Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(4):440-446

Development of Environmentally Sustainable Pavement Mix

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Abstract: Sustainable road construction is now one of the major interests of highway authorities. In this study, recycled material (steel slag aggregates) was used to replace granite aggregates in the construction of a porous pavement surface course. Besides using recycled aggregates, the asphalt mixture was designed to achieve improved environmental sustainability performance by providing enhanced wet-pavement skid resistance and visibility of road markings in wet weather conditions, and reduced tyre-pavement noise. Two new asphalt mix types using steel slag aggregate of different gradations (i.e. maximum aggregate size of 13.2 mm and 16 mm) were tested in the laboratory and the performance monitored on the site. From the results obtained from field monitoring tests, it was observed that the new asphalt mixes provided sufficient drainage of water, displayed comparable wet-pavement skid resistance and better reduction in tyre-pavement noise as compared with the other types of asphalt mix currently used in Singapore.

DOI:10.6135/ijprt.org.tw/2013.6(4).440

***Key words**: Porous mix; Skid resistance and permeability; Steel slag aggregates; Tyre-pavement noise.*

Introduction

Sustainable road construction has become the interest of highway authorities in recent years. In this study, steel slag aggregates were used in place of normal granite aggregate in the design of environmentally friendly mix. Steel slag is a by-product of steel making process and an industry waste. The steel slag used in this study is produced from the steelmaking process in an electric arc furnace (EAF). The use of steel slag aggregate in the asphalt mix can improve the strength, durability and skid resistance of the mix. In addition, the use of steel slag in road construction will reduce the waste for landfills and thus enhance the conservation of natural resources by promoting the sustainable road construction industry [1-4]. The main objective of this study is to develop an asphalt mix with improved environmental sustainability having low tyre-pavement noise, and good skid resistance and good pavement marking visibility on rainy days. Mix designs with air voids content higher than 10% are known to be effective in absorbing tyre-pavement interaction noise. In addition, mix with high voids content allows water to flow through the continuous voids in the mix and reduces surface flow on pavement, thereby helping to maintain sufficient skid resistance and enhancing the visibility of road markings during rainy days. However, high voids content in the mix leads to lesser tyre and pavement contact area, which could result in lower available skid resistance of the pavement. Therefore, a balanced design must be developed to achieve adequate wet-weather skid resistance. In this study, porous mixes with designed air voids content of approximately 15% were developed by compromising between noise reduction in dry weather and wet weather driving benefits.

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Note: Submitted January 31, 2013; Revised June 25, 2013; Accepted June 26, 2013.

Materials

Aggregates

Steel slag aggregates used in this study were supplied by NSL Chemicals Ltd and the properties of the steel slag aggregates are shown in Table 1. As shown in Table 1, the physical properties of steel slag aggregates met the requirements of the Land Transport Authority, Singapore (LTA) for Porous Asphalt/Open Graded Asphalt except for the Los Angeles Abrasion Value. The frictional and polishing properties of steel slag aggregates were also measured by performing the skid resistance test using the British Pendulum Tester and the PSV test as per ASTM E303-93 (2008) and BS812-114 (1989), respectively. Similarly, the frictional and polishing properties of granite aggregates were measured as a standard aggregate. Skid resistance tests for both granite and steel slag aggregates were performed in dry and wet conditions and the results are summarised in Table 2. It was observed from the experimental results that the frictional and polishing properties of steel slag aggregates were observed to be better than that of granite aggregates.

Table 1. Physical Properties of Steel Slag Aggregates.

Property	Results	LTA requirement for Porous Asphalt/Open Graded Asphalt [5]
Los Angeles Abrasion Value (500 revolutions)	23%	Not more than 20%
Magnesium Sulfate Soundness	1.90%	NA.
Elongation Index	7%	Not more than 30%
Flakiness Index	16%	Not more than 25%
Impact Value	21%	Not more than 25%
Crushing Value	21%	Not more than 25%

Table 2. Frictional and Polishing Properties of Granite and Steel Slag Aggregates.

Aggregate type	BPN		PSV
	Dry	Wet	
Granite	51	41	35
Steel slag	58	48	42

Table 3. Properties of Shell Cariphalte PG76

Property	Value	Specification
High Temperature Grade	PG 76 Minimum	AASHTO-TP5
Flash Point	> 230 ˚C	ASTM D92-90
Dynamic Viscosity at 135 ˚C	< 3 Pa.s	ASTM D4402
G*/sinδ at 76 ˚C	> 1.0 kPa	AASHTO-TP5
Loss of Mass after RTFOT	< 1.0%	ASTM D2872
G*/sinδ at 76 ˚C After RTFOT	> 2.2 kPa	AASHTO-TP5

Asphalt Binders

Two types of binders i.e. the Penetration Grade 60/70 asphalt binder (PEN 60/70) and a polymer modified binder (PMB) were considered and tested for comparison in this study. PEN 60/70 is a normal bitumen commonly used for dense wearing surface mix known as W3B wearing course and its softening point is between 50-56˚C. PMB is manufactured by Shell and the specific grade adopted for this study is Shell Cariphalte PG76 which has a high service temperature of 76˚C. The technical specifications of Shell Cariphalte PG76 are summarised in Table 3.

Laboratory Tests and Experimental Procedure

Laboratory tests such as Marshall Stability tests, immersion wheel tracking tests and moisture susceptibility tests were firstly performed to determine the mix design for this study. Different types of mix with different gradations (i.e. gradations with top size aggregates of 19 mm, 16 mm and 13.2mm) using the normal penetration grade and polymer modified binder respectively were tested in the laboratory. The oven dried density of steel slag aggregate ranged from 3.414 g/cm3 to 3.450 g/cm3 for all three gradations. The bulk density of the asphalt mix samples using coarse gradation (i.e. top size aggregate of 19 and 16 mm) varied from 2.50 g/cm3 to 2.60 g/cm3 and that using fine gradation (i.e. top size aggregate of 13.2 mm) varied from 2.66 g/cm3 to 2.73 g/cm3. In addition, a traditional dense-graded mix W3B used in Singapore was also tested as a standard mix for comparison. Based on the laboratory results, two mixes with top size aggregates of 16 mm and 13.2 mm using polymer modified binder were selected for field trial together with the two porous mixes used in Singapore which are Drainage mix and open-graded wearing course (OGW).

Experimental Procedure

For the wheel tracking test, the following experimental procedure was adopted.

- Two tracks of each mix were tested. Three blocks of sample were inserted into a long steel mould to form a wheel track. The bottom surfaces of the 3 samples were levelled by inserting a thin sheet of aluminum below the samples at required positions.
- The samples were heated with a water batch for 3-5 hours to allow the sample to reach a constant and uniform temperature of 60 ℃.
- Two rubber tyre wheels of 200mm diameter with a base width of 45 mm were used to roll on the specimens. A total of 19. 813 (kg) steel weights were added to each extension arm of the wheels to achieve a pressure of 690 (kPa). The speed of the wheel was set to 40 passes per minute.
- The test was carried out until either one of the following failure criteria was reached: (a) rut depth exceeds 20 mm, or (b) the number of wheel passes reaches 5000.

For indirect tensile test, the following experimental procedure for water immersion treatment was adopted before measuring the indirect tensile strength of the mix.

- Six Marshall samples were prepared for each mix type, and indirect tensile test was adopted to evaluate the moisture susceptibility of the mixtures.
- For each mix type, three samples were tested for their indirect tensile strength without water immersion treatment, while the other three samples were tested after water immersion treatment.
- In the water immersion treatment, test samples were submerged in a water bath at 60℃ for 24 hours, followed by drying at room temperature for 1 hour before the indirect tensile strength test was conducted on the sample.

Equipment Used for Field Monitoring

The following equipment was used for field monitoring and they can be listed as:

- SCRIM machine for measurement of skid resistance in terms of Sideway-force Coefficient (SFC)
- Laser profiler for measurement of riding quality in terms of International Roughness Index (IRI)
- On-board Sound Intensity (OBSI) for measurement of noise generated from tyre-pavement interaction
- NUS K-permeameter for measurement of permeability

Fig. 1 shows the pictures of the equipment used in this study to monitor the performance of mixes on site.

Results and Discussions

Laboratory Results.

Marshall Stability Tests

Experiments were performed for the samples with top size aggregates of 19 mm, 16 mm and 13.2 mm respectively, using the normal penetration grade and polymer modified binder and the samples are denoted as AN and AP, respectively, in which A represents the size of maximum aggregate used and N and P represent the normal penetration grade and polymer modified bitumen, respectively. Fig. 2 shows the gradations of the samples with different top size aggregates. Table 4 summaries the average

(a) SCRIM machine for measurement of SFC

(b) Laser Profiler for measurement of IRI

(c) OBSI configuration for measurement of tyre-pavement noise

(d) NUS k-permeameter for measurement of permeability

Fig. 1. Equipment Used for Field Monitoring for Different Types of Mix.

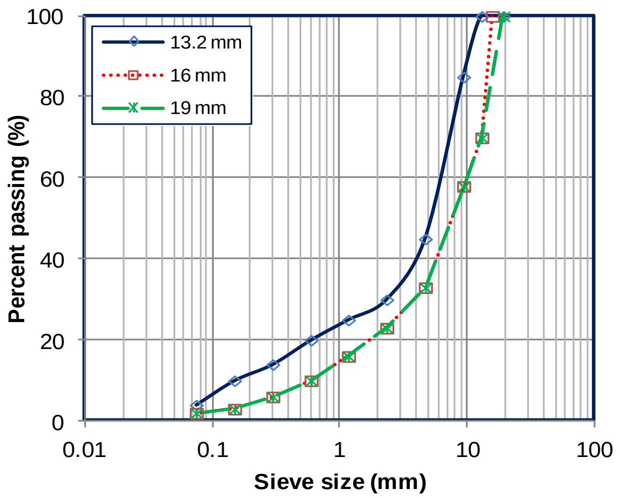


Fig. 2. Gradations Used in this Study.

optimum binder content, % air voids, Marshall Stability, Marshall Flow and Marshall Quotient of each tested sample. For dense mix, LTA requirement for Marshall Stability is 9 kN and flow value ranges from 2 to 4 mm [5]. From the experiments, it was observed that samples using polymer modified binder generally produced higher Marshall Stability as compared to the ones using normal penetration grade binder especially for the coarser gradations (i.e. 16 and 19 mm). This observation agreed well with the observation made in the earlier studies in which it was reported that the modified binder is more appropriate for porous mix with coarser gradations [6,7,8]. It was also noted that the flow values of all the tested samples marginally exceeded the requirement mentioned in LTA Materials and Workmanship Specification. Percent air voids is the main design criteria for the proposed mix and therefore binder contents of 5.5 % was used for the samples with the top size aggregates of 16 mm and 19 mm and 4.5 % was used for the

Table 4. Summary of Optimum Binder Content, %Air Voids, Marshall Stability, Marshall Flow and Marshall Quotient.

Mix Type	Optimum Binder Content (%)	% Air Voids	Marshall Stability (kN)	Marshall Flow (mm)	Marshall Quotient (MQ)
19.0N	5.5	16.47	10.58	4.8	2.19
19.0P	5.5	15.16	14.05	7.1	1.98
16.0N	5.5	16.32	7.8	6.6	1.18
16.0P	5.5	15.5	13.24	3.4	3.89
13.2N	4.5	14.42	14.36	4	3.59
13.2P	4.5	12.14	15.25	4.9	3.13

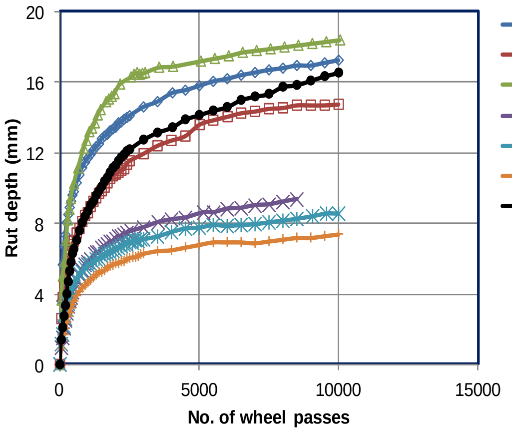


Fig. 3. Comparison of Rut Depth of the Samples Using PEN 60/70 and PMB.

Table 5. Summary of Rut Depth for Different Types of Mix at 5000 Wheel Passes.

Mix Type	Rut depth @ 5000 wheel passes (mm)
19.5P	6.80
16.0P	7.75
13.2P	8.60
19.5N	17.20
16.0N	13.60
13.2N	15.80
W3B	14.15

(a) Sample using normal binder (b) Sample using PMB (c) W3B mix

Fig. 4. Wheel Tracking Samples After Test.

Table 6. Summary of Indirect Tensile Strength Tests.

Mix Type	Indirect Tensile Strength- Dry (MPa)	Indirect Tensile Strength- Wet (MPa)	ITSR
19N	0.56	0.35	62.80%
16N	0.51	0.28	56.10%
13N	0.64	0.50	77.70%
19P	0.67	0.45	67.50%
16P	0.62	0.43	68.80%
13P	0.88	0.65	73.90%
W3B	0.80	0.52	64.30%

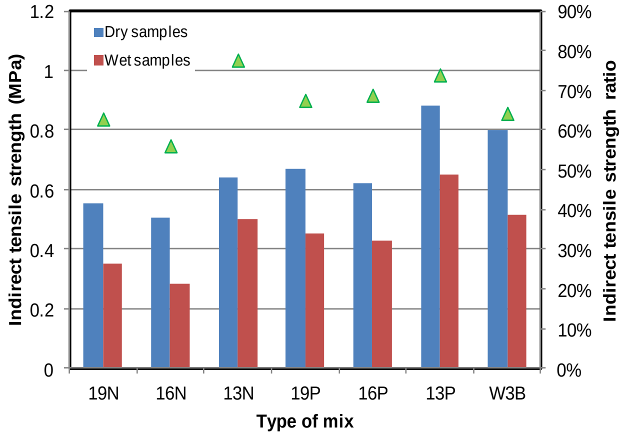


Fig. 5. Indirect Tensile Strength and ITSR of all Tested Samples.

samples with the top size aggregate of 13.2 mm to achieve air voids of 15 % and 13%, respectively.

Immersion Wheel Tracking Test

The experimental results for all the samples are plotted in Fig. 3 and W3B sample was tested as the standard sample for comparison. As shown in Fig. 3, permanent deformation of the sample or rut depth increased with the number of wheel passes. It was noted from the experimental results that the rut depth of all samples after 5000 wheel passes did not exceed the failure criteria (i.e. rut depth = 20 mm). In addition, it was observed that the samples prepared using the polymer modified binder produced lesser deformation than that using the normal binder. The values of rut depth at 5000 wheel passes are summarised in Table 5. Fig.4 shows the pictures of the samples taken after the wheel tracking tests for the samples prepared using the normal penetration grade and polymer modified binder and the standard W3B sample.

Moisture Susceptibility by Water Immersion Test

Dry and wet indirect tensile strength of all samples are summarised in Table 6. Indirect tensile strength ratio (ITSR) was calculated as the ratio of wet indirect tensile strength to dry indirect tensile strength. The values of ITSR are plotted together with the dry and wet indirect tensile strength in Fig. 5. It was observed that the values of ITSR for the samples using modified binder are generally higher than that using normal penetration grade binder.

Field Monitoring Results

Based on the experimental results, the two mixes 13P and 16P were selected for the field trial together with the other types of mix used in Singapore (OGW and Drainage mix) as the control sections. These four types of mix were laid on site in series as shown in Fig. 6. The length of test section for each mix was selected as 178 m to provide sufficient travel distance for OBSI measurement. The performance of these asphalt mixes were monitored in terms of tyre-pavement noise, skid resistance, riding quality and

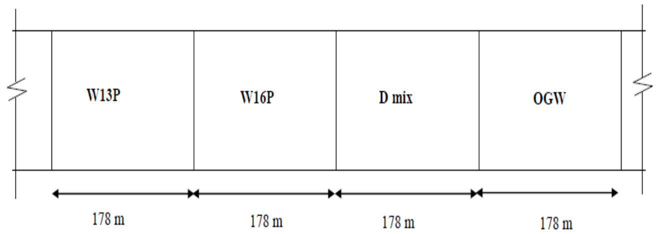


Fig. 6. Schematic Layout of the Mixes at the Trial Site.

permeability. The results are discussed in detail in the following sections.

Tyre-pavement Noise

On-board sound intensity method was used to measure the tyre-pavement noise. The OBSI configuration used in this study consists of two microphones as shown in Fig. 1(c). These microphones are attached as close as possible to the tyre and pavement contact point to eliminate the environmental noise. Tests were carried out periodically to monitor changes in noise level with time. Measurements were also carried out using different speed to investigate the effect of speed on noise intensity level for different types of mix. A typical relationship of tyre-pavement noise with speed is presented in Fig. 7. This figure shows that the rate of change of noise decreased with increasing speed for all types of mix. Fig. 8 shows the results measured at different speeds on different days. By comparing the results, it was observed that the values of tyre-pavement noise of OGW and D mix are generally higher than that of W13P and W16P by approximately 2 (dBA). From visual

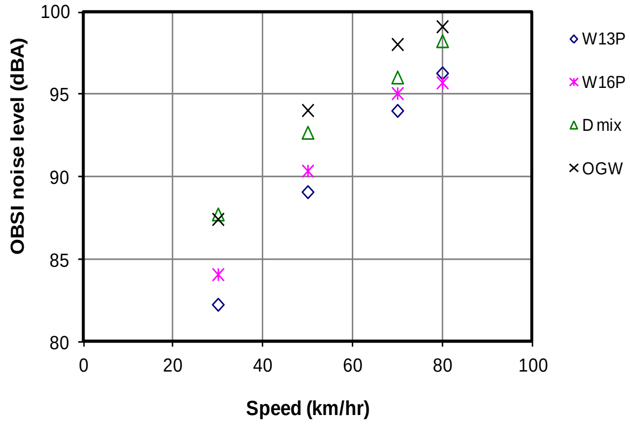
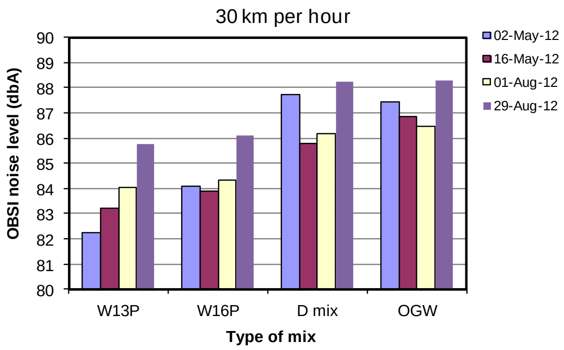


Fig. 7. Typical Relationship of Noise Intensity with Speed.

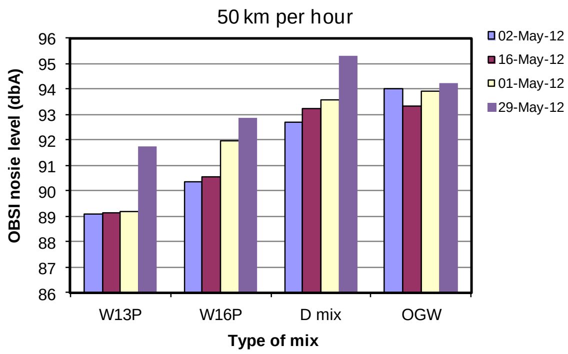
inspections, the surface textures of OGW and D mix are rougher than that of W13P and W16P (Fig. 9). It was expected that this lower noise generation from W13P and W16P is attributed to the smaller macro texture and the smaller top size aggregates used in the mix. In addition it was observed that the high air voids content of the mix (i.e. D mix which has air voids content ranging from 20-25%) did not significantly affect the reduction in tyre-pavement noise.

Skid Resistance

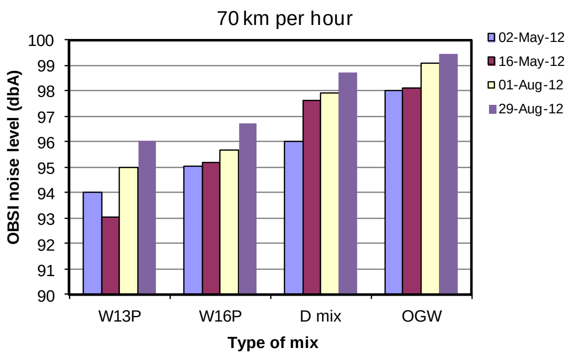
The skid resistance for different types of mixes was monitored using



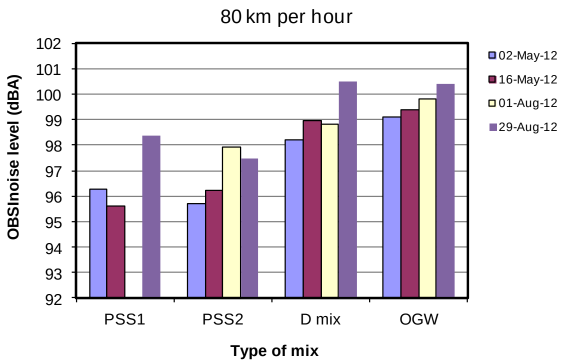
(a)



(b)



(c)



(d)

Fig. 8. Comparison of Tyre-pavement Noise for Different Types of Mix.

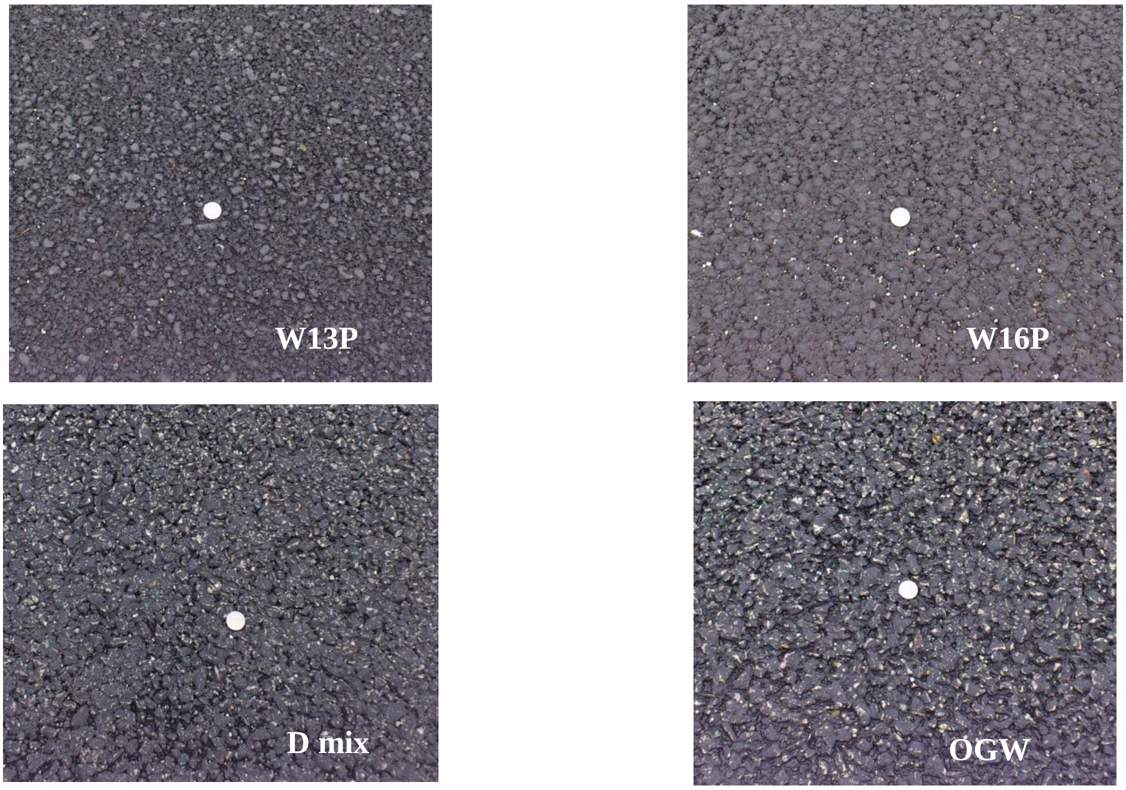


Fig. 9. Surface Texture of Different Types of Mix.

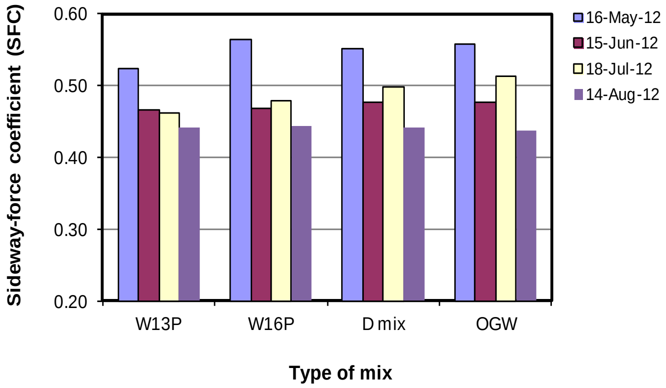


Fig. 10. Comparison of SFC for Different Types of Mix.

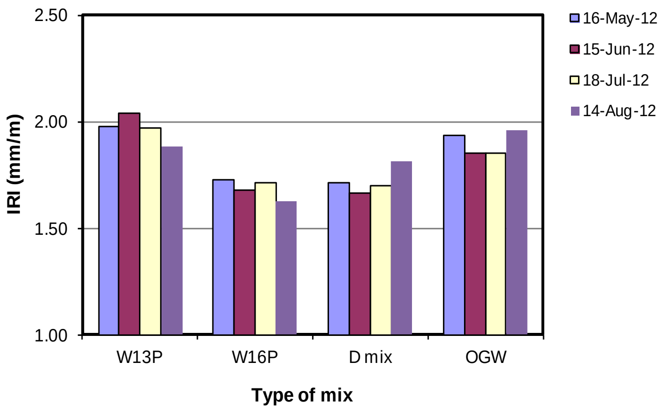


Fig. 11. Comparison of IRI for Different Types of Mix.

the SCRIM [Fig.1(a)]. Measurements were performed at different time intervals and the results obtained from the different mixes are plotted in Fig. 10. As shown in Fig.10, similar skid resistance values were obtained for different types of mix. Steel slag aggregates were used for the mixes (W13P and W16P) to enhance the skid resistance. However, high PSV of steel slag aggregate did not significantly provide higher skid resistance as expected.

Riding Quality

The riding quality was measured in terms of IRI using a laser profiler [Fig.1(b)]. Fig. 11 shows the results obtained from the four types of mix. It was noted that the values of IRI for all the mixes are less than 2 mm/m and the results obtained from W16P and D mix were found to be better than the other two mixes.

Permeability

Permeability tests were carried out by using the NUS K-permeameter [Fig.1(d)] for all four types of mixes. A total of 9 permeability tests were carried out at different locations along the section of each mix and the test points were staggered evenly along the section. The measured permeability results for all mixes together with the average permeability values are presented in Fig. 12. It was noted that the values of permeability varied with test locations and the average permeability values of the mix can be arranged in the following decreasing order: D mix, OGW, W16P and W13P.

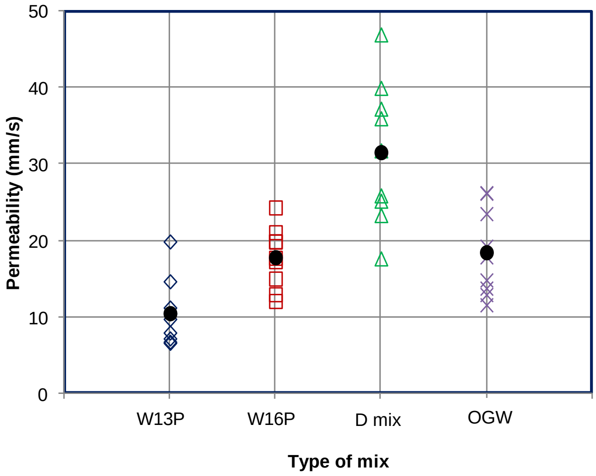


Fig. 12. Comparison of Permeability for Different Types of Mix.

Permeability measured by the NUS K-permeameter includes the flow through the air voids of the premix as well as the horizontal flow on the surface [9]. Substantial horizontal flow on the surface was observed during the measurements. It was expected that the values of permeability measured on site were significantly affected by the horizontal flow on the surface rather than the air voids in the mix.

Conclusions

Two environmentally friendly asphalt mixes (W13P and W16P) were developed using steel slag aggregates. Laboratory tests were performed to confirm the stability of the design mixes. Field monitoring tests were carried out periodically to investigate the performance of W13P and W16P as compared with the other types of asphalt mix commonly used in Singapore (i.e. D mix and OGW). The following conclusions can be made based on the results obtained within a 4-month monitoring period after laying of the mixes.

- From the OBSI measurement, it was observed that the values of tyre-pavement noise of W13P and W16P were lower than that of D mix and OGW by approximately 2 (dBA).
- The skid resistance of W13P and W16P were observed to be the same as that of D mix and OGW. It is expected that conclusive findings could not be obtained based on the results measured within the 4-month monitoring period. Therefore, the skid resistance will be monitored over a longer period to better understand the effect of PSV of steel slag aggregates on the skid resistance.
- The values of IRI for all four mixes (W13P, W16P, D mix and OGW) were obtained to be lower than 2 mm/m. Based on the field monitoring results, the riding quality of W16P and D mix were observed to be better than that of W13P and OGW.
- From the permeability tests, the highest and lowest permeability values were obtained for D mix and W13P, respectively and similar permeability values were obtained for W16P and OGW. It was noted from the field measurements that the surface texture of the mixes significantly affected the values of permeability.

Acknowledgments

The authors would like to thank A/Prof. Chew Chye Heng from the National University of Singapore for the advice given for the development of OBSI instrument used in this study. The assistance provided by NSL Chemicals Ltd for the laboratory tests and supply of steel slag aggregates for this study is also deeply appreciated.

References

1. Kehagia, F. (2009). Skid resistance performance of asphalt wearing courses with electric arc furnace slag aggregates. *Waste Management and Research*, 27, pp. 288-294.
2. Motz, H., Geiseler, J. (2001). Products of steel slags an opportunity to save natural resources. *Waste Management*, 21, pp. 285-293.
3. Huang, Y., Bird, R.N., and Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements, *Resources, Conservation and Recycling*, 52(1), pp. 58–73.
4. Wang, G. and Thompson, M. (2011). Slag Use in Highway Construction - the Philosophy and Technology of its Utilization, *International Journal of Pavement Research and Technology*, 4(2), pp. 97–103.
5. Rail & Engineering Groups, Land Transport Authority, Singapore (2010). Materials & Workmanship Specification for Civil & Structural Works, Singapore.
6. Suresha, S.N., Varghese, G., Ravi Shankar, A.U. (2009). A comparative study on properties of porous friction course mixes with neat bitumen and modified binders. *Construction and Building Materials*, 23, pp. 1211-1217.
7. Becker, Y., Méndez M.P., and Rodríguez, Y. (2001). Polymer modified asphalt. *Vision Technologica*, 9, pp.39-49.
8. Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials*, 21, pp. 66-72.
9. Tan, S.A., Fwa, T.F., and Chuai, C.T. (1999). Automatic field permeameter for drainage properties of porous asphalt mixes. *Journal of Testing and Evaluation*, 27(1), pp. 57-62.