MARSHALL PROPERTIES OF ASPHALT CONTAINING ALTERNATIVE FINE AGGREGATES UNDER DIFFERENT AGEING CONDITIONS

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Abstract

Fine aggregate is a main asphalt component, which provides essential effect on the performance of asphalt mixture. Major consumption of aggregate for construction has caused depletion of natural resources and needs for alternative aggregate. Industrial wastes generated from manufacturing processes were laboratory evaluated as alternative fine aggregates in hot mix asphalt with variation in hardness, density and water absorption. Detailed design of the asphalt containing the potential aggregates of garnet and coal bottom ash was prepared and compared with the conventional granite aggregate using Marshall mix design method. The asphalt mixtures were tested for volumetric properties and stability under different ageing conditions. Results showed that fine aggregate has considerably affected the asphalt properties. Garnet improves the asphalt density and stability compared with other fine aggregates under both ageing conditions, thereby suggesting the suitability of garnet as an aggregate in asphalt pavement.

Keywords: **Fine aggregate, bottom ash, garnet, Marshall mix, asphalt ageing**

Introduction

Asphalt pavement is conventionally used in the construction and rehabilitation of roads worldwide. Researchers seek to use alternative materials in conventional asphalt mixtures, owing to the large quantities of raw materials consumed in asphalt production. For example, industrial wastes have the largest potential in recycling these materials into alternative aggregates for asphalt pavement. Using these waste materials not only reduces the damage from their accumulation but also contributes to the sustainability practices in the road construction (Hinojosa *et al.*, 2014; Torkittikul *et al.*, 2017). Several types of waste materials can potentially be used in asphalt pavements particularly as aggregate replacement. For example, application as fine aggregate at more than 30% from the dense graded asphalt remarkably affects the asphalt mixture properties (Shang *et al.*, 2014).

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Two types of potential fine aggregates were selected from the industrial waste materials, i.e., bottom ash and garnet and compared with the granite aggregate. Garnet is a natural mineral abrasive irregular in shape that is extensively used to treat surfaces for coating and painting (Olson, 2003). The blasting process produces large amounts of exhausted garnet interspersed wastes, such as paint chips. A previous study highlighted that Malaysia imported approximately 2,000 million tons of garnets for its shipyard industry (Muttashar *et al*., 2018). This material is available in large quantity with interesting element of cooling effect, hardness and high percentage of Fe_2O_3 and some TiO_2 (Noor *et al*., 2017; Muttashar *et al*., 2018). Its application in asphalt mixture was reported with better stability than asphalt made with 100% granite aggregate. The increase in stability could reduce the potential of the mixture to deform permanently under loading (Aletba *et al*., 2018). However, further study should be conducted to verify the garnet potential as an aggregate in asphalt. In addition, bottom ash is a type of industrial waste, which consists of coarse particles produced from power plants as a result of coal burning (Ksaibati and Stephen, 2017). Tanjung Bin is one of the largest power plants in Malaysia; it generates electricity by-product from the burning of coal ash, producing 8,000 metric tons of bottom ash every month (Abdullah *et al*., 2018). Realising the potential of coal bottom ash for use in civil engineering, especially in highway engineering, researchers have studied approaches to convert these waste materials into wealth (Mohammed and Karim, 2017). Laboratory studies have also been conducted to evaluate the feasibility of using coal bottom ashes as partial or full replacement of natural aggregates in Hot Mix Asphalt (HMA) and develop guidelines for their use. The properties of HMA containing bottom ash are dependent on ash content. Generally, as ash content increases, the optimum asphalt content increases, mixture density decreases and then air voids and voids in the mineral aggregate increase. The stability of the HMA mix decreases to an ash content of 30% and then levels off (Colonna *et al*., 2012).

One of the most significant and dynamic features of asphalt materials is ageing; it can aid in estimating a flexible pavement's life on the basis of the adhesive characteristics of its binders. Most ageing occurs due to weather conditions (Sirin *et al*., 2017). The chemical and mechanical properties of asphalt mortar evolve with time, owing to the effect of bitumen ageing (Jing *et al*., 2018). Asphalts undergo changes in their physical and chemical properties because of exposure to different environmental conditions in the field. Studies have been striving to better understand the mechanisms behind long-term and short-term ageing (Sirin *et al*., 2018). Various mechanisms lead to binder ageing, including volatilisation, oxidation, thixotropy (or steric hardening), condensation, polymerisation resulting from heat and polymerisation resulting from actinic light (Bell *et al*., 1994). Amongst these mechanisms, the most notable to be related to the ageing of asphalt mixtures are oxidation, steric hardening and volatilisation (Apeagyei, 2011). The changes present as increased stiffness and viscosity (Roberts *et al*., 1991). These processes lead to losses in plasticity and result in hard, brittle pavements that are susceptible to cracking under stress, ultimately affecting their durability and functional lifetime (Chen *et al*., 2009). However, according to Sirin *et al*. (2019), long-term ageing occurs at a lower temperature, primarily during service periods; it is the result of the oxidation mechanism. This process involves the asphalt's exposure to its surroundings (e.g., temperature, rainfall and solar radiation) for longer durations. In addition, the extent and rate of ageing in asphalt mixture are influenced by multiple properties, including type and source of asphalt, void content/permeability, thickness of asphalt binder film over the aggregate and aggregate gradation and absorption. For example, albedo increased with ageing in many studies; mainly, it could be affected by the composition and type of binder and aggregate used in the asphalt mixture (Sen and Roesler, 2015). Therefore, the Marshall mix design criteria were evaluated for the selected aggregates, namely, garnet and coal bottom ash compared with conventional granite and gradually narrow into an optimum mix design.

Experimental Program

Materials

The binder used was 60/70 penetration grade bitumen produced by Kemaman Bitumen Company (KBC) Sdn. Bhd. The properties of bitumen were tested, as shown in Table 1. All results comply with the standard requirements. The asphalt mixture of AC14 dense graded (nominal maximum aggregate size (NMAS) of 14 mm was prepared with two types of alternative aggregates (waste garnet and bottom ash) in addition to granite as control sample (CS) for comparison. Detailed descriptions of the materials are as follows:

Garnet (GFA) was collected from a shipyard in Pasir Gudang, Johor. It was determined suitable to replace the fine aggregate with approximately 25% of the total aggregate volume (32% of total

Table1. Basic bitumen properties

Properties	Specification	Result	Standard
Penetration at 25°C, 100 g, 5 sec	60-70 PEN	66 PEN	ASTM D5/ D5M-13 (ASTM, 2013)
Ductility at 25°C	>100 cm	112 cm	ASTM D113 (ASTM, 2017)
Softening Point	45-60°C	49°C	ASTM D36/D36M-14 (ASTM, 2020)
Viscosity	0.2 Pa.s @165°C 0.5 Pa.s @135°C	Mixing 169°C Compaction 153°C	ASTM D4402/ D4402M (ASTM, 2015a)
Specific Gravity	1.02		ASTM D70 (ASTM, 2014)

Table 2. Bulk specific gravity and water absorption of selected aggregate

Aggregate		Specific gravity	Water absorption%
Granite	Coarse	2.6395	1.06
	Fine	2.6192	0.70
Garnet	Fine	3.5908	0.04
Bottom ash	Fine	2.4175	1.61

mass) in the selected asphalt mixture. The particle size distribution used was less than 1.18 mm.

Bottom ash (BAA) is a coarse, granular, incombustible by-product that was collected from the bottom of the furnace of coal combustion. Bottom ash was used to replace 30% of the total aggregate (25% of total mass), including fine aggregate and filler passing 3.35 mm sieve size.

The specific gravity was determined according to the standard test methods ASTM C127-15 and ASTM C128-15 for coarse and fine aggregate, respectively. In addition, the water absorption (WA) (ASTM, 2015b; 2015c) was measured. The results are shown in Table 2.

Asphalt Mix Design and Ageing Conditions

The Marshall mix design method was conducted to determine the optimum bitumen content (OBC) of the AC14 mix. The compacted samples were prepared within the range of bitumen content 4%-6% at 0.5% increment as specified in the JKR (JKR SPJ/2008-S4, 2008). The aggregate and bitumen were heated prior to mixing and compaction at the temperature of 169°C and 153°C, respectively (temperature was determined on the basis of bitumen viscosity). The loose mixtures were compacted by standard Marshall hammer until 75 blows, and then allowed to cool for one day. The samples were then extruded from the mould and tested for specific gravity and Marshall stability tests to determine the volumetric properties and stiffness. The specific gravity and the stability tests were conducted according to ASTM D2726 (ASTM, 2009) and ASTM D6927 (ASTM, 2015a), respectively. The theoretical maximum density (TMD) was measured according to ASTM D2041 (ASTM, 2003). For the stability test, the samples were conditioned in water bath at 60°C for 40 min. The load was applied to the sample by means of the constant rate of movement of 50.8 mm/min until the maximum load was reached, and then the load decreased. During loading, an attached dial gauge measured the sample's plastic flow (deformation) due to the loading. The flow value was recorded in 0.25 mm increments at the same time as the maximum load was recorded for the stiffness. The Marshall mix design method considers two primary features, namely, the volumetric properties of density and void analysis. The volumetric properties of an asphalt mixture include the specific gravity, quantity of voids in total mixture (VTM) and quantity of voids filled with bitumen (VFB). The Marshall stability was conducted using the Marshall testing machine in accordance with ASTM standards and Malaysian Public Works Department specifications (JKR SPJ/2008-S4, 2008). After determining the OBC for each mixture, the values of VTM, VFB, bulk density, stability flow and stiffness were verified and compared with the design requirements.

In addition, asphalt mixtures suffer from ageing during production, during use and exposure to the external environmental condition. The samples of the three mixtures (control, garnet and bottom ash) were prepared in the laboratory, and the ageing procedure was performed on the samples according to the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 2002). Details of the ageing conditions are as follows;

Short-term ageing is a laboratory procedure that is applied for loose mixture. The loose mixture was placed in an oven for four hours at a temperature of 135°C, with stirring every 60 min to obtain uniform conditioning process. This approach was followed by compaction of the loose mixture.

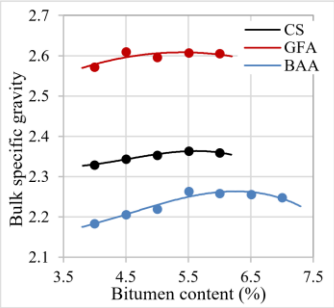

Figure 1. Bulk specific gravity

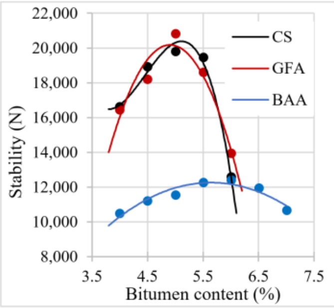

Figure 2. Stability results

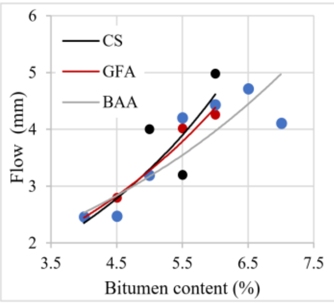

Figure 3. Flow results

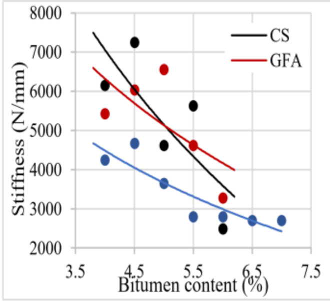

Figure 4. Stiffness results

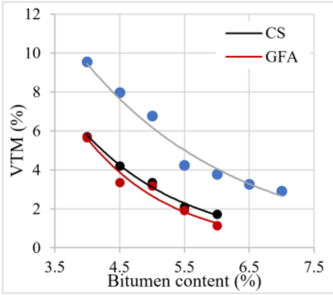

Figure 5. VTM results

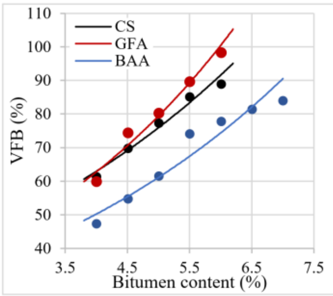

Figure 6. VFB results

Long-term ageing is the step taken after short-term conditioning, where the compacted samples were cooled down for 16 h and placed in an oven at 85°C for 120 h. The samples were then allowed to cool at room temperature prior to testing.

Results and Discussion

Marshall Properties and OBC

Three groups of samples (CS, GFA and BAA) were prepared. The bitumen content in the range of 4% to 6% was tested for samples containing CS and GFA. Figures 1- 6 show the results of Marshall properties and for different bitumen contents added to the asphalt mix. For BAA, the percentage of the bitumen content was increased up to 7% to obtain the required curves based on the standard. The results, as shown in Figure 1 of bulk specific gravity (Gmb) of the CS, increased when the bitumen content was increased from 4% to 5%. Then, Gmb decreased as the bitumen content increased further to 5.5% and 6%. The Gmb of GFA also increased when the bitumen content increased. For BAA, Gmb gradually increased as bitumen content increased, reaching its highest value at a bitumen content of 5.5% prior to decreasing as the bitumen content continues to increase to 6% and 7%.

Generally, the type of aggregates used affects the mix density because of the high density of garnet, thereby increasing Gmb. On the contrary, the low density of the bottom ash decreased the density of the BAA sample. In terms of stability (Figure 2),

Table 3. Determination of Optimum Bitumen Content (OBC)

Mixture	Bitumen content (%)					
	Flow	**Stability**	**VTM**	**VFB**	**Density**	**OBC**
CS	4.6	5.2	4.5	4.9	5.6	5.0
GFA	4.6	4.9	4.4	4.7	5.3	4.8
BAA	4.7	5.7	6.1	6.1	6.2	5.8

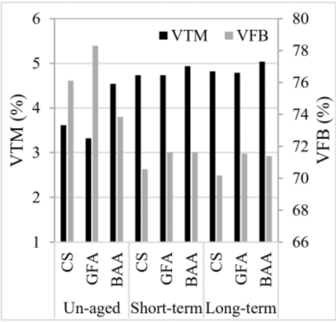

Figure 7. Volumetric properties after ageing

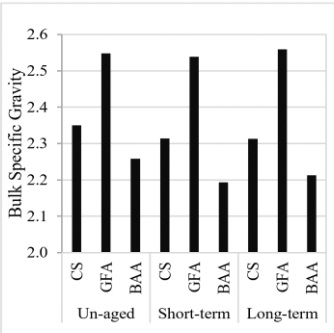

Figure 8. Density after ageing

the trend for GFA samples, comparable to the CS samples with the highest peak, was obtained at approximately 5% bitumen content. The stability of the GFA sample achieved more than 20 kN, exceeding that of the CS and decreased with the increase in bitumen content. The BAA sample was less stable than the other samples but still comply with the minimum specification of 8 kN (JKR SPJ/2008-S4, 2008). This finding is supported by other findings, where the bottom ash has a tendency to reduce the stability of HMA mix compared with the conventional aggregate (Kandhal, 1992). Similar trend was observed for the stiffness of all aggregates used, where GFA and CS produce greater stiffness than the BAA sample.

The results in Figure 3 show that using 4% bitumen content, the flow values obtained for GFA and BAA samples are comparable.

As the bitumen content increases, the flow of the samples increases.

However, the BAA showed acceptable stiffness, though its stiffness was lower than that of the other samples. In addition, the consistency of the results obtained can be observed from voids in the total mix (VTM) plot, which refers to the voids that are present in the mixture.

The VTM of the samples reduces with the increase in bitumen content. Figure 5 shows that the BAA mixture has the highest VTM percentage, and the GFA mixture has the least air voids with the same bitumen content. The porosity of the bottom ash particles has led to increase in air void content, which subsequently affects the stability of the mixture.

Similar to VTM, the VFB result (Figure 6) shows that GFA is a good candidate that can be used to replace the conventional granite aggregate with comparable VFB character for the bitumen distribution within the mix. However, the VFB value of BAA sample was relatively low. This finding indicates that the garnet in the GFA mixture has the least bitumen absorption to obtain the desired void percentage. Meanwhile, the presence of bottom ash in the BAA mixture reduced the VFB percentage, signifying a requirement for more bitumen to be added in the mixture to obtain an optimum mix.

Table 3 summarises the OBC obtained based on the JKR, 2008 requirements for the three asphalt mixtures produced with different aggregate types, i.e., CS, GFA and BAA. The stability and density values were obtained from the highest value (peak) in the curves; the flow was 3 mm, VTM at 4% and VFB at 75% as specified for the wearing layer. The OBC value was calculated at 5.0% (CS), 4.8% (GFA) and 5.8% (BAA). The Marshall test results revealed that the selected optimum bitumen content satisfied all the Malaysian Public Works Department specifications. On the basis of the results of the Marshall test, the OBC of each mixture was then verified, and samples were evaluated further for the different ageing conditions.

Effect of Ageing on Volumetric Properties

Figures 7 and 8 show the results of volumetric properties from the Marshall samples produced for the CS, GFA and BAA samples under different ageing conditions un-aged, short-term aged (STA) and long-term aged (LTA).

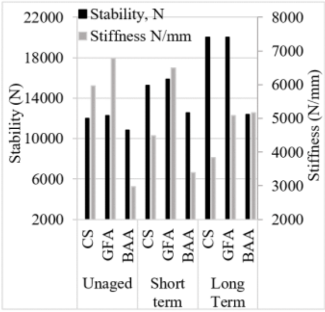

Figure 9. Stability and Stiffness after ageing

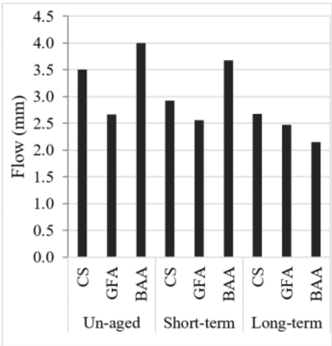

Figure 10. Flow after ageing

This condition allows the properties of an asphalt mixture to be predicted over the service life of the pavement. The results indicate the variations in volumetric properties with ageing, showing that ageing remarkably affects air voids.

In summary, the exposure of the samples against ageing conditions has further increased the air void content within the asphalt due to the increment in the binder hardness and compaction resistance, but the value is still within the acceptable limit, according to the specification. This observation is followed by a significant reduction in VFB that reduces the binder tendency to fill up the voids as a result of ageing compared with the un-aged samples. However, interestingly the GFA samples do not show remarkable difference because the high density of the garnet influences the bulk specific gravity of the asphalt compared with greater decrease experienced by the CS and BAA samples.

Effect of Ageing on Stability, Flow and Stiffness

Figures 9 and 10 show the effects of ageing on stability, stiffness and flow of the asphalt mixtures prepared with different types of fine aggregates, namely, CS, GFA and BAA. The graph shows that ageing slightly reduced the Marshall flow values particularly for the CS and BAA samples. The flow values for LTA samples were lower than those of STA and the un-aged samples. However, the difference in flow values for the GFA samples is unremarkable after the short-term and long-term ageing. This condition indicates that the samples have good resistance against permanent deformation under loading. On the contrary, for stability and stiffness, ageing increases the stability of the mix particularly for the long-term aged samples. However, samples with garnet show greater stability amongst all the selected aggregates. This finding suggests that garnet can be potentially used as pavement material. The unique features of high angularity (sharp-edged particles), durable and good hardness are significant criteria in aggregate selection for the road construction.

Conclusions

The potential of using industrial waste as fine aggregate in asphalt mixture was studied through Marshall tests. In general, asphalt containing garnet as fine aggregate has the highest density and stability amongst the tested aggregates. Moreover, the angular shape of the garnet particles and relatively high hardness, reduced the potential of deformation and increased the stiffness of the asphalt. Meanwhile, the mixture containing bottom ash has the highest air void content even after ageing conditions due to the material's low density and high porosity. Therefore, garnet has the most comparable properties to the conventional granite aggregate, which could potentially be used in asphalt pavement as fine aggregate.

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