

Laboratory Investigation on Enhancing Stiffness Performance of Garnet Modified Hot Mix Asphalt

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DOI: <https://doi.org/10.30880/rtcebe.2024.05.02.012>

Article Info

Received: 26 September 2024

Accepted: 21 November 2024

Available online: 20 December 2024

Keywords

Waste garnet, aggregate, asphalt mix,
Marshall stiffness

Abstract

Due to many high stress on the pavement, the asphalt road is exposed to numerous strains, which results in numerous defects and cracks. Road users face numerous issues as a result of these flaws, including discomfort and decreased safety. All types of pavement require regular maintenance due to several factors such as temperature changes, overload, and the impact of precipitation from the weather. This paper presents a pavement stiffness assessment incorporating garnet in hot mixture asphalt. In order to evaluate the performance of garnet as replacement of fine aggregate in Hot-Mix Asphalt, the Marshall mix design AC-14 was employed with proportions of garnet used 0%, 5%, 15% and 25%. A total of 60 samples were investigated through Marshall stability and flow test. The result reveals incorporating 25% of Garnet, improved Marshall properties remarkably. It is anticipated that the replacement of fine particles in hot-mix asphalt mixtures with garnet increased the stiffness of the pavements and the increased traffic volume, loading, and variable weather conditions may be managed by the better-quality asphalt pavements.

1. Introduction

Pavement engineering has changed significantly over the last century, with changes in structural composition, new materials, building technology, design techniques, traffic demands, environmental factors, material recycling, and more. Researchers and engineers are focusing on finding ways to improve the quality of asphalt pavement over the years and according to the previous study, waste material can lead to product development (Ameri et al, 2016) [1]. Due to many high stresses on the pavement, the asphalt road is exposed to numerous strains, which results in numerous defects and cracks. Road users face numerous issues as a result of these flaws, including discomfort and decreased safety. All types of pavements require regular maintenance due to several factors such as temperature changes, overload, and the impact of precipitation from the weather (Asadi et al, 2020; Behiry, 2021; Borsani et al., 2022) [2-4]. When one of the variables impacting the road's surface causes cracks to form in it, maintenance is necessary, but sometimes the cost of treating or reconstructing the cracks makes the work expensive. Therefore, the researchers proven that utilizing waste materials to modify asphalt pavement can enhance pavement performance, lower the amount of garbage dumped in landfills, and lessen the environmental effect of the pavement (Choudhary et al., 2022; Corrales et al., 2021; El-Badawy & Ragab, 2021) [5-7]. The pavement's performance is significantly impacted by the aggregate quality. Various test techniques have been developed over time to choose appropriate aggregate for pavement construction. The goal

is to find a material that will be durable, long-lasting, and compatible with other materials long enough to fulfil the road's intended lifespan (Gao & Hu, 2020) [8]. The performance of the aggregates in the bituminous mix is influenced by a wide range of factors in addition to the elemental and mineral composition, including pavement type, pavement design, subgrade conditions, maintenance procedures, traffic characteristics, and meteorological circumstances (Hasheminejad & Ameri, 2021; Hu & Ma, 2019; Kang & Wu, 2022) [9-11]. The longevity of an asphalt pavement is determined by the quality of the material and the thickness of the granular layer (Khedmat & Tashman, 2021; Liu & Xiao, 2019; Moghaddam et al., 2021) [12-14]. Stabilized bases or subbases typically consist of a blend of aggregates, water, cementitious materials, and/or emulsified asphalt. In the context of the base course, the asphalt-wearing material not only ensures a smooth riding surface but also functions as a waterproofing mechanism (Mohajeri & Tehrani, 2023) [15]. Incorporating stabilized materials in base and subbase construction enhances pavement performance and durability, mitigating issues like fatigue cracking at the bottom of the asphalt layer due to the greater stiffness of these materials compared to conventional ones (Rezaei & Sadeghian, 2020) [16]. Conversely, reflective cracks occurring in the asphalt layer are commonly a result of cracking originating within the stabilized base layer. Hence, a well-designed and constructed stabilized base layer can resist asphalt maintenance and/or overlays. Alternatively, a stabilized subbase layer can be employed beneath, replacing the conventional base layer (Safari & Yang, 2020) [17]. Fig. 1 shows the various kinds of cracks developed in asphalt pavements.

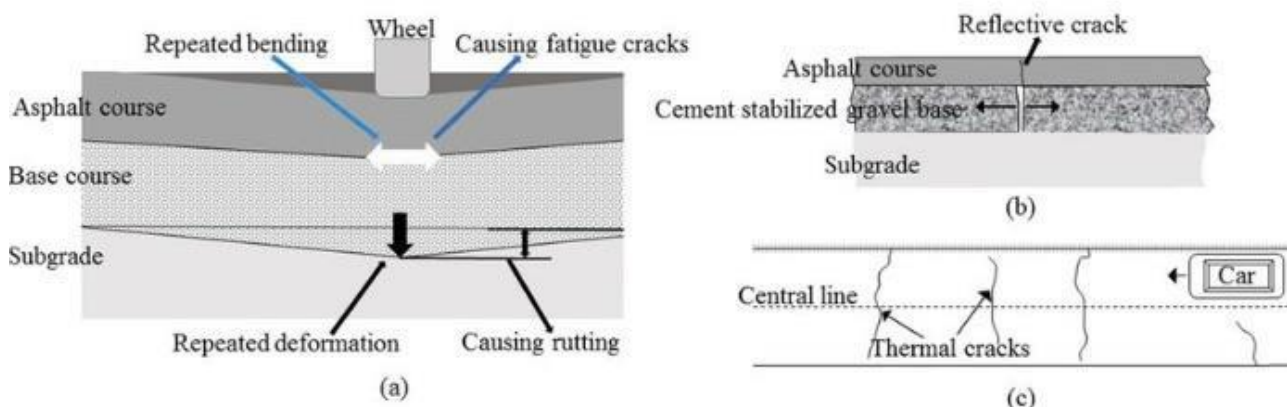


Fig. 1 Various kinds of cracks developed in asphalt pavements. (a) Fatigue cracks; (b) reflective crack; (c) low temperature induced shrinkage cracks

Garnet is one of the waste material and general name for a group of complex silicate minerals with similar crystalline structures and diverse chemical compositions. It is important properties such as angular fractures and relatively high hardness, specific gravity and resistance to degradation combined with its ability to be recycled makes it desirable for many industrial applications. Since garnets are a waste product of surface treatment processes, they continue to be a major global environmental concern. According to a recent evaluation of the shipbuilding sector in Malaysia, the nation imported around 2000 million tons of garnets in 2013 alone, with a significant portion being disposed of as waste (Shafabakhsh & Asadi, 2022) [18]. Furthermore, a great deal of ecological and health risks results from garnet wastes. For instance, runoffs during surges could have introduced these materials into streams.

The purpose of this investigation is to enhance stiffness performance of garnet in Hot Mix Asphalt. In order to compare with granite aggregate as a typical asphalt sample, garnet was intended up to 25% in the AC14 asphalt mixture. The Marshall mix design approach was used, and the specific Marshall properties such as volumetric characteristics, the ideal bitumen content, stability, and flow were compared.

2. Material and Methods

This section describes the material and method employed in this study. The raw material was characterized using various methodologies outlined in this section.

2.1 Material

The material used in this investigation were coarse and fine aggregate of granite obtained from Hanson quarry, Johor. Aggregate was dried at 110°C and sieved according to Marshall mix design specifications. Laboratory samples were created using the aggregate gradation designated for the HMA mixture AC 14 Wearing Course (Soltani & Tahami, 2021) [19]. Then, multiple aggregate percentage combinations were employed in this study for garnet at level of 5%, 15%, and 25% of the total fine aggregate weight as shown in as shown in Fig 2. The

mixture was made using the penetration grade of asphalt binder 60/70 supplied by Petronas with small amount of ordinary Portland cement as filler. The purpose of this experiment is to determine how garnet waste composition and its interactions with granite aggregate in hot mix asphalt (HMA) mixes affect the final product. Table 1 shows the job mix formulae of garnet hot mix asphalt according to AC 14 mix design. In general, the physical properties of garnet resulted fineness modulus, bulk density, a high melting temperature, strong hardness, minimal water absorption, and a specific gravity significantly higher than typical aggregates as tabulated in Table 2.



Fig. 2 Waste Garnet

Table 1 Aggregate gradation AC14

Size (mm)	Percentage passing (%)	Design (%)	Retained (%)	Mass retained (g)
20	100	-	-	-
14	90-100	95	5	55
10	76-86	81	14	154
5	50-62	56	25	275
3.35	40-54	47	9	99
1.18	18-34	26	21	231
0.425	12-24	18	8	88
0.150	6-14	10	8	88
0.075	4-8	6	4	44
Pan	2	1	5	55
Cement	-	-	1	11

Table 2 Physical and Chemical properties of waste garnet

Properties	Waste Garnet
Specific gravity	3.0
Fineness modulus	2.05
Bulk Density	1922 kg/m ³
Water absorption	6%
Hardness	7.5
Chemical content	- Alumina (Al ₂ O ₃) - Silicon oxide (SiO ₂) - Iron oxide (Fe ₂ O ₃)

2.2 Sample Preparation

The asphalt mixture utilized approximately 1200g of aggregates, with mineral filler in the form of ordinary Portland cement added at a rate of 2% of the combined aggregate weight. PEN60/70 bitumen was prepared in three samples for each trial of binder content, ranging from 4% to 6% in increments of 0.5% of the total aggregate mass. The mixing and compaction temperatures were selected based on the standard viscosity-

temperature chart for Asphalts (ASTM D2493). Prior to mixing, the aggregates for PEN 60/70 bitumen were heated to temperatures of 165 °C and 175 °C respectively, for two hours. The bitumen was heated to temperatures of 165 °C. Subsequently, the aggregates, garnet and bitumen were combined in a mixer for 120 seconds or until the aggregates were uniformly coated with the bitumen. After mixing, the asphalt mixtures were subjected to short-term aging by heating them in an oven at 155 °C for PEN 60/70 bitumen and 165 °C for the modified asphalt mixture for two hours. Following the aging process, the mixes were compacted at 155°C using the Marshall compactor with 75 blows per face, as specified in JKR/SPJ/2008-S4. The compacted samples were then cooled and demoulded.

2.3 Experimental Program

This section describes the mechanical performance of the hot mixture asphalt (HMA) mixtures subjected to Marshall stability and flow test incorporating garnet aggregates. All the test strictly followed American for Testing and Material (ASTM), British Standard (BS), American Association of State Highway and Transportation Officials (AASHTO) and Jabatan Kerja Raya Malaysia (JKR) standard and specifications.

(i) Volumetric Properties

The volumetric characteristics were assessed in order to determine the design asphalt binder content in terms of stability, flow, density, and total air voids content. In this study, the bulk specific gravity of the samples was assessed according to ASTM D 2726 guidelines. Initially, the compacted samples were dried in an oven at 110 °C until they reached a constant mass, following the standard method for determining asphalt binder content in asphalt mixtures using the nuclear method (AASHTO T2870). After cooling to room temperature, the samples were weighed, and the bulk specific gravity was computed. Then, the compacted samples were immersed in a water bath for 3 to 5 minutes at a temperature of 25 °C ± 1 °C, and their weight was recorded while submerged. Subsequently, the samples were removed from the water bath and weighed again after surface drying, accomplished by gently blotting with a damp cloth towel.

To evaluate the air void percentage in compacted aggregates, bitumen-filled aggregates, and the overall compacted mixture, specific gravity and air void parameters were examined. Air voids (V_a) represent the total volume of air trapped between coated aggregate particles in a compressed mixture. The presence and volume of these air spaces have a substantial influence on the stability and longevity of the compacted mixture. Following the completion of stability and flow tests, each test specimen must undergo specific gravity and void analyses to determine the percentage of voids in mineral aggregate (VMA), which includes both air voids and effective binder content. This analysis also evaluates the air void percentage in the compacted aggregate filled with bitumen (VFB) and the total air void percentage in the overall compacted mixture (VIM).

(ii) Marshall Stability Test

The Marshall stability and flow test as shown in Figure 2 was used to determine the optimal binder content suitable for the specific aggregate mix type and expected traffic conditions. The maximum load required to induce failure in preheated samples positioned beneath a specialized test head were recorded. Following ASTM D6927 protocols, the load was applied at a constant strain rate of 5 cm per minute. Afterward, the flow test was conducted to measure the vertical deformation of the samples. During the test, deformation failure was recorded in 0.25 mm increments, spanning from no load to the maximum load sustained by the samples.



Fig.2 Marshall Compression Machine

3. Result and Discussions

This section presents an analysis of the experimental data obtained from the laboratory investigation. The performance of garnet as an additive in hot mix asphalt (HMA) was evaluated, focusing on its impact on stiffness and bulk specific gravity (Gmb). Variations in the garnet content, aggregate gradation, and compaction methods were systematically studied to assess their influence on the mix properties. The data, presented in the following tables and figures, highlight the critical relationships between garnet incorporation and the resulting enhancements in the mechanical performance of the asphalt, particularly in terms of stiffness and density. Table 3 shows the bulk specific gravity.

Table 3 The result of Bulk Specific Gravity of compacted sample

Parameter/ Garnet Content	0%	5%	15%	25%
Weight dry (g),	1093.8	1179	1334.6	1342.9
Weight SSD (g),	1119.3	1190.5	1350.3	1364.47
Weight IN WATER (g),	654.4	690.5	786.6	824.5
Bulk specific gravity, Gmb	2.350	2.358	2.368	2.486

From the data in Table 3, it is evident that the inclusion of higher percentages of garnet in the asphalt mix results in an increase in bulk specific gravity (Gmb). For instance, at 0% garnet, the Gmb is 2.350, serving as the baseline value. As the garnet content increases to 5%, the Gmb rises to 2.358, indicating a slight improvement in the material's density. With further increases in garnet content to 15%, the Gmb continues to rise to 2.368, and at 25% garnet, it reaches its highest value of 2.486. This suggests that garnet enhances the particle interlock and packing density within the aggregate structure when combined with bitumen. The weight data also supports this, with the dry weight of the samples increasing from 1093.8 g at 0% garnet to 1342.9 g at 25% garnet. Similarly, the saturated surface-dry weight (SSD) increases from 654.4 g at 0% garnet to 824.5 g at 25% garnet. These weight increases correlate with the improved packing and compaction behaviour as more garnet is added.

The variation in Gmb is influenced by factors such as aggregate gradation, compaction energy, moisture content, and the properties of the binder. Fine-tuning these variables during the mix design and production processes is crucial for obtaining consistent and accurate Gmb values. The observed increase in Gmb with rising garnet content underscores the importance of adjusting aggregate proportions and optimizing mix designs to ensure the asphalt mixture achieves the targeted density and performance characteristics. Specifically, higher bulk specific gravity contributes to improved stiffness, durability, and resistance to deformation in the final pavement, with the mix at 25% garnet showing the most significant enhancement in density and performance potential.

Table 4 Result of Marshall stability and flow test

Parameter/Garnet Content	0%	5%	15%	25%
Stability, S (N)	13108	13638	16845	17708
Flow, F (mm)	3.041	2.505	2.418	2.316
Stiffness, S/F (N/mm)	4310	5440	6967	7646
Air void in mix, VIM (%)	3.63	3.54	3.48	3.24
Voids in aggregate filled with bitumen, VFB (%)	73	75	76	79

Table 4 presents the results of the Marshall Stability and Flow test, showing that all mixtures meet the JKR (Jabatan Kerja Raya) standards for stability, flow, stiffness, air voids, and voids filled with bitumen (VFB). The data indicates that increasing garnet content from 0% to 25% significantly enhances the stability, rising from 13,108 N to 17,708 N, and stiffness, which increases from 4,310 N/mm to 7,646 N/mm. This improvement demonstrates that higher garnet content strengthens the mix's ability to resist deformation under load while

maintaining acceptable levels of flow, decreasing from 3.041 mm to 2.316 mm, which ensures that the mixture is neither too rigid nor too flexible. The air voids (VIM) and VFB remain within acceptable ranges, ensuring proper mix density and durability.

The increase in garnet content not only improves the mechanical properties of the asphalt mix but also enhances its overall performance by increasing bulk specific gravity (Gmb), which rises from 2.350 to 2.486. This increase in density suggests that the garnet particles enhance particle packing within the asphalt matrix, improving compaction and reducing the void spaces between aggregates and bitumen. Factors such as aggregate gradation, compaction techniques, moisture content, and binder properties influence the bulk specific gravity, which contributes to the mix's ability to meet JKR's density and performance standards. Additionally, the results show an increase in the specimen's volume as garnet content increases, which correlates with the rise in bulk specific gravity. This highlights the importance of garnet in influencing the density and compactness of asphalt mixtures. As the garnet content grows, it positively impacts the structural integrity and longevity of the pavement, making it more durable and resistant to deformation under heavy traffic and environmental stress. These results reinforce the importance of optimizing garnet content in asphalt design to ensure high-quality pavement structures.

The optimal garnet content in an asphalt mix, based on the Marshall stability test, would be the bitumen content that balances both strength and flexibility to ensure long-term pavement performance. The test results show that as bitumen content increases, stability and stiffness improve, meaning the mix can bear heavier loads and resist deformation more effectively. At the same time, there is a reduction in flow and air voids, indicating that the mix becomes denser and less susceptible to deformation. However, if the bitumen content is too high, the mix may become overly stiff, reducing its flexibility and making it more prone to cracking under temperature changes or heavy traffic loads. The goal is to avoid excessive stiffness while maintaining high stability. From the test results, garnet content around 15% to 25% seems to provide optimal performance, where the mix achieves high stability and stiffness without excessive reduction in flow or flexibility. Therefore, the optimal garnet content likely lies in this range, where the balance between strength, stiffness, and flexibility ensures durable, long-lasting pavement capable of withstanding heavy loads without premature cracking or deformation.

4. Conclusions

This paper reports the results of a laboratory study conducted at the Advanced Highway Laboratory, UTHM, to evaluate the stiffness performance of garnet modified asphalt mixture. The following findings were observed:

- (i) The result Marshall stability and flow test (ITS) at 25% of Garnet shows significant effect for stability and flow conditions compared to the control and all the modified samples were exceeding min requirement which compliance with the JKR limitation stated.
- (ii) Incorporating 25% of Garnet with 7646 N/mm stiffness values proved better performance of the bitumen mixture with a greater withstands to stiffness.
- (iii) This enhancement is due to better aggregate interlock and ideal void ratios, which improve binder-aggregate adhesion and overall durability. The increase in bulk specific gravity with higher garnet content underscores its role in enhancing particle packing and density.

Overall, this study shows that garnet not only meet the specified specifications but also provide superior performance in improving the mechanical properties and resistance of bituminous mixtures to rutting. The implication is that the use of garnet can be considered an effective option in the preparation of bituminous mixtures that meet standards and are resistant to wet weather conditions.

Acknowledgement

The researchers express their gratitude for the financial supported by Universiti Tun Hussein Onn Malaysia (UTHM) which made it possible for this paper to be produced.

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