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Performance Evaluation of Stone Mastic Asphalt (SMA) Using Geopolymer As an Asphalt Modifier

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ABSTRACT

Nowadays, the knowledge of mechanism controlling the alkali activation process is considerably advanced, especially in pavement engineering, but there are still many things to be investigated. In this study, the mechanism controlling highly alkaline solution (NaOH and Na_2SiO_3) and fly ash was discussed and the essential aspects of the performance of SMA mixture through geopolymerization process were investigated. Virgin asphalt of 80/100 penetration grade and asphalt modified with geopolymer at four different modification levels; namely, 0%, 1%, 2% and 3%, respectively, by the weight of the asphalt, were used in this study. Two aggregate gradations were selected for this study; namely, SMA14 and SMA20. The experimental test was conducted to evaluate the performance of these new mixtures in terms of resilient modulus and permanent deformation (static creep and dynamic creep). The results showed that geopolymer modified SMA mixture with 3% of geopolymer is applicable.

KEYWORDS: Geopolymer, Stone mastic asphalt (SMA), Fly ash, Modified asphalt, Resilient modulus, Permanent deformation.

INTRODUCTION

According to the Malaysian Automotive Association (2012), statistics show that the total registered vehicles in Malaysia have increased over the past 32 years. The number of vehicles on roads has increased dramatically over the past few decades due to the advancement in automotive technology. The impact of the increasing traffic volume or number of vehicles will impose a great amount of stress or strain on the road or highway pavement in the form of traffic loading and axle loads.

The pavement structure can bear the loads to some extent. However, exceeding the limit leads to permanent deteriorations of the pavement, such as potholes, surface deformation, longitudinal cracking, fatigue cracking, edge defects, patching and rutting. To solve these problems, new techniques and material types for the road pavement structure need to be established.

Various techniques have been investigated by scientists and engineers to enhance the road pavement performance. Stone Mastic Asphalt (SMA) is one of the suitable materials for pavement design to be implemented in heavily trafficked roads due to the outstanding performance on the pavement structure. SMA is safer for the motoring public, as it improves

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skid resistance due to high percentage of fractured aggregates, particularly on wet pavements (Hongbin and Watson, 2004). In addition, this type of surface is able to extend the performance life by 30%-40% compared to HMA mixture (conventional dense graded) pavements and provide higher resistance to rutting due to heavy axle load (Hainin et al., 2013).

Typically, modifiers and fillers are used to decrease optimum binder content, increase stability, increase bond between asphalt cement and aggregates and improve density (Brown, 1989). The main reason for using these modifiers and fillers is to improve quality and performance of the paving mixture to meet the requirements under the prevailing conditions and provide safe road surface for road users. Besides, such modifiers minimize the environmental impact on roads in terms of traffic noise, total expenditure for repair and maintenance of road structures, in addition to enabling exploitation of natural resources (Syamsunur et al., 2013).

Worldwide, many studies have been conducted by exploiting different types of waste materials as modifiers in flexible pavements. Waste materials that are used as modifiers into bituminous mixes are crumb rubber (Mashaan et al., 2013; Hassan et al., 2014), natural rubber (Ali et al., 2013), used cylinder oil (UCO) (Borhan et al., 2007), palm oil fuel ash (POFA) (Borhan et al., 2010), among others. The use of alternative materials such as fly ash will definitely be environmentally beneficial. These materials not only can improve the asphalt binder properties and durability, but also have a potential to be cost-effective and save the environment (Mashaan, 2012).

In this study, alkaline activator and fly ash were used in the geopolymerization process. This research shifted from chemistry domain to engineering applications and commercial products of geopolymer SMA mixtures.

Geopolymer has two main constituents which are: the alkaline liquid and the source of materials. Alkaline liquids are soluble alkaline metals that are usually sodium-based or potassium-based. Alkaline liquids most commonly used in geopolymerization are combinations of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) or potassium hydroxide (KOH) and potassium silicate (K_2SiO_3). The source of materials for geopolymer is based on alumina-silicate rich in aluminum (Al) and silicon (Si). These could be natural minerals, such as clays and kaolinite. Alternatively, by-product materials, such as rice husk ash, silica ash, red mud, fly ash,… etc. could be used as sources of materials. The factors in choosing sources of materials for making geopolymers are: cost, availability, specific demand of end users and types of application (Bhosale and Shinde, 2012).

This paper is devoted to heat-cured low-calcium fly ash-based geopolymer SMA mixtures. Low-calcium (ASTM Class F) fly ash is more preferred as the source of materials than high-calcium (ASTM Class C) fly ash. The presence of calcium in high amounts may interfere with the polymerization process and alter the microstructure (Mathur et al., 2005).

Fly ash is a byproduct of electric power industry. It is reported to exhibit great potential as an asphalt modifier in road construction. Fly ash is a waste material that can be recycled as a road construction material. Nowadays, the production of fly ash is extensive and the demand on dumping areas on which to dispose of this material is high. The Malaysian Department of Environment (DoE) reported that the production of fly ash in Malaysia generated approximately 2 million metric tons annually and that the total amount increased to 4 million metric tons in 2013.

ACAA(2003) claims that the usage of fly ash in this field will improve the performance of pavements and increase the environment quality in terms of reducing the dumping area to dispose of this material and saving natural resources.

In Malaysia, the applications of geopolymers in SMA mixtures are still new and there has been little research conducted relating to the Malaysian conditions. Therefore, the main aim of this study is to investigate the effects of using geopolymer-based fly ash as a modifier on SMA mixture performance properties. This study investigated the essential aspects of modified asphalt mixtures in order to better understand the influence of geopolymer modifier on the performance of geopolymer SMA mixtures. Contractors from developing countries like Malaysia may suffer problems with SMA mixes because of lack of experience, since this is considered to be a new type of mix for road pavement compared to the standard HMA. This type of information would be valuable to agencies that desire to construct SMA pavements.

MATERIALS AND METHODS

Materials

80/100 penetration grade and average softening point of 44°C asphalt were utilized. Table 1 and Table 2 illustrate some physical properties of asphalt and the chemical constitution of bitumen, respectively.

Table 1. Physical properties of asphalt

Asphalt test	Asphalt grade 80/100	Standard test method
Penetration (mm)	83	ASTM D5
Ductility (cm)	>100	ASTM D113
Softening point (°C)	44	ASTM D36

Table 2. Chemical constitution of bitumen

Bitumen	80/100
Saturated	5.4
Aromatic	72.5
Resin	15.5
Asphaltene	6.6

In this study, class F fly ash (low calcium) was selected with alkaline activators, such as sodium hydroxide (98% purity) and sodium silicate (8M). Table 3 and Table 4 illustrate the chemical composition and physical properties of fly ash that can be used.

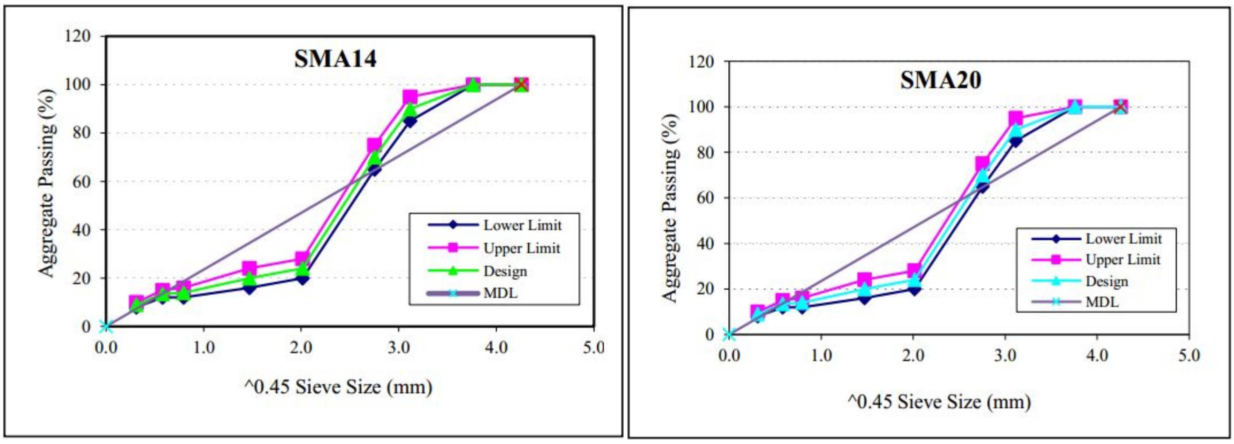
Table 3. Chemical composition of fly ash (Class F)

Characteristics	Fly ash (%)
Silica	55-65
Iron oxide	5-7
Aluminum oxide	22-25
Calcium oxide	5-7
Magnesium oxide	<1
Titanium oxide	<1
Phosphorous oxide	<1
Sulphates	0.1
Alkali oxide	<1

Table 4. Physical properties of low calcium class F fly ash

Physical properties	Properties of fly ash used	Properties of fly ash according to IS 1320-1981
Specific gravity	2.51	-
Initial setting time	120 minutes	-
Final setting time	280 minutes	-
Fineness specific surface in m^2/kg min	320	340
Lime reactivity average compressive strength	4.00	6.20

The crushed aggregates supplied from the Kajang quarry were used throughout the study. The aggregate gradation of the adopted aggregates is according to the JKR Malaysia standard as illustrated in Figure (1a, b). The aggregate test results are shown in Table 5. The reason behind the aggregate test was to ensure that the standard of aggregates is according to the JKR/SPJ/2008 specification.



(a) **(b)**

Figure (1): Aggregate gradation for SMA14 (a) and SMA20 (b)

Table 5. Aggregate testing results

Testing	Result	Procedure	Specification JKR/SPJ/08
Los Angeles Abrasion	28%	ASTM 131	<25%
Aggregate Impact Value	15%	BS 812: Part 112	-
Flakiness Index	8%	BS 812: Section 105	<25%
Aggregate Crushing Value	32%	BS 812: Part 110	<30%

Sample Preparation and Test Method

The superpave mix design for SMA14 and SMA20 was used for the conventional and modified asphalt concrete mixtures. To incorporate geopolymer in the bituminous mix, a wet process was conducted. In the wet process, the geopolymer modifier replaced the percent of virgin asphalt to form geopolymer modified asphaltt before the modified asphalt was added to the aggregate mixture. The percentages of geopolymer used are: 0%, 1%, 2% and 3% of asphalt weight, while the binder contents utilized in this study are: 5%, 5.5%, 6%, 6.5% and 7% by weight of the total mix. In the current study, Portland cement was used as the mineral filler and the amount of Portland cement used was 2% of the total weight of the mixture (Public Work Department, 2008).

To prepare the SMA mixture, an amount of 1200 g of the mixed aggregates was placed in the oven at 160°C for 2 hours. Asphalt was also heated at 120°C before mixing with the geopolymer. As the method applied is wet process, geopolymer modifier has undergone a process of mixing with virgin asphalt at a temperature, stirring speed of mixing tool and time period as stated in the standard. After the asphalt modifying process was finished, the geopolymer modified asphalt was added directly to the mixture. Mixing temperature was kept constant between 160°C and 165°C. The mixture was then transferred into a superpave mold. The stainless thermometer was put in the center of the mold and the mixture was then ready for compaction at the temperature of 160±5°C. All samples were subjected to 120 gyrations of compaction by the gyratory compactor at the temperature of 145°C.

Laboratory test was conducted to find the optimum binder content, then the asphalt-concrete binder that was mixed with the optimum binder content was investigated and evaluated to determine the performance properties of the geopolymer SMA asphalt mixture using the resilient modulus test, static creep test and dynamic static test.

RESULTS AND DISCUSSION

Optimum Binder Content

The optimum binder content (OBC) is the most important criterion in preparing the samples, as any error in obtaining OBC will influence the results. The OBC values for the test samples are shown in Table 6 for SMA14 and Table 7 for SMA20, respectively. It is shown that the selected OBC for each type of SMA mixture met the requirement of JKR/SPJ/2008-S4 (Bhosale and Shinde 2012). This is very important to ensure that the samples will produce reliable results when testing the performance of the asphalt concrete.

Table 6. Optimum binder content for SMA14

Type	% of Geopolymer	OBC
SMA14	0	6.10
	1	7.00
	2	6.29
	3	6.70

Table 7. Optimum binder content for SMA20

Type	% of Geopolymer	OBC
SMA20	0	6.50
	1	6.30
	2	6.60
	3	5.60

Resilient Modulus

A resilient modulus testing program is typically used to evaluate the ability of the mixture to bounce back upon releasing the applied stress. The resilient modulus can be measured as the ratio of the repeated stress to the corresponding resilient strain (by recoverable deformation) (Hassan et al., 2014). The resilient modulus testing procedure was carried out according to the ASTM D4123 standard. Three samples for each different percent of geopolymer were tested under the diametral resilient modulus (Mr) test at the temperature of 40°C.

Results revealed that the resilient modulus for 3% geopolymer in SMA14 was 204Mpa and was recorded to be the highest resilient modulus reading compared to the other percentages of geopolymer. SMA14 with 2% geopolymer also recorded a higher resilient modulus than conventional SMA14 with a reading of 179MPa as presented in Figure 2. This finding indicates that SMA14 with 2% and 3% geopolymer may perform better than the conventional SMA14 under traffic loading.

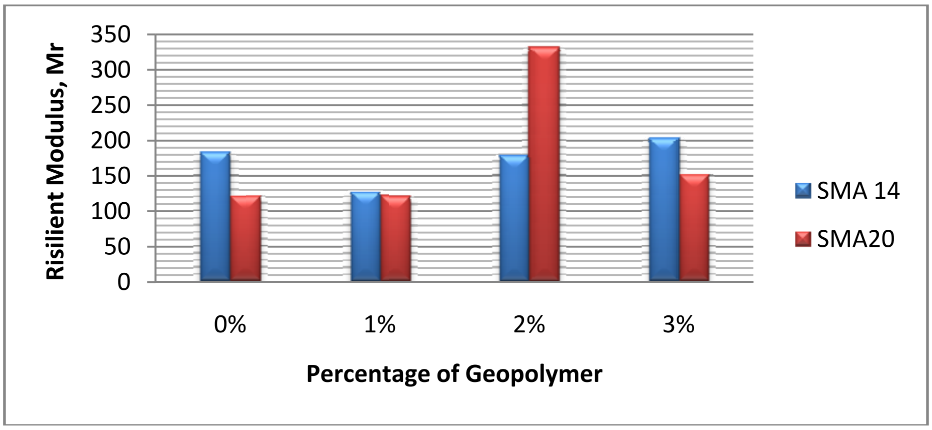


Figure (2): Resilient modulus of SMA14 and SMA20 *versus* the percentage of geopolymer

As shown in Figure 2, the highest resilient modulus value at 40°C was recorded by SMA20 with 2% geopolymer. SMA20 with 3% geopolymer also showed a higher resilient modulus value compared to the conventional SMA20 mixture. For SMA20 with 1% geopolymer, the geopolymer mixture still produces a higher resilient modulus value compared to conventional SMA20. However, the differences were not huge.

Comparing both SMA14 and SMA20 at 40°C shows that the usage of geopolymer as asphalt modifier resulted in higher resilient modulus values.

Permanent Deformation Resistance

The potential of permanent deformation at high temperatures for the asphalt mixture can be determined from the permanent strain accumulated at the end of testing under vertical compressive stress (Hassan et al., 2014). Researchers claimed that the usage of geopolymer modified asphalt into the asphalt mixture will enhance the strength of the mixture and allow it to recover at high service temperatures to counter permanent deformation experienced on road surfaces. Creep tests were conducted by Lee et al. (2008) and Fontes et al. (2010) to characterize permanent deformation in terms of creep modulus under static axial load.

The static creep test can measure permanent deformation of a specimen after unloading the static load applied to the specimen. The test was conducted to determine permanent deformation of the asphalt mixture. The observed permanent deformation of the asphalt mixture was then correlated with the rutting potential. Creep deformation under uniaxial load of cylindrical specimen was measured as a function of the sample dimensions and time, and the test conditions were standardized. High temperatures and heavy loads that were incurred by the pavement will increase the risk of permanent deformation. For that reason, the following test parameters were selected: the temperature was 40°C, the uniaxial load was 0.4 MPa and the test duration was 3600s (Borhan et al., 2010).

A comparison between SMA14 and SMA20 for the static creep test at 40°C with a load value of 100kPa shows that permanent deformation for both types of asphalt mixture showed the same trend as illustrated in Figure 3. Permanent deformation for the geopolymer SMA mixture was recorded to be slightly higher than for the conventional asphalt mixture. The inclusion of geopolymer as asphalt modifier for the SMA mixture under static load condition like parking area was found to increase the value of permanent deformation over that of a conventional asphalt mixture.

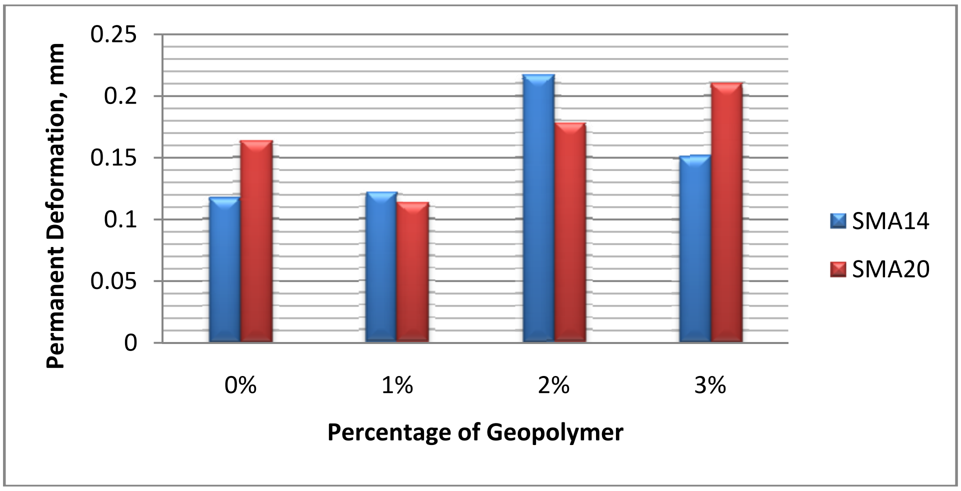


Figure (3): Static creep results for SMA14 and SMA20

Other than the static creep test, this study also used a confined repeated load axial test (dynamic creep test) to evaluate the geopolymer asphalt mixture by measuring the total strain and the strain rate on the mixture after the application of the load cycles. This experiment was realized at a test temperature of 40°C. Samples were exposed to a starting load of 100 kPa. An average of 138 kPa load was put into practice during the duration of the test. Testing was continued until the maximum axial strain limit reached 10000 microstrains or until 10000 cycles (whichever occurred first) (Borhan et al., 2007).

For the dynamic creep test, the results totally reflected the static creep test. Both types of mixture, SMA14 and SMA20, recorded that a higher percentage of geopolymer causes lower permanent deformation. Figure 4 presents that geopolymer modified SMA14 and SMA20 mixtures have lower permanent deformation values compared to conventional mixture.

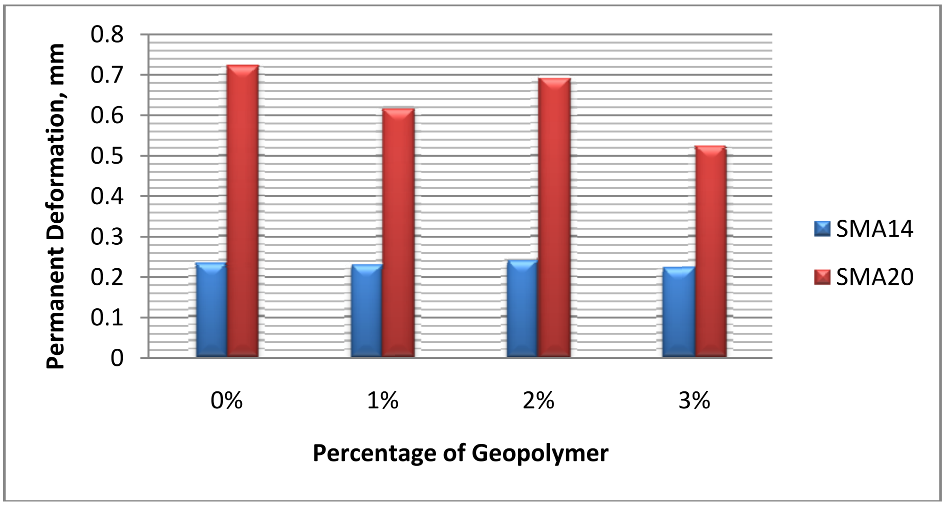


Figure (4): Dynamic creep result for SMA14 and SMA20

The inclusion of geopolymer as asphalt modifier in SMA mixtures was found to increase permanent strain and strain rate to values higher than those for conventional asphalt mixture. On the other hand, strains rate was found to decrease as the geopolymer content in the mixture was increased. This demonstrated that higher geopolymer content could potentially improve the permanent deformation resistance of the geopolymer modified asphalt mixture.

CONCLUSIONS

This investigation has provided detailed insight and a better understanding of a wet mixed geopolymer asphalt mixture. This is necessary to justify the function and the behavior of the geopolymer within the mixture prior to performance evaluation. Thus, it would be possible to identify factors that play a significant role in improving the geopolymer asphalt mixture properties.

From the investigation results, several conclusions can be drawn the most important of which are:

a) Fly ash is an ecofriendly and "green" material which is durable and can improve the performance of SMA mixtures.
b) The resilient modulus test reported that mixtures containing geopolymer modified asphalt have a higher value than the conventional SMA mixtures.
c) Permanent deformation that was tested using the static creep test showed that conventional SMA

mixtures produced less permanent deformation than geopolymer SMA mixtures. However, the difference is not huge for all mixtures, so the result of using geopolymer modified asphalt concrete in SMA mixtures is still acceptable.

Although only based on the dynamic creep test, geopolymer modified asphalt mixtures have lower permanent deformation compared to conventional asphalt mixtures. It can be concluded that geopolymer asphalt mixtures could perform admirably during high traffic loading.

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