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Laboratory Evaluation on Steel Slag as Aggregate Replacement in Stone Mastic Asphalt Mixtures

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Graphical abstract

Abstract

The stone mastic asphalt (SMA) mixture has been used in many developed countries with the addition of by-product to reduce the consumption of aggregates in road construction. Recently, the Malaysian Public Works Department (PWD) has launched the new specifications on specialty mixture and surface treatment, including SMA. Therefore, this study was conducted to investigate the use of steel slag as an aggregate replacement in Malaysian SMA. Two types of mixes; namely SMA14 and SMA20 were used in this study. The Marshall Mix design method with 50 compaction efforts was used for the design mix for both mixes, where all the standards were referred to the PWD specification (JKR/SPJ/2008-S4). The performance of SMA14- and SMA20- steel slag mixtures was evaluated in terms of the resilient modulus, rutting and creep deformations, conducted by means of a universal testing machine (UTM) and a Wessex wheel tracking. Except for the water absorption test, it was observed that the strength and shape of the steel slag aggregate meet the PWD specification. In addition, the results also show that the use of steel slag improves the strength and resistance to rutting compared to the control SMA samples.

Keywords: Stone mastic asphalt; steel slag; resilient modulus; rutting and creep

■1.0 INTRODUCTION

The stone mastic asphalt (SMA) mixture is designed to have a high proportion of coarse aggregate content typically 70–80%, 6–7% of asphalt content or binder, 8–12% of mineral filler content and 0.3% fibre [1]. The high percentage of stone skeleton content results in stone-on-stone contact that produces a mixture that is highly resistant to rutting and permanent deformation. Hence, SMA has clear that the mechanical property is far superior then the conventional hot-mix asphalt (HMA), making it more favourable for application.

SMA was originally developed in Germany during the mid- 1960s as an impervious wearing surface to provide rut resistant and durable pavement surface layer. It then has been first introduced in Europe for more than 20 years for resisting damage from the studded tires better than other type of HMA [2]. Typically, SMA mixes have polymer-modified asphalt (PMA) contents that range between 5.5–7.5%. The PMB may further stabilise using cellulose fibres to prevent excessive binder drain down. In addition, the presence of fibre enhances the durability of SMA Mix by allowing the use of higher asphalt content. SMA is also able to provide durable surfacing and exhibit high resistance to rutting due to heavy axle loads [3]. This type of surfacing offers improved texture depth, in the range of 0.7–1.0 mm, thus providing good skid resistance [4]. Besides that, SMA provides a friendly and safety due to the high percentage of fractured aggregate to motoring public particularly on wet pavement [5].

Although water does not drain through SMA, its surface texture is similar to open graded aggregate so that the noise generated by traffic is lower than that on dense graded aggregate [6]. Therefore the courses surface texture characteristic may reduce sound from the tire and pavement contact as well as water spray and glare. SMA also provides anti-splash features during wet and rainy conditions thus reducing hydro-planning which results from water draining through the voids in the matrix. SMA has been used successfully in Europe, Canada, Australia and as well as in the USA. However, very limited research and work has been done in Malaysia regarding the performance of the SMA.

The development of the highway construction industry is increasing rapidly, and consequently the aggregate resources in Malaysia are becoming depleted and land is being sacrificed to obtain raw materials. Thus, it is necessary to find a recycled material that can replace aggregates in highway construction. Much research has been done to improve and upgrade the materials used for preparing HMA. The utilization of waste material as a replacement for aggregate in the production of HMA could have many benefits to mankind. Waste materials can be categorized broadly as follows: industrial waste (e.g. cellulose waste, wood lignins, slags, bottom ash and fly ash), municipal or domestic waste (e.g. incinerator residue, scrap rubber, waste glass and roofing shingles) and mining waste (e.g. coal mine refuse) [7].

Steel slag is a by-product of the steel industry, and is reported to exhibit great potential as a replacement for natural aggregates in road construction. Steel slag is a waste material that can be recycled as a road construction material. Steel slag aggregates have been reported to retain heat considerably longer than natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous for HMA construction, as less gas (energy) is used during the execution of HMA works. Based on high frictional and abrasion resistance, steel slag is used widely in industrial roads, intersections and parking areas where high wear resistance is required. Nowadays, the production of steel slag is extensive and the demand for dumping areas on which to dispose of this material is high. Based on the Malaysian Department of Environment (DoE) reports, approximately 350 000 metric tons of steel slag were generated in 1987, and the total amount increased to 620 000 metric tons in 2000 [8]. This report proves that the amount of steel slag is increasing every year, as steel is used for many purposes. In flexible pavement design, it can be used as an aggregate replacement for HMA, road base and sub-base.

Steel slag is chemically stable and shows excellent binding properties with asphalt, has a low flakiness index, good mechanical properties and good anti-skid resistance [9].Work done by various researchers has found that the addition of steel slag in HMA enhances the performance characteristics of pavement [10-12]. Since steel slag is rough, the material improves the skid resistance of pavement. Also, because of the high specific gravity and angular, interlocking features of crushed steel slag, the resulting HMA concrete is more stable and resistant to rutting [12-14]. Recently, the use of steel slag with SMA has been further investigated. It has been observed that the use of steel slag in SMA mixtures enhances resistance to cracking at low temperatures. In addition, this mixture also presents excellent performance in roughness and the British Pendulum Number (BPN) coefficient of the surface at in-service temperature [15].

The national specifications for SMA were first introduced in Malaysia in 2008 when the Public Works Department (PWD) launched the specifications on specialty mixes. Two SMA gradations, designated as SMA14 and SMA20 were used in this study [4]. Based on the new standard, known as JKR/SPJ/2008-S4, this study is conducted to determine the feasibility of steel slag as an aggregate replacement in the Malaysian SMA. The laboratory testings were conducted in 2011 at the Highway and Transportation Laboratory, Universiti Teknologi Malaysia (UTM) to evaluate the performance of these new grades in terms of resilient modulus, rutting and creep deformations. All the method and testing are based on specifications of the America Society for Testing and Materials (ASTM), America Association of State Highway and Transportation Officials (AASHTO) and JKR/SPJ/2008-S4.

2.0 EXPERIMENTAL DESIGN

2.1 Materials

The main materials used for this study were steel slags, natural aggregates and polymer-modified asphalt (PG-76). All properties of the material were evaluated for further study consideration. Several tests were conducted in order to measure their properties according to the SPJ/JKR/2008 and ASTM 1992 specifications. Steel slag aggregates that used in this study were obtained from Purata Keuntungan Sdn. Bhd. located at Pasir Gudang and for natural aggregate was from Malaysia Rock Products (MRP) Quarry Sdn. Bhd**.** The aggregates were sieved and separated based on the sizes prepared according to the JKR/SPJ/2008. Figure 1 shows the aggregate gradations for SMA14 and SMA20.

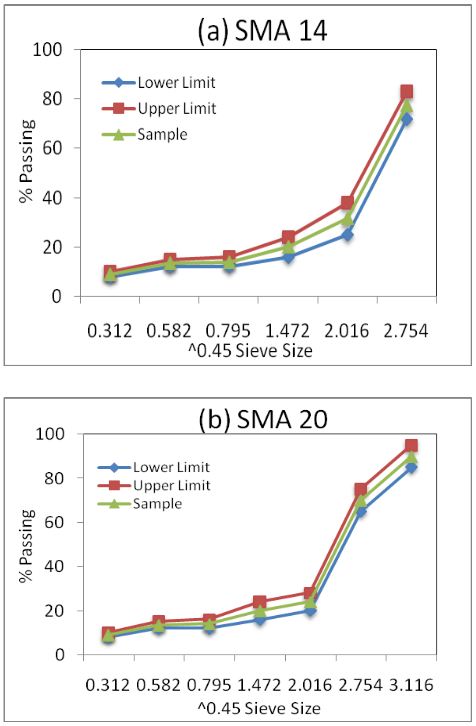

Figure 1 Gradation Limits for (a) SMA14 and (b) SMA20

2.2 Laboratory Compacted Specimen

SMA mixtures should be compacted in the laboratory by means of the Marshall method, in accordance with ASTM D 1559. The specimen can then be used for further analysis, and because of the limited compactive effort applied in the field of SMA mixture, the 50 blows per face was used. For each mix design, three specimens were prepared for each combination of aggregates and binder contents at 5, 5.5, 6.0, 6.5 and 7.0%. Each sample was prepared with the weight of 1300 g. The voids in total mix (VTM), voids in mineral aggregate (VMA), stability and flow of control and steel slags SMA were then compared with the JKR/SPJ/2008-S4 specification.

2.3 Resilient Modulus Test

The resilient modulus is an important parameter to determine the performance of pavement and to analyse pavement response to traffic loading. Although it was once believed that stiffer pavements had greater resistance to permanent deformation, it has since been concluded that the resilient modulus at low temperatures is somewhat related to cracking, as stiffer mixtures (higher resilient modulus) at low temperatures tend to crack sooner than more flexible mixtures (lower resilient modulus) [16]. In this study, the resilient moduli at 25 and 40 ^{o}C were obtained for the mixture. The procedures of this test were based on ASTM D 4123-82. The resilient modulus test was conducted using a universal testing machine (UTM), as shown in Figure 2a.

2.4 Wheel Tracking Test (Rutting)

Rutting, also sometimes called grooving or channelling, is a longitudinal surface depression in the wheel paths [17]. Rutting displaces the HMA in the wheel path, creating a channel. A major type of HMA pavement failure is rutting, which is manifested at the surface [18]. The rutting potential of various types of mixture was measured with accumulated permanent deformation at an interval of 25 load cycles to 5000 load repetitions or 15 mm rut depth. The procedures of this test were based on ASTM D 3203-91. Figure 2b shows the wheel tracking machine used in this study.

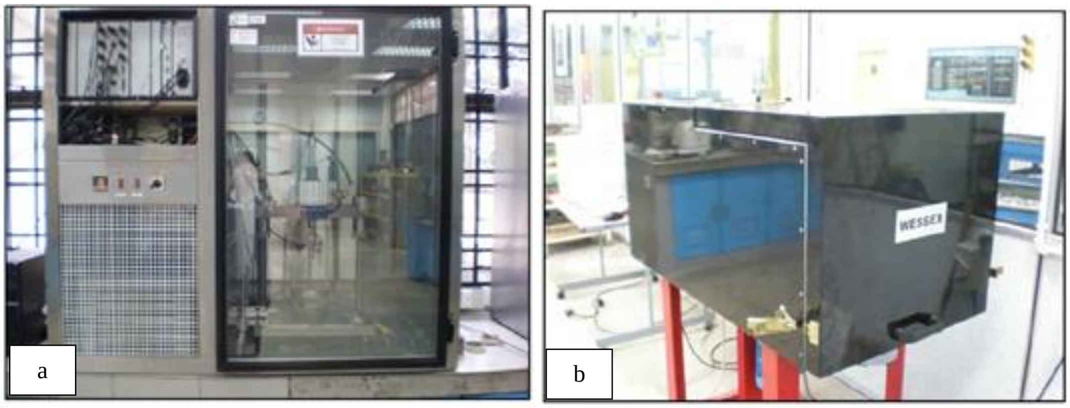

Figure 2 (a) Universal testing machine and (b) wheel tracker machine

2.5 Creep Test

The creep test, as shown in Figure 3, was conducted to determine permanent deformation of asphalt mixtures. The static load is measured as a function of time, while the mixture dimensions and test conditions are standardized. The duration of the test was 3600 seconds loading and 600 seconds unloading. A static loading stress of 200 kPa was applied at a temperature of 40 °C.

3.1 Determination of Steel Slag Characteristics

The quality of the material is very much related to its characteristics; hence, in this study, conventional aggregate and steel slag aggregate were subjected to several tests, as shown in Table 1. The reason behind these tests was to ensure the feasibility of using steel slag as a conventional aggregate replacement in SMA mixtures. Based on the results, steel slag meets all the requirements established by the Malaysian PWD except for water absorption (more than 2%). Water absorption was calculated using the following equation:

$$W_{abs} = 100\,(A - B) / B$$

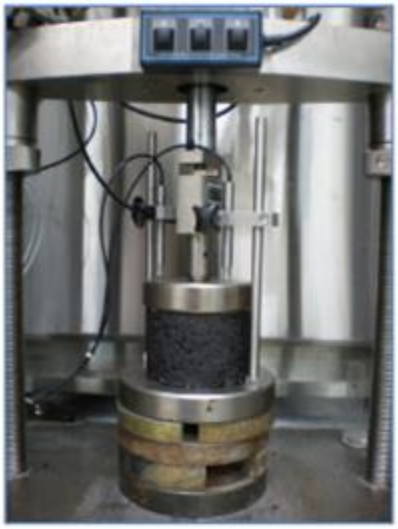

Figure 3 Fixing for creep test

where W_{abs} is water absorption, A is the mass of the saturated surface dry-aggregate in air (g) and B is the mass of the oven-dry aggregate in air (g). The water absorption of the steel slag mixtures was found to be 2.89% and 3.08% for SMA14 and SMA20 respectively. This phenomenon could be attributed to the fact that steel slag aggregates possess many pores (honeycomb), which allow the water to fill the voids. To ensure that water absorption does not affect the degree of coating between the asphalt and steel slag aggregate, a stripping test was conducted and showed a satisfying result.

■3.0 RESULTS AND DISCUSSION

3.2 Specific Gravity

In this study, the specific gravity and absorption of the aggregates were analysed based on ASTM C 127-88 and ASTM C 128-88 for coarse and fine aggregates respectively. Table 2 shows the specific gravity of both coarse and fine aggregates. Because steel slag aggregate is harder and denser than conventional, obviously the specific gravity has significant different as shown in Table 2.

3.3 Theoretical Maximum Density

The Theoretical Maximum Density (TMD) test was performed using the Rice Method based on the optimum asphalt binder content. The amount of the samples is determined based on ASTM D 2041 and depends on the size of the largest particle of aggregate in the mixtures. Table 3 summarises the results of TMD at 5% for each type of mixture.

3.4 Optimum Asphalt Binder Content

The optimum asphalt binder content (OAC) is the most important criterion in preparing the sample, as any error in obtaining OAC will influence the result. The OAC values for the tested samples are shown in Table 4. It shows that the selected OAC for each grade met the requirement of JKR/SPJ/2008-S4. This is very important to ensure that the samples will produce reliable results when testing for rutting, resilient modulus and permeability.

Table 1 Aggregate testing results

Testing	Procedures	Conventional Aggregate	Steel Slag	JKR/SPJ/2008-S4
Aggregate Crushing Value	BS 812 Part 110: 1990	23%	23 %	< 30 %
Los Angeles Abrasion	ASTM C 131 - 1981	26%	24 %	<25 %
Aggregate Impact Value	BS 812: Part 112:1990	24%	23 %	-
Flakiness (Coarse, 28 mm)	BS812: Section 105.1: 1989	8%	3 %	<30 %
Flakiness (Coarse, 20 mm)	BS812: Section 105.1: 1989	8%	2 %	<30 %
Flakiness (Coarse, 14mm)	BS812: Section 105.1: 1989	9%	3 %	<30 %
Soundness	AASHTO: T 104-86	1.07%	2.07 %	<18 %
Polished Stone Value	BS 812: Part 14: 1989	50	54	>40
Water Absorption SMA 14/SMA 20	BS 812: Part 2: 1975	1.35%	2.886/3.075%	<2%
Stripping	AASHTO: T 182	>95%	>95%	>95%

Table 2 Specific gravity of the materials used

Materials		**Specific Gravity**	**Absorption (percent)**
Asphalt	PG 76	1.030	-
Fine aggregate	SMA14	2.437	7.088
	SMA14 (control)	2.593	0.463
	SMA20	2.447	9.540
	SMA20 (control)	2.593	1.051
Coarse aggregate	SMA14	2.833	2.268
	SMA14 (control)	2.596	0.860
	SMA20	2.836	2.533
	SMA20 (control)	2.608	0.628
Ordinary Portland Cement (OPC)		3.130	-

Table 3 Results from theoretical maximum density test

Types of mixture		**SG maximum (G_{mm})**	**SG effective (G_{eff})**
SMA14	Sample	2.368	2.582
	Control	2.325	2.528
SMA20	Sample	2.440	2.674
	Control	22.365	2.578

Table 4 Optimum asphalt binder content (OAC)

Types of mix		**OAC**
SMA14	Sample	6.1 %
	Control	5.6 %
SMA20	Sample	6.3 %
	Control	5.6 %

3.5 Marshall Specification

Table 5 shows the Marshall result obtained for both control and sample of SMA14 and SMA20. It was observed that all the results are in good agreement with the JKR/SPJ/2008-S4 specification.

Table 5 Marshall Specification

Specifi-cation	SMA14		SMA20		Specifi-cation
	Sample	Control	Sample	Control	
VTM (%)	3.00	4.35	4.40	4.20	3 – 5
VMA (%)	22.47	18.52	22.40	17.00	Min 17%
Stability (kg)	1108	1202	1390	1202	Min 632 Kg
Flow (mm)	3.50	3.30	3.40	3.20	2 – 4
Stiffness (kg/mm)	316.57	364.24	408.82	375.63	-

3.6 Resilient Modulus

A resilient modulus of 1280.9 MPa for the steel slag SMA14 was recorded, which is almost double the value recorded for the conventional SMA14 at 25 ^{o}C of 789.7 MPa. This finding indicates that the mixture made from steel slag aggregate may perform almost twice as well as the mixture made with conventional aggregate under traffic loading. The trend is almost similar at 40 ^{o}C; the resilient modulus of the mixture containing steel slag is almost twice that of conventional aggregate at 367.2 MPa and 207.0 MPa respectively, as presented in Figure 4.

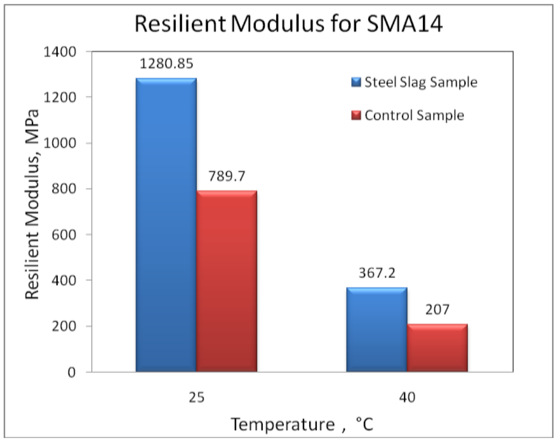

Figure 4 Resilient Modulus for SMA14

For SMA20, the resilient moduli at 25 ^{o}C are 1390.8 MPa and 1140.7MPa for the steel slag aggregate mixture and conventional mixture respectively. The steel slag aggregate mixture still produces a higher resilient modulus value compared to the conventional aggregates mixture; however, the difference is not as huge as for SMA14 at the same temperature. At 40^{o}C, the modified mixture also possesses a higher resilient modulus value of 385.9 MPa compared to 314.0 MPa for the unmodified mixture. This shows that at the higher temperature, the strength of the steel slag remains high (Figure 5).

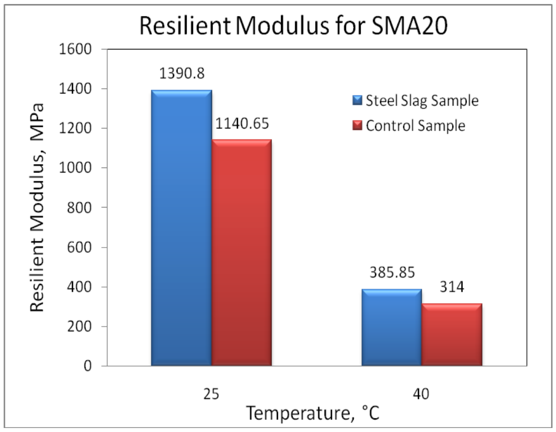

Figure 5 Resilient Modulus for SMA20

Comparing both SMA14 and SMA20 at temperatures of 25 ^{o}C and 40 ^{o}C shows that steel slag has a higher resilient modulus value. This is because steel slag is hard, dense and possesses abrasion resistance as well as containing significant amounts of free iron, giving the material high density and hardness [1].

3.7 Creep Test

Figure 6 shows the results for the permanent deformation and strain of SMA14. From the results it is clear that permanent deformation and strain for the steel slag mixture is lower than for the conventional mixture. Permanent deformation for the steel slag mixture is 0.019 mm, while for the conventional mixture it is 0.152 mm. The strain for the steel slag mixture is 0.288 % and 0.404 % for the conventional mixture. The steel slag mixture has good behaviour in terms of interlocking and adhesion. Thus, the steel slag mixture proves that it can resist greater deformation and can last longer when compared to the conventional mixture.

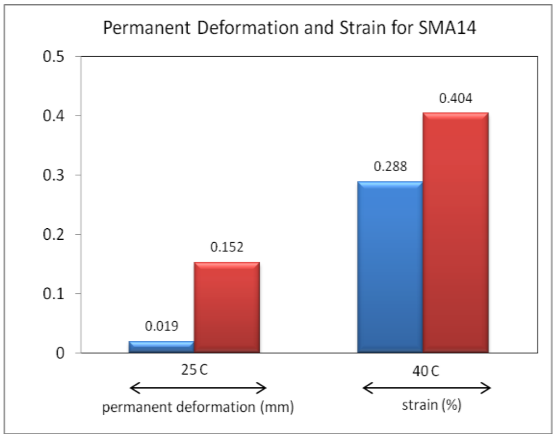

Figure 6 Creep test for SMA14

Meanwhile, the permanent deformation and strain for SMA20 is presented in Figure 7. The result exhibits a similar trend to that of SMA14, in that the steel slag mixture has smaller deformation and strain possibilities than the conventional mixture in terms of rutting depth. Permanent deformation for the steel slag mixture is 0.024 mm, whereas it is 0.156 mm for the conventional mixture. The strain value for the steel slag and conventional mixture is 0.291% and 0.414% respectively. Therefore, it can be concluded that SMA mixtures using steel slag has a higher resistance to deformation and could therefore cater for higher traffic loadings.

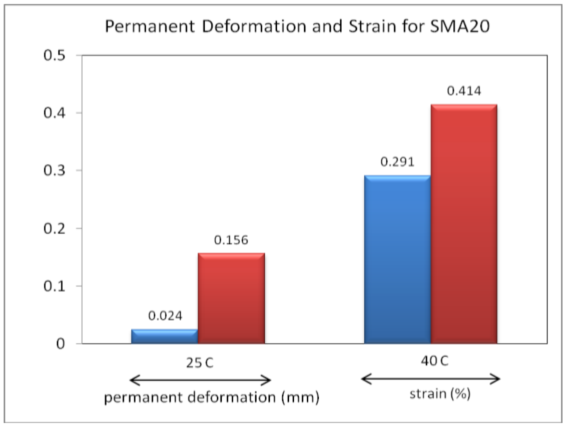

Figure 7 Creep test for SMA20

3.8 Rutting

The rutting potential of various types of mixture was measured according to accumulated permanent deformation at intervals of 25 load cycles until 5000 load repetitions or 15 mm rut depth were achieved, whichever came first. In SMA14, there is a significant difference in the rutting depth between conventional aggregate and steel slag aggregate. The rutting depth of the conventional aggregate was 2.3mm, while a rutting depth of only 1.5 mm was recorded for the steel slag aggregate, which means that the rutting depth of conventional aggregate is two times higher than the steel slag aggregate (Figure 8). The reason behind this result is that the strength possessed by steel slag is much higher than conventional aggregate. In addition, steel slag aggregate also has excellent binding properties with asphalt and a low flakiness index [15].

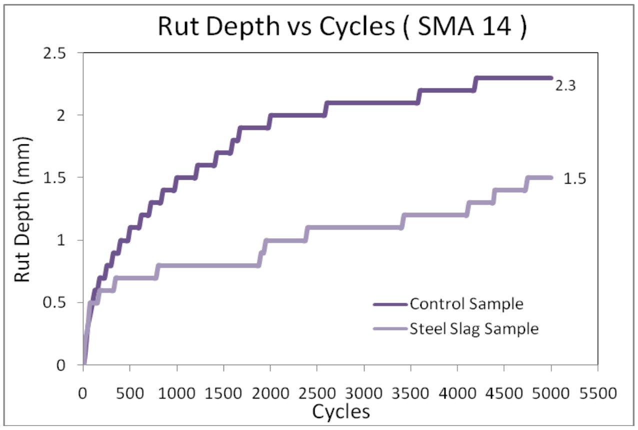

Figure 8 Results of wheel tracking test for SMA14

Rutting depth in SMA20, as shown in Figure 9, also shows the same trend as in SMA14. The rutting depth of conventional aggregate was higher than for steel slag aggregate. The rutting depth of conventional aggregate conventional aggregate was 2.6 mm, while a rutting depth of 2.3 mm was recorded for the steel slag aggregate. A comparison between SMA14 and SMA20 shows that the rutting in SMA14 is less than in SMA20. This result could be due to a smaller amount of fine aggregate in SMA20 than SMA14; hence, SMA20 has a higher air void density. The presence of more air voids results in further compaction during testing, and hence increases rut depth.

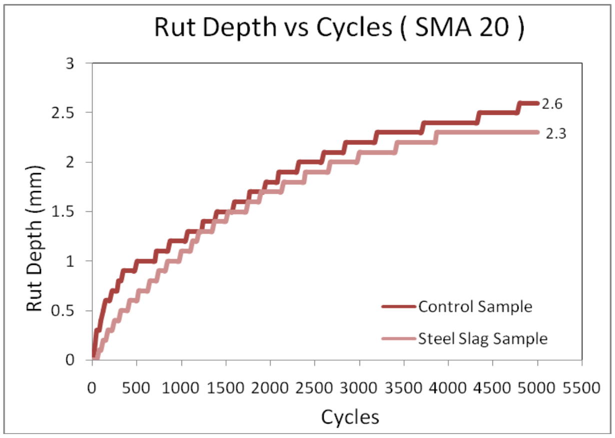

Figure 9 Results of Wheel Tracking Test for SMA20

4.0 CONCLUSIONS

Based on this study, several conclusions can be drawn:

- Steel slag aggregates meet all the requirements of aggregates that are to be used in road construction, such as in terms of strength and shape in accordance to the PWD requirements. However, the value for water absorption of steel slag aggregate for both SMA14 and SMA20 exceeded the value established in JKR/SPJ/2008-S4, which should be lower than 2.0%. This phenomenon is because steel slag possesses more pores, enhancing its tendency to absorb water.
- The optimum asphalt binder content (OAC) content for steel slag SMA mixture is higher compared to the control sample.
- As for the performance evaluation, the resilient modulus test shows that SMA mixtures containing steel slag aggregate have a higher value than those containing conventional aggregate. High resilient modulus also results in great resistance to rut development in asphalt pavement by reducing residual deformation in subgrade soil.
- It was observed that the steel slag SMA mixtures show better results compared to the control sample. This finding indicates that the steel slag SMA mixtures are able to improve performance of mixture in terms of permanent deformation

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