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Utilisation of Steel Slag as an Aggregate Replacement in Porous Asphalt Mixtures

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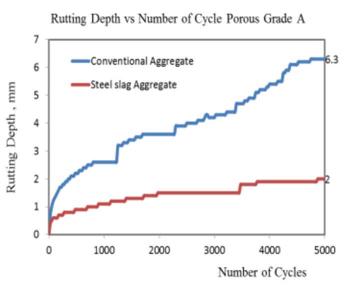
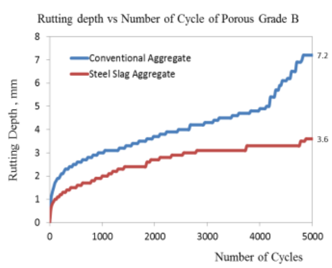
Graphical abstract





Abstract

The utilization of porous asphalt mixtures has become increasingly important. This type of pavement has been used in many developed countries for many years with the addition of by-products to reduce the consumption of aggregates in road construction. Recently, the Malaysian Public Works Department (PWD) launched specifications for specialty mixtures and surface treatments, including porous asphalt. Therefore, this study was conducted to investigate the use of steel slag as a conventional aggregate replacement in porous asphalt mixtures. Two porous asphalt gradations, designated as Grade A and Grade B, were used in this study in accordance with the new specification – JKR/SPJ/2008-S4. Steel slag was chosen because its characteristics are quite similar to those of aggregates compared with other by-products such as crumb rubber, glass and many more. It was observed that steel slag aggregate meets all the criteria of the PWD specification except for the water absorption test. The samples of steel slag aggregate mixtures produced were tested for resilient modulus, rutting and permeability, which were later compared with conventional aggregate mixtures. The results show that there is a significant difference in terms of resilient modulus between the steel slag aggregate-based mixture and the conventional aggregate-based mixture. The same scenario was observed in the rutting test, where the steel slag aggregate mixture possesses a higher rut resistance. However the mixtures made from conventional aggregate had higher permeability values compared to the steel slag mixtures. It can be concluded that the use of steel slag could performed admirably during high traffic loading.

Keywords: Porous asphalt; steel slag; resilient modulus; rutting and permeability

Abstrak

Penggunaan campuran asfalt berliang telah menjadi semakin penting. Turapan jenis ini telah digunakan di negara-negara maju selama bertahun-tahun lamanya dengan penambahan produk tambahan untuk mengurangkan penggunaan agregat di dalam pembinaan jalan raya. Baru-baru ini, Jabatan Kerja Raya Malaysia (JKR) telah melancarkan spesifikasi untuk campuran khusus dan rawatan permukaan, termasuklah asfalt berliang. Oleh itu, kajian ini dijalankan untuk menyiasat penggunaan jermang keluli sebagai pengganti agregat biasa di dalam campuran asfalt berliang. Dua penggredan asfalt berliang, yang ditetapkan sebagai Gred A dan Gred B, telah digunakan dalam kajian ini berdasarkan spesifikasi baru – JKR/SPJ/2008-S4. Jermang keluli telah dipilih kerana ciriannya agak sama dengan agregat berbanding dengan produk-produk tambahan yang lain seperti serdak getah, kaca dan banyak lagi. Telah diperhatikan bahawa agregat jermang keluli memenuhi semua kriteria spesifikasi JKR kecuali ujian penyerapan air. Sampel campuran agregat jermang keluli yang dihasilkan telah diuji terhadap modulus kebingkasan, pengeluman dan kebolehtelapan, yang kemudiannya dibandingkan dengan campuran agregat biasa. Keputusan menunjukkan bahawa terdapat perbezaan yang ketara dari segi modulus kebingkasan di antara campuran berasaskan agregat jermang keluli dan campuran berasaskan agregat biasa. Senario yang sama diperhatikan di dalam ujian pengeluman, di mana campuran agregat jermang keluli mempunyai rintangan pengeluman yang lebih tinggi. Walau bagaimanapun, campuran yang diperbuat daripada agregat biasa mempunyai nilai kebolehtelapan yang lebih tinggi berbanding dengan campuran jermang keluli. Dapat disimpulkan bahawa penggunaan jermang keluli dapat menanggung bebanan trafik yang tinggi dengan jayanya.

Kata kunci: Asfalt berliang; jermang keluli; modulus kebingkasan; pengeluman dan kebolehtelapan

1.0 INTRODUCTION

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 hot-mix asphalt (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) [1].

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 asphaltic concrete 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 [2]. 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 bitumen, has a low flakiness index, good mechanical properties and good anti-skid resistance [3]. Work done by various researchers has found that the addition of steel slag in HMA enhances the performance characteristics of pavement [4-6]. 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 [6-8]. Recently, the use of steel slag with stone mastic asphalt (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 [9].

It is well known that the biggest cause of pavement failure is water. A high annual rainfall of more than 2,000 mm per year is reported in Malaysia, often resulting in flooding [10]. Water allows moisture to seep through and saturate the gravel base, leaving the pavement vulnerable to heavier vehicles. As a result, roads tend to deteriorate faster. Subsequently, the use of porous asphalt mixtures becomes an alternative because of their efficiency during poor weather, which could be very beneficial particularly in Malaysia. Porous asphalt is described as a bituminous-bound mixture with selected grading and high-quality aggregates to provide a HMA with 20–25% air voids [11]. The national specifications for porous asphalt were first introduced in Malaysia in 2008 when the Public Works Department (PWD) launched the specifications on specialty mixes, including porous asphalt. Two porous asphalt gradations, designated as Grade A and Grade B in this study, are specified, and they differ in terms of their nominal maximum aggregate sizes, 10 mm and 14 mm respectively [11-12]. To improve the durability of pavement, the use of additives and modifiers (e.g. polymer) in 70/100 pen grade bitumen was introduced by the Malaysian PWD. Based on the new standard specifications, known as JKR/SPJ/2008-S4, this study was conducted to determine the feasibility of steel slag as an aggregate replacement in porous asphalt. The new porous asphalt grades were used in this study, designated as Grade A and Grade B. The experimental tests were conducted to evaluate the performance of these new grades in terms of resilient modulus, rutting and permeability.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials required to produce porous asphalt samples are steel slag aggregate, polymer modified asphalt (PG 76) and ordinary Portland cement, which acts as a filler. The aggregates were washed, dried and sieved into the selected range of sizes, according to the JKR/SPJ/2008-S4. Table 1 shows the basic properties of the crushed aggregate. This table shows that all aggregate properties satisfy the specification. Meanwhile, Figure 1 (a and b) show the gradation limit curves for both Grade A and Grade B of the porous asphalt mixtures. It was found that the design gradation limits fell inside the limits of the referred envelope. After the materials were proved to be suitable for the experimental work, samples of both Grade A and Grade B porous asphalt were prepared using steel aggregate as well as conventional aggregate. The steel slag aggregate, which was obtained from Purata Keuntungan Sdn Bhd, was sieved and graded based on size in accordance with the porous gradation of both Grade A and Grade B, as stated in JKR/SPJ/2008-S4. The weight of the steel slag aggregate required to produce one Marshall sample was 1100 g. This weight was chosen in order to produce a sample with a thickness of around 62–65 mm. Wash sieve analysis, specific gravity and theoretical maximum density (TMD) tests were also conducted. Although this study uses steel slag aggregate as a conventional aggregate replacement, samples made with conventional aggregate were also produced for the purpose of comparison with the steel slag aggregate-based mixtures. The conventional aggregate was obtained from Malaysian Rock Product (MRP) quarry; 950 g of conventional aggregate was required to produce one Marshall sample with a thickness of 62–65 mm.

2.2 Laboratory Compacted Specimen

Porous asphalt mixtures were compacted in the laboratory by means of the Marshall method, in accordance with ASTM D 1559. Since 75 compaction blows tend to break down the aggregate and do not cause a significant increase in density over that provided by 50 blows, previous researchers have suggested application of 50 blows per side of each mixture [13-14]. This is also in accordance with the specification of the JKR/SPJ/2008-S4 [11].

2.3 Resilient Modulus Test

Indirect tensile test for resilient modulus of bituminous mixtures was performed in accordance with ASTM D4123 – 82. Figure 2a shows the resilient modulus test set-up. According to this standard test, the specimens used should have a height of at least 51 m) and a minimum diameter of 102 mm for aggregate up to 25 mm maximum size, and a height of at least 76 mm and a minimum diameter of 152 mm for aggregate up to 38 mm maximum size. The specimens used in this study were Marshall samples which have average height of 70 mm and average diameter of 101.6 mm. Test was conducted at temperature of 25 and 40°C (± 1°C), at loading frequency of 0.5 and 1 Hz for each test temperature as well as load duration of 0.1 second. The test was conducted by applying compressive loads with a haversine waveform. The load was applied vertically in the vertical diametric plane of a cylindrical specimen. The resulting horizontal deformation of the specimen was measured and, with assumed Poisson's ratio was used to calculate a resilient modulus. For test temperature of 25 and 40°C Poisson's ratio was assumed 0.4. The values of vertical and horizontal deformation were measured by linear variable differential transducer (LVDTs). The total resilient modulus was calculated using the total recoverable deformation which includes both the instantaneous recoverable and the time dependent continuing recoverable deformation during the unloading and rest-period portion of one cycle.

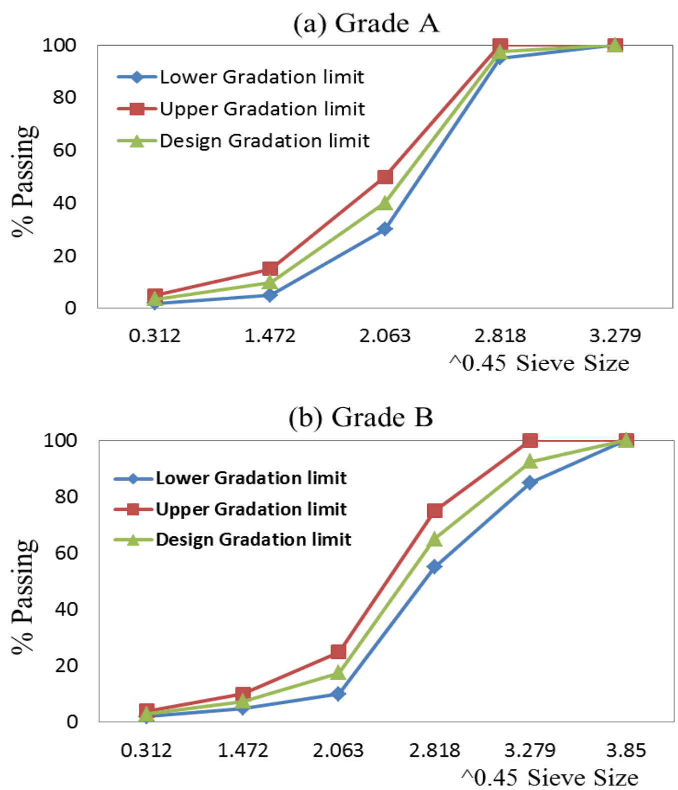


Figure 1 Gradation limits for (a) Grade A and (b) Grade B porous asphalts

2.4 Wheel Tracking Test (Rutting)

This test is conducted to evaluate the potential of rutting appear on the porous asphalt sample after they are loaded under moving wheel in order to simulate the moving traffic loads. Samples for this test were prepared for the steel slag samples with which the result obtained were compared to the conventional asphalt mixes as a control sample. Wessex S867 Wheel Tracking Machine was used to measure the rutting resistance (Figure 2b). This computerized machine met the requirements of both BS 598 and BS EN 12697-22 1999. Two samples for each mix were prepared for wheel tracking test. Before conducting the test, each sample was compacted using compaction hammer until the surface layer of the sample reach the desired level. The compacted sample was cooled at room temperature and extracted from the mould. Then percentage of air voids was checked within 22 ± 1% (ASTM D 3023) on each sample. If the sample achieve the target air voids, then it is dried first before proceed with wheel tracking test.

2.5 Permeability Test

Permeability, as shown in Figure 2c, is one of the most important characteristics of porous mixtures. This is because permeability is the most significant characteristic to differentiate porous asphalt from other types of mixture such as stone mastic asphalt and asphaltic concrete. Research by Hainin and Cooley [15] found that permeability is very much related with air void density. More air voids result in higher permeability. Although there is no specific permeability value provided in JKR/SPJ/2008-S4, it is recommended that the mixture should possess permeability greater than 0.116 cm sec^{-1} (100 m day^{-1}) to ensure the permeability of mixture [11]. In this study, a permeability test was performed with a falling head water permeameter.

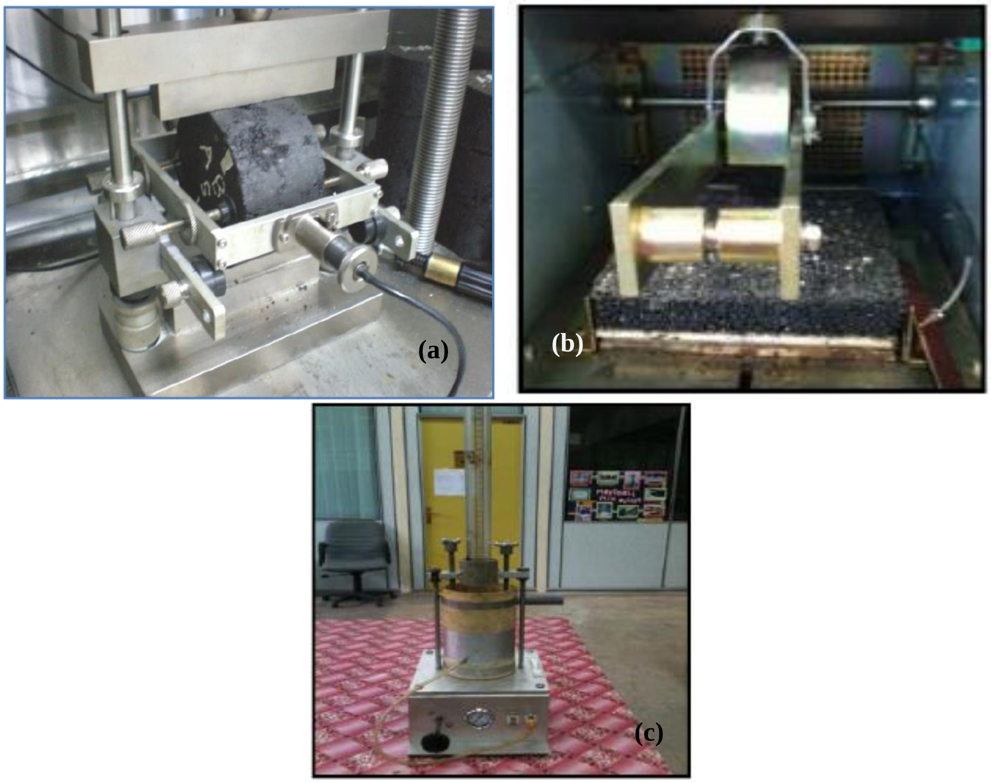


Figure 2 (a) resilent modulus test, (b) wheel tracker test and (c) permeability test

3.0 RESULTS AND DISCUSSION

3.1 Determination of Steel Slag Characteristic

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 porous asphalt mixtures. Based on the results, steel slag meets all the requirements established by the PWD except for water absorption. The water absorption of the steel was found to be more than 2%. 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.

Table 1 Steel slag aggregate testing results

Testing	Procedures	Conventional Aggregate	Steel Slag	Specification JKR/SPJ/2008
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 %	<25 %
Flakiness (Coarse, 20 mm)	BS812: Section 105.1: 1989	8%	2 %	<25 %
Flakiness (Coarse, 14 mm)	BS812: Section 105.1: 1989	9%	3 %	<25 %
Soundness	AASHTO: T 104-86	1.07%	2.07 %	<18 %
Polished Stone Value	BS 812: Part 14: 1989	50	54	>40
Absorption Grade A/Grade B	BS 812: Part 2: 1975	1.35	5.227 /5.088	< 2%
Stripping	AASHTO: T 182	>95	> 95	> 95

3.2 Washed Sieve Analysis

Washed sieve analysis was carried out to determine the quantity of filler (material passing through 75 µm) that should be used in the preparation of the Marshall sample. Ordinary Portland cement that passed through a 75 µm sieve was used as the filler. Details of the procedures used in this test can be found in ASTM C 117-90. Thus, only ordinary Portland cement was used as the filler. Table 2 shows the amount of dust after conducting the wash sieve analysis for the Marshall sample.

Table 2 Washed sieve analysis

Mixture	Percentage of dust (%)	
	Steel Slag Sample	Conventional Sample
Grade A	20.30	20.68
Grade B	18.10	18.96

3.3 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 3 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 3.

Table 3 Specific gravity of the materials used

Materials			Specific Gravity
Bitumen	PG 76		1.030
Fine aggregate	Grade A	Steel slag	2.846
		conventional	2.569
	Grade B	Steel slag	2.815
		conventional	2.576
Coarse aggregate	Grade A	Steel slag	2.775
		conventional	2.567
	Grade B	Steel slag	2.791
		conventional	2.573
Ordinary Portland Cement (OPC)			3.130

3.4 Theoretical Maximum Density (TMD)

The Theoretical Maximum Density (TMD) test is performed using the Rice Method based on the optimum bitumen content, as mentioned earlier. Each mixture is tested twice to verify the results obtained. 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 4 summarises the results of TMD at 5% for each type of mixture.

Table 4 Results from theoretical maximum density test

Types of mixture		SG maximum (G_{mm})	SG effective (G_{eff})
Grade A	Steel Slag	2.805	3.085
	Conventional	2.388	2.567
Grade B	Steel Slag	2.782	3.056
	Conventional	2.424	2.610

3.5 Optimum Bitumen Content (OBC)

The optimum bitumen content (OBC) is the most important criterion in preparing the sample, as any error in obtaining OBC will influence the result. The OBC values for the tested samples are shown in Table 5. It shows that the selected OBC 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 5 Optimum bitumen content (OBC)

Types of Mixture		OBC (%)
Grade A	Steel slag	5.5
	Conventional	4.5
Grade B	Steel slag	5.5
	Conventional	5.0

3.6 Resilient Modulus

The resilient modulus is an important parameter in determining the performance of pavement and to analyse pavement response to traffic loading. A resilient modulus of 1318.2 MPa for the steel slag porous Grade A was recorded, which is almost double the value recorded for the conventional porous Grade A at 25 °C of 683.7 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. At 40 °C, the trend is almost identical to the resilient modulus at 25 °C; the resilient modulus of the mixture containing steel slag is almost twice that of conventional aggregate at 463.0 MPa and 293.8 MPa respectively, as presented in Figure 3.

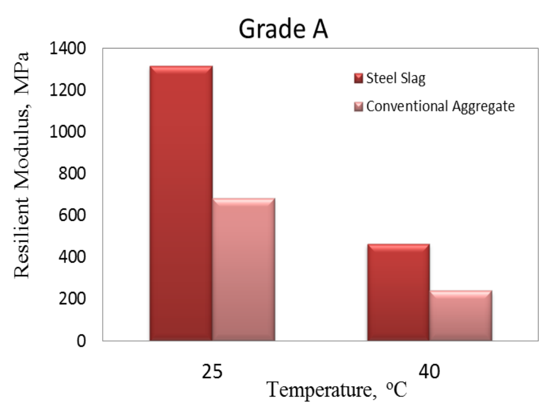


Figure 3 Resilient modulus of steel slag and conventional aggregate porous Grade A

Meanwhile for porous Grade B, as shown in Figure 4, the resilient moduli at 25 °C are 975.2 MPa and 726.2 MPa 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 Grade A at the same temperature. At 40 °C, the modified mixture also possesses a higher resilient modulus value of 463.5 MPa compared to 239.8 MPa for the unmodified mixture. This shows that at the higher temperature, the strength of the steel slag remains high.

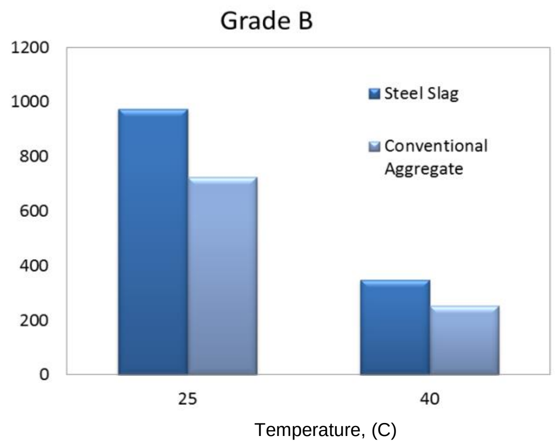


Figure 4 Resilient modulus of steel slag and conventional aggregate porous Grade B

Comparing both Grade A and Grade B 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]. The presence of higher bitumen content and roughness of steel slag aggregates, giving the modified mixtures higher resilience properties. This finding was in good agreement with the previous study done by Behnood and Ameri [14] for stone-mastic asphalt (SMA) mixtures.

3.7 Rutting Resistance

In porous asphalt Grade A, there is a significant difference in the rutting depth between conventional aggregate and steel slag aggregate. Figure 5 shows that the rutting depth of the conventional aggregate was 6.3 mm, while a rutting depth of only 2.0 mm was recorded for the steel slag aggregate, which means that the rutting depth of conventional aggregate is as much as three times higher than the steel slag aggregate. 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 bitumen and a low flakiness index [16]. The increase in rutting resistance may be attributable to the excellent angularity and friction angle of the steel slag, and the interlocking mechanism of aggregate gradation results in high shearing resistance [17].

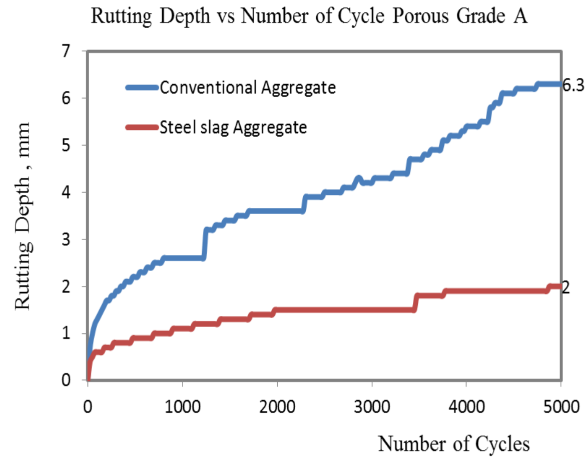


Figure 5 Rutting depth (mm) of porous Grade A

Rutting depth in porous Grade B also shows the same trend as in Grade A. The rutting depth of conventional aggregate was higher than for steel slag aggregate (Figure 6). The rutting depth of conventional aggregate is twice that of steel slag aggregate, at 7.2 mm and 3.6 mm respectively. A comparison between porous Grade A and Grade B shows that the rutting in Grade A is less than in Grade B. This result is because there is a smaller amount of fine aggregate in Grade B than Grade A; hence, the porous Grade B has a higher air void density. The presence of more air voids results in further compaction during testing, and hence increases rut depth. In general, the presence of steel slag aggregates improves the resilience to rutting compared to the conventional asphalt mixture. A similar finding was observed by Wang and Wang [18]. Based on the Asphalt Pavement Analyzer (APA) test results, the rutting resistant ability of the steel slag mixture is better than the granite mixture.

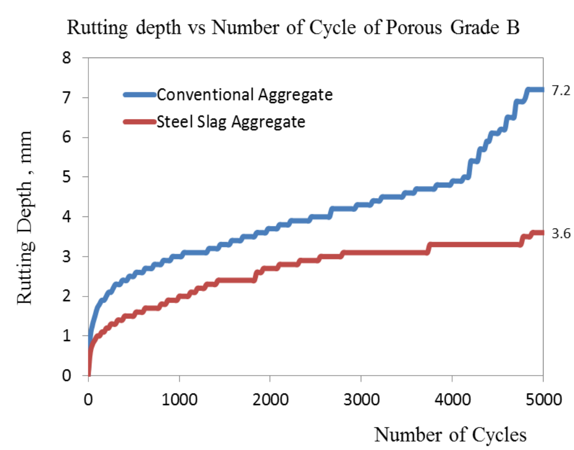


Figure 6 Rutting depth (mm) of porous Grade B

3.8 Permeability

The coefficients of permeability (k) are summarised in Table 6. The analysis of the results clearly shows that mixtures made with conventional aggregates possess a higher degree of permeability compared to those made with steel slag aggregate. Mixtures made with conventional aggregate had a permeability of 10870.5×10^{-5} cm/sec compared to 5127.6×10^{-5} cm/sec for mixtures made with steel slag aggregate. In Grade B, the trend of the results is similar to those of Grade A; permeability is higher for mixtures made with conventional aggregate than for those made with steel slag aggregate, at 11423.1×10^{-5} and 5925.2×10^{-5} cm/sec respectively. The results implies that the there is a reduction in the coefficient of permeability for both conventional and steel slag aggregates asphalt mixtures as the binder content increases [12]. The higher bitumen content for steel slag mixture could have caused blockage in the interconnected voids that resulted in lesser permeability as compared to conventional mixture.

Table 6 Coefficient of permeability

Types of mixture		Permeability, K ($\times10^{-5}$cm)
Grade A	Steel Slag	5127.6
	Conventional	10870.5
Grade B	Steel Slag	5925.2
	Conventional	11423.1

A comparison between Grade A and Grade B shows that Grade B has a higher permeability value. This is because porous Grade B has more voids due to the small amount of fine aggregate (filler). Since the amount of fine aggregate is lower than that in Grade A, the void inside the sample is filled less, hence allowing the water to move much more freely.

■4.0 CONCLUSIONS

Based on this study, several conclusions can be drawn:

- Steel slag aggregate meets all the requirements of aggregates that are to be used in road construction, such as in terms of strength and shape in accordance with PWD requirements. However, the value for water absorption of steel slag aggregate for both porous Grade A and Grade B exceeded the value established by PWD, which should be lower than 2.0%. This phenomenon is because steel slag possesses more pores, enhancing its tendency to absorb water.
- As for the performance evaluation, the resilient modulus test shows that mixtures containing steel slag aggregate have a higher value than those containing conventional aggregate. It can be concluded that steel slag could performed admirably during high traffic loading.
- Rutting depth also shows that steel slag would make a significant contribution to road durability. This is based on the fact that rutting depth was significantly lower for the steel slag-based mixture compared to the conventional aggregates mixture.
- Although the mixture containing steel slag aggregate had a lower permeability value compared to the conventional aggregate-based mixture, it is still possesses an acceptable value of permeability

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