mixtures with varying crumb rubber (5% to 15% by weight of bitumen) and silica fume (5% and 10% by fine aggregate weight) contents.

The selected percentage of crumb rubber (5% to 15%) and was based on previous studies (Zahran and Tan, 2022; Hisham and Rosnawati, 2023; Al-Rubaie and Joni, 2021), which reported optimal improvements in binder elasticity and mixture stiffness within these ranges. All tests were conducted in accordance with ASTM and BS standards to ensure the compliance with international testing procedures. The details of the mechanical tests are summarised in Table 5.

TABLE 2. Gradation limit for AC14 and mass of aggregates used

Sieve Size (mm)	Gradation Limit	% Passing	% Retained	Mass Retained (g)
20	100	100	0	0
14	90-100	95	5	60
10	76-86	81	14	168
5	50-62	56	25	300
3.35	40-54	47	9	108
1.18	18-34	26	21	252
0.425	12-24	18	8	96
0.15	6-14	10	8	96
0.075	4-8	6	4	48
PAN	0	0	6	72

TABLE 3. Total amount of bitumen sample

Sample	Penetration Test (ASTM D5-97)	Softening Point Test (ASTM D36)	Ductility Test (ASTM D113)	Total Sample
100% bitumen (control sample)	3	3	3	9
5% crumb rubber + 90% bitumen	3	3	3	9
10% crumb rubber + 85% bitumen	3	3	3	9
15% crumb rubber + 80% bitumen	3	3	3	9
			Total Sample	36

TABLE 4. Total amount of aggregate sample

AIV Test (BS 812-112:1990)	ACV Test (ASTM D5821)	LAAV Test (ASTM C535-16)	Water Absorption Test (ASTM C127-15)	Total Sample
3	3	3	3	12

TABLE 5. Total amount of asphalt mixture sample

Sample	Resilient Modulus (ASTM D 7369)		Dynamic Creep Test (EN 12697-25)	Total Sample
	25 ˚C	40 ˚C		
100% bit + 100% CA + 100% FA (Conventional)	3		3	6
100% bit + 100% CA + (95% FA + 5% SF)	3		3	6
100% bit + 100% CA + (90% FA + 10% SF)	3		3	6

continue...

...cont.

(95% bit + 5% CR) + 100% CA + 100% FA	3	3	6
(95% bit + 5% CR) + 100% CA + (95% FA + 5% SF)	3	3	6
(95% bit + 5% CR) + 100% CA + (90% FA + 10% SF)	3	3	6
(90% bit + 10% CR) + 100% CA + 100% FA	3	3	6
(90% bit + 10% CR) + 100% CA + (95% FA + 5% SF)	3	3	6
(90% bit + 10% CR) + 100% CA + (90% FA + 10% SF)	3	3	6

*bit = bitumen, CA = coarse aggregate, FA = fine aggregate, CR = crumb rubber, SF = silica fume

(a) Mix the aggregate with bitumen
(b) Pour into the cylindrical mould
(c) Compact and cold for 24 hours
(d) Demould and measure the dimension

FIGURE 2. Preparation for asphalt mixture sample

TEST PROCEDURES

BITUMEN TEST

Bitumen is a critical component of asphalt mixtures because of its role as a binding agent, blending the aggregate particles together. It gives the mixture longevity and resistance to deformation under environmental and traffic loads by endowing it with cohesion and flexibility. The overall quality and longevity of asphalt pavements are ensured through the bitumen tests, where bitumen's properties are examined and optimised meticulously.

The penetration test was carried out to measure the hardness or consistency of bitumen by the depth that a standard needle penetrates at 25°C. It is a measure of bitumen resistance to deformation when loaded. The bitumen sample will be immersed in a water bath at a constant temperature of 25°C for 1 hour before the test. The lower the penetration value, the harder the bitumen will be, which could lead to increased rutting resistance. More soft bitumen will have a higher penetration value and be more flexible for use in pavement construction in another aspect. This test was done followed by the ASTM D5-97 standards which the final penetration value should be in the range of 60-70 mm.

The softening point test was conducted to determine the temperature at which bitumen softens. This test will measure the temperature sensitivity of bitumen. All the apparatus and bitumen samples that were used in the test must be placed in the water bath at 5ºC for 15 minutes before starting with the testing of softening point test. The greater the softening point, the more the bitumen can resist high-temperature flow and rutting. This test is conducted as per ASTM D36 standards which the temperature must be in the range between 49-56ºC.

The ductility test was also conducted to determine the extent to which bitumen elongates before it ruptures. It was utilized to test the overall cohesion and flexibility of the bitumen. The molten bitumen sample will be poured into the briquette and submerged in the water bath until it reaches 25ºC. The higher the ductility length, the better performance against cracking at low temperatures. This test is conducted by ASTM D113 standards which the ductility length should not be less than 100 mm.

AGGREGATE TEST

Aggregates form the skeleton of asphalt mixture that provide them with structural strength to withstand traffic loads, temperature variations and moisture. Poor quality aggregates may lead to premature pavement failure in the form of cracking or rutting. To ensure dependability, aggregates undergo rigorous quality tests before construction use.

The Aggregate Impact Value (AIV) test is used for the determination of the durability and shock impact resistance of the aggregate. In this test, the aggregates will be placed in a steel mould and struck 15 times with a hammer, and the fine particles less than 2.36 mm will be sieved to determine the percentage of impact value. The aggregates for road construction must withstand fragmentation from vehicular loading and dynamic forces. For lower impact values, it suggests it will be harder against the load of traffic. This experiment was performed as per BS 812-112:1990 standards, and the impact value should not exceed 30%.

The Aggregate Crushing Value (ACV) test is used to determine the resistance of an aggregate to compressive loads over a longer period. The test can measure the strength of aggregates under traffic pressure. In this test, the aggregates are crushed in a cylindrical mould under 400 kN pressure for 10 minutes. Particles with dimensions less than 2.36 mm will be sieved to obtain the percentage of crushing value. The Lower the value of ACV, the stronger the aggregates that are suitable to be used for load-carrying layers. The test was carried out in accordance with ASTM D5821 standards which the crushing value should be less than 30%.

Los Angeles Abrasion Value (LAAV) testing quantifies the abrasion resistance of aggregates. It formerly tested how aggregate performance over time compares to surface wear under traffic loadings. Aggregates and steel balls are placed in a rotating drum for 500 revolutions, and the fine particles retained on a 1.70 mm sieve will be recorded. Higher LAAV indicates poorer durability and more surface degradation. It was performed according to ASTM C535-16 standards which the abrasion value should be less than 25%.

The water absorption test is conducted to determine the amount of water that the aggregate will absorb. It indicates aggregate porosity and the potential for moisture damage. The dry aggregates used in this test are weighed and soaked in water for 24 hours. After that, the wet aggregates were weighed to determine the results of the water absorption test. Lower water absorption enhances the bonding and moisture resistance between bitumen and aggregate. The test was performed in accordance with ASTM C127-15 standards which the water absorption value should not be more than 2%.

ASPHALT MIXTURE TEST

The Resilient Modulus test is the test for determining permanent deformation under repetitive loading. It will indicate material stiffness under traffic loading. All the samples will be preheated for 4 hours at the test temperature (25˚C and 40˚C) before starting the testing. The higher the modulus value, the stiffer the asphalt mixture which enhances the rutting resistance. If the modulus value is too high, the asphalt mixture may crack easily. This test is conducted as per the standards of ASTM D 7369 which the result for modulus value should be more than 2500 MPa at the temperature of 25˚C.

Dynamic Creep Test is used to quantify permanent deformation under repeated loading, especially for the hot climates area. This test is conducted at the temperature of 40˚C and all the test samples will need to preheat by 4 hours before testing. It will demonstrate the situation of long-term traffic loading. The higher the creep stress, the greater the strength or stiffness of the asphalt mixture. This test is performed as per the BS EN 12697-25 standard which the creep stress should be more than 75 MPa.

Some of the samples were analysed using scanning electron microscopy (SEM). SEM is used to view the microstructural details and surface texture of the modified asphalt mixture. SEM provides high magnification images in which observation of detailed surface morphology such as bitumen matrix, aggregate surface, and incorporated modifiers such as crumb rubber and silica fume can be observed. This observation facilitates the observation of distribution and material interaction among the components in the asphalt mixture.

TEST RESULTS

BITUMEN TEST RESULTS

The penetration test is used to determine the extent to which a typical needle penetrates bitumen under specific conditions to measure its hardness and consistency. In this study, the mean penetration of conventional bitumen was 69.2 mm, which was in the range between 60–70 mm specified by the ASTM D5-97 standard. The penetration values of the 5% and 10% crumb rubber modified bitumen were 67.4 mm and 63.2 mm respectively and also satisfied the standard conditions. As the crumb rubber content increased, needle penetration decreased, which clearly proved that with the increase in crumb rubber, the hardness and stiffness of bitumen had been increased, and thus the anti-rutting property of the mixture was also increased (Al-Rubaie and Joni 2021).

The softening point test measures the temperature at which the bitumen changes from a semi-solid to a liquid state, which reflects its sensitivity to temperature. In this study, all samples of softening points were between 49°C and 55°C, which fulfil the standard requirement of ASTM D36. These results show that they can remain stable under the medium and high-temperature conditions commonly found on roads. The increased of stiffness and softening point can be attributed to the swelling of crumb rubber particles, which absorb lighter fractions of oil and produced a gel-like phase within the bitumen matrix (Wang et al. 2020). This enhances viscosity and creates a stronger polymer network that resists deformation under load. This result proves that both conventional bitumen and crumb rubber modified bitumen are suitable for road paving, especially in warm climates.

The ductility test evaluates the ability of bitumen to be stretched without breaking, expressed as the extension length (mm) of a standard specimen. The ductility of conventional bitumen meets the minimum requirement of 150 mm specified by the ASTM D113 standard. In contrast, the ductility of crumb rubber modified bitumen is lower, which is mainly attributed to the fact that the addition of crumb rubber increases the rigidity and elasticity of bitumen (Zhao et al. 2023a). Crumb rubber absorbs light oils in the bitumen, reducing its plasticity and ductility. Despite the decrease in ductility, the increase in stiffness improves the bitumen's resistance to permanent deformation and rutting under repeated traffic loads (Nuha et al. 2011).

As presented in Table 6, all bitumen test results from penetration, softening point, and ductility satisfy the relevant specifications, confirming that both conventional and crumb rubber modified bitumen are suitable for asphalt pavement. The inclusion of crumb rubber improves high-temperature performance, though it slightly compromises ductility, a trade-off that supports better long-term pavement durability (Yang et al. 2024). Moreover, the use of recycled tyre rubber contributes to sustainable pavement construction by diverting waste from landfills. Hence, the utilization of crumb rubber as a bitumen modifier is both reasonable and practically applicable to be used as pavement materials.

TABLE 6. Result for bitumen test

Bitumen Test		Standard Requirement	Average Result	
Penetration Test	100% bitumen (control sample)	(ASTM D5-97) 60 mm -70 mm	69.2 mm	
	5% crumb rubber + 90% bitumen		67.4 mm	
	10% crumb rubber + 85% bitumen		63.2 mm	
	15% crumb rubber + 80% bitumen		58.0 mm	
Softening Point Test		100% bitumen (control sample)		49.7ºC
	5% crumb rubber + 90% bitumen	51.3ºC	(ASTM D36) 49 ºC -56 ºC	
	10% crumb rubber + 85% bitumen	52.6ºC		
	15% crumb rubber + 80% bitumen	54.7ºC		
Ductility Test		100% bitumen (control sample)		150.0 cm
	5% crumb rubber + 90% bitumen	73.8 cm	(ASTM D113) > 100 cm	
	10% crumb rubber + 85% bitumen	61.1 cm		
	15% crumb rubber + 80% bitumen	37.9 cm		

AGGREGATE TEST RESULT

The Aggregate Crushing Value (ACV) test checks how well aggregates resist crushing under steady pressure. Aggregates with lower ACV are better for pavements because they are harder to crush. In this study, the granite aggregate had an ACV of 18.11%, which meets the minimum standard requirement of less than 30%. This result indicates that the aggregate is of good strength and can be utilized in high-quality asphalt mixtures.

The Aggregate Impact Value (AIV) test examines how well aggregates endure unexpected shocks, such as a situation with vehicle movement. The AIV value of aggregate in this study was 16.15% which shows great impact resistance while meeting the minimal standard requirement of less than 30%. Therefore, the aggregate is outstanding for flexible pavement layers since it is unlikely to break down under traffic loads.

Los Angeles Abrasion Value (LAAV) testing evaluates the total abrasion resistance that is critical to long-term durability in the case of using aggregates in pavement. The test aggregate produced an LAAV value of 22.40%, which satisfied the ASTM standard requirement. Additionally, due to its low risk of breaking under traffic stresses, the granite aggregate is a suitable material for flexible pavement layers.

The water absorption test is used to evaluate the hygroscopicity of aggregates, which has an important impact on the bonding effect between aggregates and bitumen and the water damage resistance of the mixture. The water absorption of the aggregate in this study was 0.35%, which is significantly less than the ASTM does not exceed 2%. This water absorption less water absorption value shows that it has a strong water resistance, which helps to improve the bitumen and aggregate adhesion strength as well as the mixture's overall structural stability and longevity.

As summarized in Table 7, all aggregate test results met the respective standards, indicating that the granite aggregate used in this study possesses strong mechanical and physical properties. These results confirm its suitability for use in asphalt pavement layers, particularly when modified with crumb rubber and silica fume.

TABLE 7. Result for aggregate test

Aggregate Test	Standard Requirement	Average Result
Aggregate Crushing Value Test	(BS 812-112:1990) < 30%	18.11%
Aggregate Impact Value Test	(ASTM D5821) < 30%	16.15%
Los Angeles Abrasion Value Test	(ASTM C535 – 16) < 25%	22.40%
Water Absorption Test	(ASTM C127-15) < 2%	0.35%

ASPHALT MIXTURE TEST RESULT

RESILIENT MODULUS TEST

The Resilient Modulus test is used to test the stiffness of the asphalt mixture. Before building an asphalt pavement, it is important that its stiffness needs to be tested and analysed so that the pavement can perform well under different conditions. Table 8 shows the resilient modulus test results at 25˚C and 40˚C for the control and modified samples. The results obtained show that the conventional asphalt mixture has a resilient modulus value of 3552.3 MPa at 25˚C and 571.3 MPa at 40˚C. The mixture with 10% silica fume replacement with fine aggregate has the highest resilient modulus value, which reaches 6199 MPa at 25 ˚C. The sample containing 10% crumb rubber and 5% silica fume has the highest index under high temperatures, which reaches 955.5 MPa at 40˚C. These results indicate that the performance of the sample with crumb rubber and silica fume is better than that of the control sample.

The silica fume has extremely fine particles and high pozzolanic activity, which can fill the micropores between aggregates, form a denser structure, improve rigidity and bonding properties, and thus improve RM values (Farag Khodary, 2016). Crumb rubber has higher elasticity and deformation resistance, which allows the mix to recover more effectively when repeatedly loaded, increasing the elastic modulus (Wang et al. 2022). The elastic polymeric chains in crumb rubber and fine reactive silica fume particle in modified mixtures increase the viscosity and filler-binder adhesion which leading to a more rigid yet resilient asphalt mixture.

Similar improvement trends were reported by Wang et al. (2022), Abdul, Rafiq and Khaliludin (2024), and Taisir Khedaywi et al. (2025) who also observed that the inclusion of rubberized modifiers and mineral fillers enhanced stiffness and elastic recovery. However, the magnitude of improvement in this study demonstrates a stronger synergistic effect between the combination for crumb rubber and silica fume. In addition, incorporating silica fume and crumb rubber supports the development of environmentally friendly "green" pavements through the beneficial reuse of industrial and rubber waste. Therefore, the combination of crumb rubber and silica fume could improve the structural stability and stress distribution ability of the overall mix, which improves the resilient modulus value.

TABLE 8. Result for resilient modulus test

Sample	Standard Requirement	Resilient Modulus	
		25 ˚C	40 ˚C
100% bit + 100% CA + 100% FA (Conventional)	ASTM D7369 > 2500 MPa (at 25˚C)	3552.3 MPa	571.3 MPa
100% bit + 100% CA + (95% FA + 5% SF)		5168.0 MPa	857.0 MPa
100% bit + 100% CA + (90% FA + 10% SF)		6199.0 MPa	795.5 MPa
(95% bit + 5% CR) + 100% CA + 100% FA		4050.8 MPa	590.5 MPa
(95% bit + 5% CR) + 100% CA + (95% FA + 5% SF)		4514.0 MPa	824.3 MPa
(95% bit + 5% CR) + 100% CA + (90% FA + 10% SF)		3790.8 MPa	510.8 MPa
(90% bit + 10% CR) + 100% CA + 100% FA		4567.5 MPa	734.3 MPa
(90% bit + 10% CR) + 100% CA + (95% FA + 5% SF)		5038.8 MPa	955.5 MPa
(90% bit + 10% CR) + 100% CA + (95% FA + 10% SF)		4852.0 MPa	872.3 MPa

*bit = bitumen, CA = coarse aggregate, FA = fine aggregate, CR = crumb rubber, SF = silica fume

DYNAMIC CREEP TEST

A Dynamic Creep test was used to A dynamic Creep test was used to determine the permanent deformation and strain of the mixture. A UTM machine conducts this test at a temperature of 40˚C. Table 9 presents the result of the Dynamic Creep test for all the asphalt mixture samples. All the samples had met the minimum standard requirement which their creep stiffness is greater than 75 MPa. The conventional asphalt mixture sample has a stiffness of 209.4 MPa. The mixture contains 5% crumb rubber and 5% silica fume and showed the highest creep stiffness, which reaches 540.5 MPa.

The silica fume contains active silica and has volcanic ash reactivity, which reacts with the calcium component in the mixture to form additional cementing material and improve structural stability (Naser et al. 2023). The crumb rubber particles will absorb the light oil in the bitumen, which causes the asphalt mixture to become harder and more heat-resistant, thereby improving its ability to resist deformation (Li et al. 2024b). The rubber enhances the elasticity of the mixture, and the silica fume increases its rigidity, which the combination of these two materials improves the resistance to rheology and permanent deformation of the sample at high temperatures.

The increased creep stiffness agrees with the findings of Li et al. (2024b), Zhao et al. (2023b), and Saberi and Azami (2017) confirming that crumb rubber enhances viscoelastic recovery while silica fume densifies the mix structure, collectively reducing permanent deformation when the mix is subjected to loading at high temperature. This improvement directly enhances the rutting performance and long-term stability of asphalt layers. Furthermore, the combined use of recycled and industrial by-product materials aligns with sustainable construction practices by minimizing raw material demand and reducing environmental impact. Therefore, the combination of crumb rubber and silica fume could improve the structural stability and stress distribution ability of the overall mix, which improves the resilient modulus value.

TABLE 9. Result for dynamic creep test

Aggregate Test	Standard Requirement	Dynamic Creep
100% bit + 100% CA + 100% FA (Conventional)	BS EN 12697-25 > 75 MPa	209.4 MPa
100% bit + 100% CA + (95% FA + 5% SF)		234.1 MPa
100% bit + 100% CA + (90% FA + 10% SF)		220.3 MPa
(95% bit + 5% CR) + 100% CA + 100% FA		227.3 MPa
(95% bit + 5% CR) + 100% CA + (95% FA + 5% SF)		540.5 MPa
(95% bit + 5% CR) + 100% CA + (90% FA + 10% SF)		427.0 MPa
(90% bit + 10% CR) + 100% CA + 100% FA		193.5 MPa
(90% bit + 10% CR) + 100% CA + (95% FA + 5% SF)		231.2 MPa
(90% bit + 10% CR) + 100% CA + (95% FA + 10% SF)		278.4 MPa

*bit = bitumen, CA = coarse aggregate, FA = fine aggregate, CR = crumb rubber, SF = silica fume

SCANNING ELECTRON MICROSCOPE

Scanning Electron Microscopy (SEM) was conducted to evaluate the microstructural properties of asphalt mixtures with varying crumb rubber (CR) and silica fume (SF) content and compare them to the control samples. The SEM images were obtained at ×350 magnifications, which allowed one to identify the bitumen matrix, modifier distribution, and aggregate interfaces distinctly. The SEM images were captured at the Control, and modified asphalt morphological differences were revealed through the SEM images (Figure 3).

From the figure shown, the conventional asphalt mixture sample appears with an illustration of the smooth and amorphous matrix that suggests a regular bitumen structure without alteration. Smoothness may suggest less interfacial bonding between the bitumen and the aggregate particles. The rough, angular character of the aggregate particles is beneficial in the creation of mechanical interlocking with the bitumen, yet the lack of modifiers could limit the general performance of the binder.

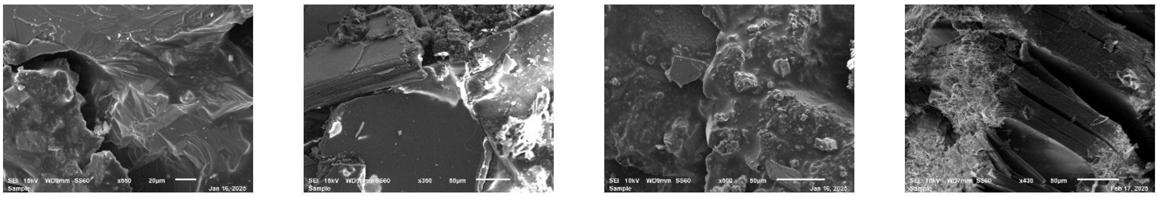
For crumb rubber modified bitumen asphalt mixture, appears with granular, textured inclusions observed in the bitumen matrix signify the dispersion of rubber particles throughout the binder. The inclusions are not for decoration but play a basic role in enhancing the performance of the asphalt mixture. Crumb rubber particles seem to fill the voids of the bitumen phase, enhancing the overall form and potentially acting as stress relievers in the interface for bitumen and aggregate (Liu et al. 2021). SEM shows a detectable change of morphology, where the rubber particles act as a physical barrier that could prevent crack growth, thus improving the rutting resistance and durability in general (Zhou et al. 2024).

For silica fume modified samples, silica fume was used as a fine aggregate in the asphalt mixture. SEM research was used to evaluate the microstructure impacts of adding silica fume into the bitumen-aggregate interface (Nonde Lushinga, Dong and Cao, 2022). The tiny and clustered morphology at both the bitumen and aggregate interfaces confirms the large surface area of silica fume particles, which has a strong micro-filling impact. When these extremely small particles are mixed with the asphalt, they aid in densifying the bitumen mastic, which can contribute to greater moisture resistance and cohesiveness for bitumen and aggregate. Silica fume appears to increase the creation of a dense network, which would be good for increasing structural integrity and reducing the possibility of gaps or air spaces that might contribute to premature collapse (Goshtasp et al. 2021).

When silica fume is mixed with crumb rubber, the microstructure displays a highly compacted and linked system. The rubber particles increase the elastic characteristics of the bitumen, and the silica fume improves adhesive density and gap filling at the micro-level. The synergy creates a more uniform structure in which both the aggregate and bitumen become better bonded, reducing the occurrence of interface failure. The SEM observation suggests that the interaction of these two modifiers produces a tighter system, which can be attributed to greater resistance to fatigue cracking, improved rutting behaviour, and the general longer lifetime of the pavement.

To further understand the impact of alterations, an SEM comparison was performed on the control and changed asphalt mixes. The control mixture had a smooth and homogeneous matrix, but the modified mixes (which contained crumb rubber and silica fume) had more complicated microstructural properties, such as granular inclusions in the bitumen matrix and improved bonding between bitumen and aggregates.

Overall, the SEM examination reveals that the addition of crumb rubber and silica fume could increase the microstructural integrity of the asphalt mixture. The modified asphalt mixture is expected to improve the mechanical properties and durability, especially rutting resistance and longevity, compared with the conventional. The denser and homogeneous microstructure in the modified samples is discovered in connection with improved outcomes in mechanical testing, such as higher resilient modulus and lower permanent deformation in the later stages of this work.



Conventional asphalt mixture

Asphalt mixture contains crumb rubber

Asphalt mixture contains silica fume

Asphalt mixture contains crumb rubber and silica fume

FIGURE 3. The SEM images for asphalt mixture with different proportion of crumb rubber and silica fume

CONCLUSION

This study examined the potential of utilizing crumb rubber and silica fume as partial replacement materials for hot mix asphalt (HMA) to improve mechanical properties without increasing the negative impact on the environment. From the overall test results, it can be concluded that the addition of 5% crumb rubber and 5% silica fume achieved a balanced optimum mix proportion, exhibiting significant enhancement in mechanical performance. Specifically, the modified mixture showed an increase of around 27% in resilient modulus and significantly enhancing dynamic creep stiffness performance compared to the control asphalt mixture. These results indicate that the combined modification improves both stiffness and deformation resistance, contributing to better pavement durability and sustainability.

The synergistic benefits of crumb rubber and silica fume in asphalt mixtures provides complementary improvements to pavement performance. Crumb rubber acts as an elastic filler in the asphalt mix, which absorbs traffic load stress and slows down crack growth. Silica fume has ultra-fine particles occupying pores among aggregates and bitumen that help in creating a denser and tougher matrix. They increase the flexibility of the asphalt mixture to resist cracking as crumb rubber and increase the rigidity of the asphalt mixture to prevent rutting as silica fume.

The enhanced performance suggests that modified asphalt mixtures can offer longer pavement service life, reduced maintenance frequency, and greater environmental benefits by utilizing waste tyres and industrial by-products. However, this study was limited to laboratory scale testing; future research should explore long term aging behaviour effects on UV exposure and oxidative hardening and field validation to confirm the durability of modified pavements under actual service conditions. Furthermore, multi-material-like combinations of crumb rubber or silica fume with recycled plastic or Recycle Asphalt Pavement, should be examined in future research.

Overall, the findings demonstrate that combining crumb rubber and silica fume provides a cost-effective and sustainable approach to improving asphalt mixture performance, aligning with the goals of green pavement development. With the use of crumb rubber and silica fume in asphalt mixtures, the current study presents a circular approach to pavement construction as per worldwide circular economy goals. The results prove the potential of waste-material modifiers for the balancing of performance, economy, and sustainability in environmental terms in infrastructural construction.

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DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abdul, A., Rafiq, W. & Khaliludin, M. 2024. Modeling and design optimization of dense graded modified crumb rubber asphalt mixtures using response surface methodology. *Construction and Building Materials* 435: 136895–136895.

Abdulaziz Alsaif & Abdulrahman Albidah. 2024. Production of rubberized concrete utilizing reclaimed asphalt pavement aggregates and recycled tire steel fibers. *Structures* 68: 107174–107174.

Aboelmagd, A., Moussa, G., Enieb, M., Khedr, S. & Abd Alla, E.-S. 2021. Evaluation of hot mix asphalt and binder performance modified with high content of nano silica fume. *Journal of Engineering Sciences*: 1–22.

Al-Rubaie, A. H. & Joni, H. H. 2021. Assessment the performance of asphalt mixtures modified with waste tire rubber at high temperatures. *Journal of Physics: Conference Series* 1895(1): 012026.

ASTM C. 2006. *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. West Conshohocken, PA: ASTM International.

ASTM D5-97. 1998. *Standard Test Method for Penetration of Bituminous Materials*. Annual Book of ASTM Standards, Vol. 04.03. Philadelphia: American Society for Testing and Materials.

ASTM D7369-11. 2011. *Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test*. West Conshohocken, PA: ASTM International.

British Standards Institution. 2023. *BS EN 12697-25: Bituminous Mixtures — Test methods — Part 25: Cyclic Compression Test*. London: BSI.

Deb, P. & Singh, K. L. 2022. Accelerated curing potential of cold mix asphalt using silica fume and hydrated lime as filler. *International Journal of Pavement Engineering* 24(2).

EN1097. t.th. BS EN 1097 - Tests for mechanical and physical properties of aggregates.

Farag Khodary. 2016. Impact of silica fume on the properties of asphalt pavement base course. *International Journal of Engineering Trends and Technology* 35(10): 487–491.

Goshtasp Cheraghian, Wistuba, M. P., Kiani, S., Barron, A. R. & Behnood, A. 2021. Rheological, physicochemical, and microstructural properties of asphalt binder modified by fumed silica nanoparticles. *Scientific Reports* 11(1).

Intan Jasmin Rosli & Abd Sukor Sarif. 2021. Performance review of crumb rubber as a modifier in asphalt pavement. *Progress in Engineering Application and Technology* 2(1): 174–182.

Jamshidi, A. & White, G. 2019. Evaluation of performance and challenges of use of waste materials in pavement construction: A critical review. *Applied Sciences* 10(1): 226.

Khaled, T. T., Aboud, G. M. & Al-Hamd, R. Kh. S. 2020. Study the effect of adding crumb rubber on the performance of hot mix asphalt. *IOP Conference Series: Materials Science and Engineering* 737: 012129.

Li, H., Han, Y., Guangxun, E., Sun, Y., Wang, L., Liu, X., Ren, J. & Lin, Z. 2024a. Recycling of waste polyethylene in asphalt and its performance enhancement methods: A critical literature review. *Journal of Cleaner Production* 451: 142072–142072.

Li, M., Gao, Z., He, Z., Ma, J., Zhao, W., Dang, S. & Wei, C. 2024b. Effects of silicone rubber on rheological properties and aging characteristics of asphalt binder. *Polymers* 16(13): 1903–1903.

Liu, J., Hao, P., Dou, Z., Wang, J. & Ma, L. 2021. Rheological, healing and microstructural properties of unmodified and crumb rubber modified asphalt incorporated with graphene/carbon black composite. *Construction and Building Materials* 305: 124512–124512.

Liu, Z., Yu, S., Huang, Y., Liu, L. & Pan, Y. 2024. A systematic review of rigid-flexible composite pavement. *Journal of Road Engineering* 4(2): 203–223.

Mamauod, S. N. L. 2024. Influence of tire reclaimed rubber (TRR) loadings on cure characteristics and mechanical properties of natural rubber/styrene butadiene rubber (NR/SBR) blends. *Journal of Mechanical Engineering* 21(3): 29–43.

Milad, A., Babalghaith, A. M., Al-Sabaeei, A. M., Dulaimi, A., Ali, A., Reddy, S. S., Bilema, M. & Yusoff, N. I. M. 2022. A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: Towards a sustainable asphalt pavement. *International Journal of Environmental Research and Public Health* 19(22): 14863.

Mohajerani, A., Kurmus, H., Conti, D., Cash, L., Semcesen, A., Abdurahman, M. & Rahman, M. T. 2022. Environmental impacts and leachate analysis of waste rubber incorporated in construction and road materials: A review. *Science of The Total Environment* 835: 155269.

Murali, G. 2023. Recent research in mechanical properties of geopolymer-based ultra-high-performance concrete: A review. *Defence Technology* 32: 67–88.

Naser, M., Mu'tasim Abdel-Jaber, Al-Shamayleh, R. A., Ibrahim, R., Nawal Louzi & Tariq Alkhrissat. 2023. Improving the mechanical properties of recycled asphalt pavement mixtures using steel slag and silica fume as a filler. *Buildings* 13(1): 132–132.

Nonde Lushinga, Dong, Z. & Cao, L. 2022. Evaluating the high-temperature properties and reaction mechanism of terminal blend rubber/nano silica composite modified asphalt using activated rubber. *Nanomaterials* 12(24): 4388–4388.

Nugroho, R. D., Rahman, T., Utomo, S. H. T. & Suparma, L. B. 2025. The effect of surface electric charges in tack coat and aggregate on the interlayer shear-bond strength of asphalt pavements. *Construction and Building Materials* 463: 140037.

Nuha, M., Asim, A., Mohamed, K. & Mahrez, A. 2011. Effect of crumb rubber concentration on the physical and rheological properties of rubberised bitumen binders. *International Journal of the Physical Sciences* 6(4): 684–690.

Panesar, D. K. & Zhang, R. 2020. Performance comparison of cement replacing materials in concrete: Limestone fillers and supplementary cementing materials – A review. *Construction and Building Materials* 251: 118866.

Ragab, M., Islam Abo El-Naga & Arnaout, M. M. 2025. Comparative optimization of crumb rubber-modified asphalt mixtures: Experimental and artificial intelligence framework. *Construction and Building Materials* 494: 143564–143564.

Saberi, K. F., Fakhri, M. & Azami, A. 2017. Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. *Journal of Cleaner Production* 165: 1125–1132.

Saqib Gulzar, Fried, A., Preciado, J., Castorena, C., Shane Underwood, B., Jhony Habbouche & Boz, I. 2023. Towards sustainable roads: A state-of-the-art review on the use of recycling agents in recycled asphalt mixtures. *Journal of Cleaner Production* 406: 136994–136994.

Taisir Khedaywi, Haddad, M., Hashem Al-Masaeid, Islam Abu Mharib & Hawari, S. 2025. Characterization of binder and asphalt mixture modified with waste toner. *International Journal of Transportation Science and Technology*.

Tiwari, N., Rondinella, F., Neelima Satyam & Baldo, N. 2023. Experimental and machine learning approach to investigate the mechanical performance of asphalt mixtures with silica fume filler. *Applied Sciences* 13(11): 6664–6664.

Wang, H., Liu, X., Erkens, S. & Skarpas, A. 2020. Experimental characterization of storage stability of crumb rubber modified bitumen with warm-mix additives. *Construction and Building Materials* 249: 118840.

Wang, T., Shi, C., Yu, Y., Xu, G., Liu, S., Wang, H., Yang, J., Gong, M., Xu, Y. & Qie, L. 2022. Mechanical properties evaluation of crumb rubber asphalt mixture for elastic trackbed. *Construction and Building Materials* 331: 127048.

Yang, X., Ning, Z., Feng, X., He, X. & Tan, S. 2024. Methods for improving storage stability of rubber bitumen: A review. *Journal of Cleaner Production* 449: 141595.

Zhao, Z., Wu, S., Xie, J., Yang, C., Yang, X., Wang, F. & Liu, Q. 2023a. Utilization of high contents desulfurized crumb rubber in developing an asphalt rubber pellets modified asphalt. *Construction and Building Materials* 402: 133043.

Zhao, Z., Xiao, F., Emanuele Toraldo, Crispino, M. & Misagh Ketabdari. 2023b. Effect of crumb rubber and reclaimed asphalt pavement on viscoelastic property of asphalt mixture. *Journal of Cleaner Production* 428: 139422.

Zhou, T., Li, L., Liu, R., Yu, F. & Dong, Z. 2024. Thermal effects on rheological characteristics and its evolution mechanism of bio-modified rubberized asphalt for sustainable road system: A focus on rubber particle size. *Journal of Cleaner Production* 452: 142168–142168.