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17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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PERFORMANCE EVALUATION OF VOID-FREE ASPHALT CONCRETE FOR HEAVY DUTY PAVEMENT

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Abstract

There are some places such as bridges in the heavily industrialized area where the pavement should have a strong resistance against heavy axle loading and waterproof function. In those places, many polymer-modified asphalt (PMA) pavements were applied to protect premature cracking, severe rutting and water intrusion without success. This study evaluated important properties of the special type asphalt concrete (AC) mix which is highly condensed to be almost void-free condition developed for those places. A PMA binder (PG82-34) was used for the mix at target air void of 0 % in the mix design. The strength against deformation (S_D) was measured by Kim Test at 60 °C. The flexural strength and fracture toughness were measured at -20 °C, and the resistance against reflection cracking at 25 °C. The void-free AC mix showed best performance in all four properties. Therefore, the void-free AC can be applied for heavy duty bridge pavement where waterproofing function and higher rutting and cracking resistance are required.

Keywords: polymer-modified asphalt, SIS, deformation strength, tensile strength, fracture toughness

1 Introduction

The primary merit of using asphalt mixture for roadway pavement is superior riding quality provided from the flexible nature of asphaltic material. However, the asphalt concrete (AC) pavement with plain asphalt is not strong enough to sustain heavy vehicle loading. Therefore, many polymer-modified asphalt (PMA) binders are used for securing better resistance against heavy axle loading. In general, the dense-graded asphalt (DGA) mixture for surface course of AC pavement is prepared with 4 % air voids at the mix-design stage because the 4 % is a design criterion in most cases. However, some mixes, such as stone-mastic asphalt (SMA), which was prepared with 2~3 % void, perform durably without rutting.

If the asphalt mix with almost 0 % air void is applied to the bridge deck pavement, it will be advantageous especially for waterproofing purpose as long as it is stable under heavy wheel loadings. Therefore, a special type mix was developed using a PMA binder of styrene-isoprene-styrene (SIS) as the primary modifier. This mix was compacted to 0 % air void ratio to withstand water intrusion through the pavement without premature damages, such as rutting and cracking.

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The objective of this study is to show the evaluated results of deformation and cracking related properties of the void-free AC mix. The void-free mix was prepared with the PG82-34 binder and the tested values were compared with the normal DGA and PMA SMA mixes.

2 Materials and Methods

2.1 Materials

A base asphalt of PG64-22 was used for DGA mix and as base asphalt of the PMA (PG82-34) binder. The performance grade of 82-34 was achieved by using mainly SIS and some other modifiers. An aggregate gradation was developed by modifying the original SMA gradation of Korea Expressway Corporation. The modification was made by adding higher contents of mineral filler and fiber to accommodate the high content of binder, as shown in Figure 1. The designation of mix, which was designed to be compacted to a zero-void state, is GKMA, which was named after developer Institute, GK (Table 1).

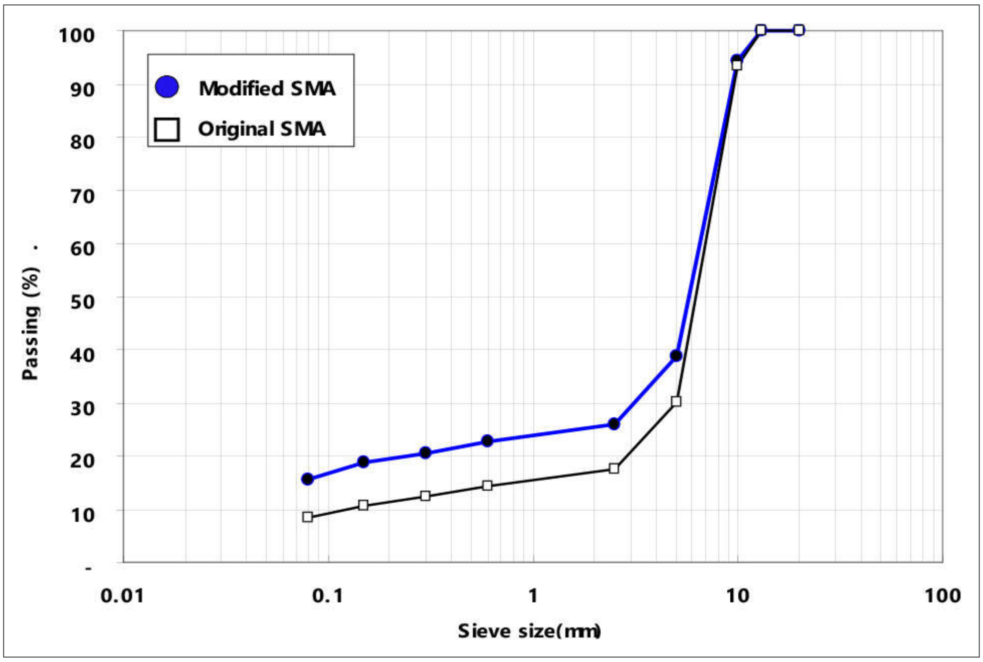

Figure 1 Two aggregate gradations used in this study

Table 1 Three mixtures used in this study

Gradation	Binder	Designation	Max agg. Size	Target air voids
DGA	PG64-22	WC-1	13 mm	4 %
SMA	PG76-22	PSMA	10 mm	3 %
SMA	PG82-34	GSMA	10 mm	2 %
Modified SMA	PG82-34	GKMA	10 mm	0 %

The GKMA mix was developed to use on the heavy-duty bridge pavement, having combined functions of the heavy duty pavement as well as the waterproofing membrane or coating together. Two SMA mixes with 10mm max-size aggregate were prepared using PG76-22 and PG82-34 binders, respectively, in addition to GKMA mix for comparison purpose, as shown in Table 1. The optimum binder content (OBC) was determined at 0 % air void in the mix design of GKMA. However, the OBC was determined at the air voids of 3 % and 2 % for the PSMA and GSMA, respectively, as shown in Table 1.

2.2 Test Methods

2.2.1 Deformation Strength (S_D)

The S_D was developed as a measure of resistance against deformation due to compression and shear pressure applied by the loading head (LH) in Figure 2 (a). The idea behind this is to create simple rutting mechanism inducing a concaved form of rut on the surface of AC specimen using the LH at 60 °C. Applying load through LH is an imitation of a tire loading, which has circular tire imprint. The test is called by the name of Kim Test after developer's last name [1-3].
A round-edge with 10mm radius (r) was made around the bottom of steel LH (40 mm diameter: D). Therefore, it has a flat circular face center (20 mm diameter) and a round edge around at bottom. The LH contour creates a compression vertically and shear pressure laterally causing a round rut when LH is pressed down at 30 mm/min (Figure 2). Therefore, the S_D is resistance against a kind of bearing stress, for which load (P) is divided by the top area of concave varying by vertical depth (ν) of deformation.

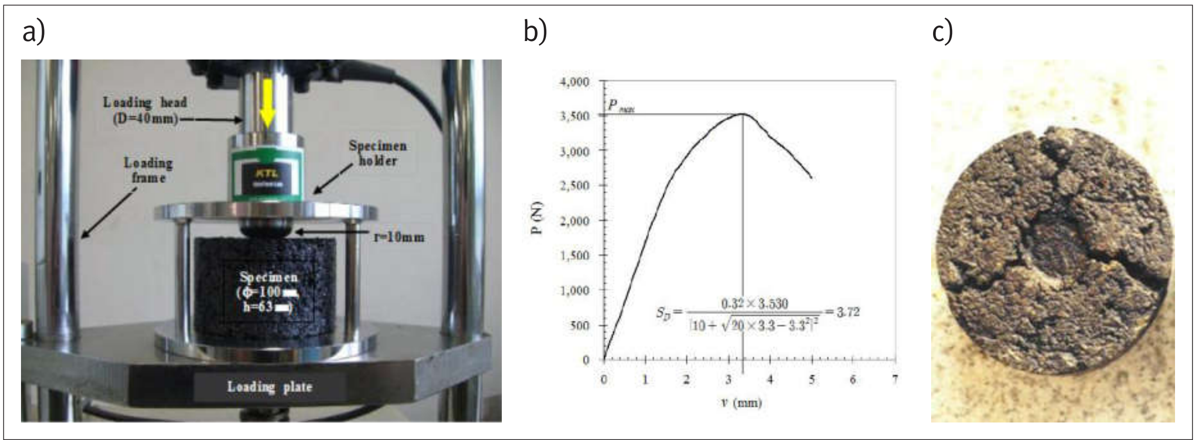

Figure 2 Illustration of a) S_D test setting, b) P-v curve and c) failure mode

Figure 2b shows a load-deformation (P-ν) curve from the test of specimen failed (Figure 2c). P_{max} and the vertical deformation ν at P_{max} were obtained from the curve and the S_D was computed using Eq. (1). The eq. was developed from the basic stress (σ) function of $\sigma = P_{max}/A$, in which the A, projected circle area of the concave (rut), was calculated using the circle diameter (d) on the surface. The diameter at surface which is function of the LH diameter (D), the rut depth ν and the r was used for determining the area of circle ($A = \pi d^2/4$). Since D = 40 mm and r = 10 mm were already selected as the standard LH dimension, the A is determined by the d which is a function of only vertical deformation, ν, for each test Since d is function of ν, the deeper the ν, the larger the d, resulting in the greater A.

$$S_D = \frac{0.32P}{\left(10 + \sqrt{20v - v^2}\right)^2} \tag{1}$$

Where:
S_D – deformation strength (MPa);
P_{max} – peak load (N);
ν – vertical deformation (mm) at P_{max}.

To heat up the specimen, it was submerged in the 60°C water for 30 min before being placed in test holder (Figure 2a). The 100 mm-diameter specimen was used in this test, but 150 mm specimen can be also used. Since the S_D was proved to show a great correlation with rut resistance [1,2,3], it was adopted as a criterion in place of Marshall Stability and Flow in Korean Guide [4].

2.2.2 Modulus of Rupture (MR) and Fracture Toughness

Asphalt concrete slab specimen (300×300×50 mm) was prepared at OBC, using a roller-press compactor, and cut into 3 pieces for 3 replications of flexural strength or MR testing. The MR value was obtained in a 3-point bending (3PB) test under vertical loading speed of 3 mm/min. The beam size of MR test was 50mm in depth,100mm in width and 300 mm in length with the span length (S) of 200 mm.
The fracture toughness was measured for prediction of crack resistance of asphalt concrete [5]. The toughness is represented by the area under the P-ν curve, as shown in Figure 3. The area under the curve was computed by Eq. (2), as shown in Figure 3. The area computed by Eq. 2 was designated as the pseudo fracture toughness (PFT) in this study.

$$PFT = \sum_{i=1}^{n} \frac{P_i + P_{i+1}}{2} \left(v_{i+1} - v_i \right) = \sum_{i=1}^{n} P_{i_{avg}} \Delta v \tag{2}$$

Where:
PFT – pseudo fracture toughness [Nmm];
P_i – load [N];
n_i – deflection at P_i [mm];
$\Delta\nu$ – unit deflection [mm].

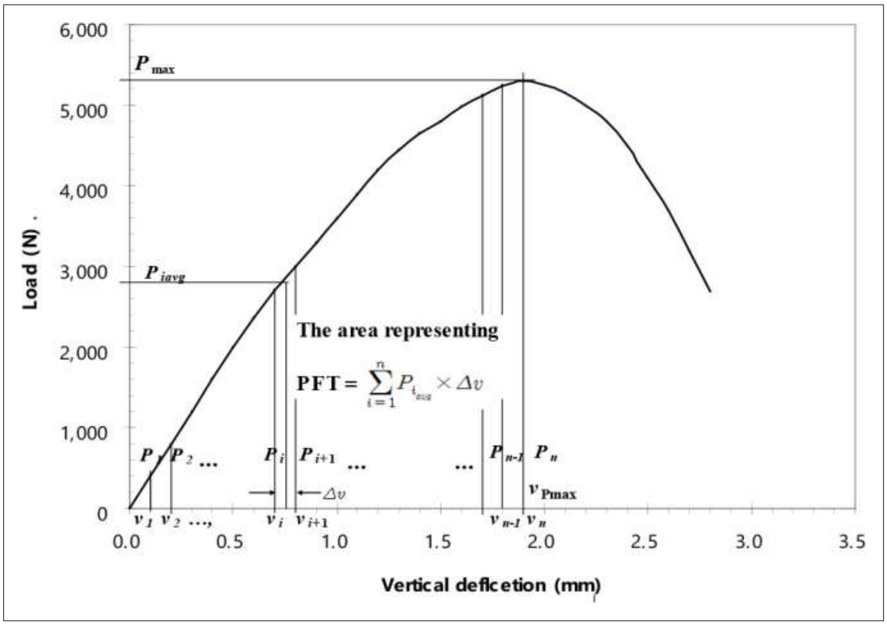

Figure 3 Schematic illustration showing calculation of PFT

2.2.3 Reflection Cracking Resistance

The mixed mode (mode I and mode II combined) reflection cracking resistance was measured by a simulated wheel moving on top of the asphalt pavement overlaid on top of concrete joint (gap) at ambient-temperature (25 °C) [6, 7]. The 1 kN of wheel load was moving back and forth at 0.5 Hz with the stroke of 200 mm on top of two steel plates placed between wheel and AC beam. The wheel material is steel with diameter of 200 mm and width of 50 mm.
A test body was made by placing two concrete blocks (30 mm depth), 20 mm apart, on top of elastic pad (10 mm thickness), applying tack coating on top of concrete blocks and placing (bonding) the AC beam on top of the two concrete blocks, as shown in Figure 4. The length, depth and width of AC beam were 300, 50 and 80 mm, respectively. The growing crack length was measured every 500 cycles from the front side of the AC beam, painted with white color.

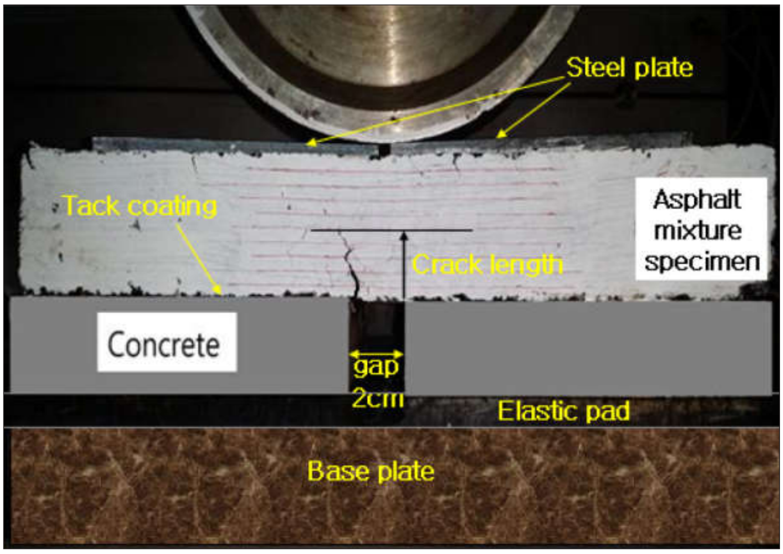

Figure 4 Illustration of test body for mode II reflection cracking test

3 Results and Discussion

The optimum binder content (OBC) by mix design, air void ratio and S_D for each mix are shown in Table 2. For GKMA mix, the 9 % of binder was required to achieve near 0 % of air void ratio. The S_D of 3.23 MPa for normal dense-graded asphalt (NDGA) mix was slightly passed the limit of 3.2 MPa for the AC mix of secondary class roadway pavement by Korean Specification. The S_D of 4.45 MPa from GKMA was above the minimum of 4.25 MPa for the mix of 1st class highway pavement. Therefore, GKMA mix is strong enough to perform properly at high temperature condition despite very high binder content (9 %). It was also shown that GKMA withstood 8.1mm of deformation before failure under the highest load level (5,465 N) than any other mixes. This implies that the material has the nature which will tolerate the higher strain before failure under very high stress condition.
It is noticeable that the 5,465 N of load was almost twice that of NDGA (1.95 = 5,465/2,809), but the S_D is 4.45 MPa with S_D ratio of only 1.38. Since the deformation (ν) is included in the denominator of S_D equation, the S_D is not as high as P, a mere measure of ultimate load, like Marshall Stability. The S_D is the strength value which is determined not by the fixed area of contact, but by varying area of contact, projected to the surface, according to the depth of deformation, ν. Therefore, the less deforming mix (smaller ν) under the same load will show greater S_D value [1]; a fundamental concept of rut resistance.

Table 2 OBC, air void and S_D [7].

Mix	OBC [%]	Air void [%]	P [N]	ν [mm]	S_D [MPa]	S_D ratio
NDGA	4.7	4.10	2,809	2.55	3.23	1.00
PSMA	7.2	3.00	2,838	4.65	2.65	0.82
GSMA	7.0	2.47	4,620	4.60	4.33	1.35
GKMA	9.0	0.03	5,465	8.10	4.45	1.38

The SMA mix is known to have a strong resistance against rutting. According to S_D results, however, the PSMA, which was prepared with 76-22, was not strong enough because S_D = 2.65 MPa is much lower than the specification limit of 4.25 MPa. The GSMA, which was prepared with 82-34 using the same gradation of SMA, showed satisfactory S_D. Therefore, PG76 binder seemed to be not strong enough for binding aggregate skeleton of SMA structure without buckling.

Table 3 shows flexural strength (modulus of rupture: MR) of four mixes. MR values were increased significantly due to stiffness increase by temperature decrease. Three mixes showed MR peak at -10 °C and then decrease at -20 °C. But GKMA showed continuous increase without drop past -10 °C. This is an indication that the GKMA mix was not affected by the differential thermal contraction (DTC), which was known to be a significant damage mechanism taking place below -15 °C [8, 9]. Because of the large difference in coefficients of thermal contraction of aggregate and asphalt binder, the asphalt matrix tends to contract more than aggregate during thermal cooling. DTC takes place as a result of this large difference in the coefficients of thermal contraction of the two materials [8, 9]. The normal mix (NDGA) was observed to be most susceptible to DTC because of the highest increase at -10 °C and then largest drop at -20 °C.

Table 3 Flexural strength (modulus of rupture: MR) of 4 mixes by temperature

Mix / Temp.	MR [MPa]			
	NDGA	**PSMA**	**GSMA**	**GKMA**
25 °C	1.42	0.75	1.43	1.42
-10 °C	10.75	10.34	8.89	9.19
-20 °C	7.85	9.07	7.05	10.12

Table 4 shows pseudo fracture toughness (PFT) of four mixes at -20 °C. It was shown that the PFT of GKMA mix was the highest and near twice the NDGA mix. Since the fracture toughness is the ability of material to resist fracture, and therefore, it was proved that the GKMA mix has stronger resistance against cracking than any other mixes evaluated in this study.

Table 4 Pseudo fracture toughness (PFT) measured from 3PB test at -20°C

Mix	P_{max} [N]	νP_{max} [mm]	PFT [N.mm]	PFT ratio
NDGA	6,637	1.34	3,242	1.00
PSMA	7,860	2.21	4,412	1.36
GSMA	7,863	1.93	4,725	1.46
GKMA	8,949	2.48	6,139	1.89

Figure 5 shows the results of reflection cracking resistance test. Both NDGA mix and PSMA mix showed less than 3,000 cycles before failure. The GSMA showed approximately 10,000 cycles before faliure. These mean the cracks in those beams were grown up to 50 mm, the depth of beam, by those number of cycles. On the other hands, the GKMA mix showed only 16 mm crack length until 75,000 cycles, and then strated to grow again up to 30 mm until end of the test at 100,000 cycles (55 hour by 0.5 Hz), which is 30 times longer than NDGA and PSMA mixes. Therefore, the GKMA mix is extreemly tough material against fracture compared with the other three materials evaluated in this study. The GKMA will have to show a great performance against reflection craking when it was placed as an overlay AC pavemet on top of old concrete pavement in the field. It will also have to show a great rut resistance and waterfroofing function in addition to the great cracking resistance as a heavy duty pavement on the bridge.

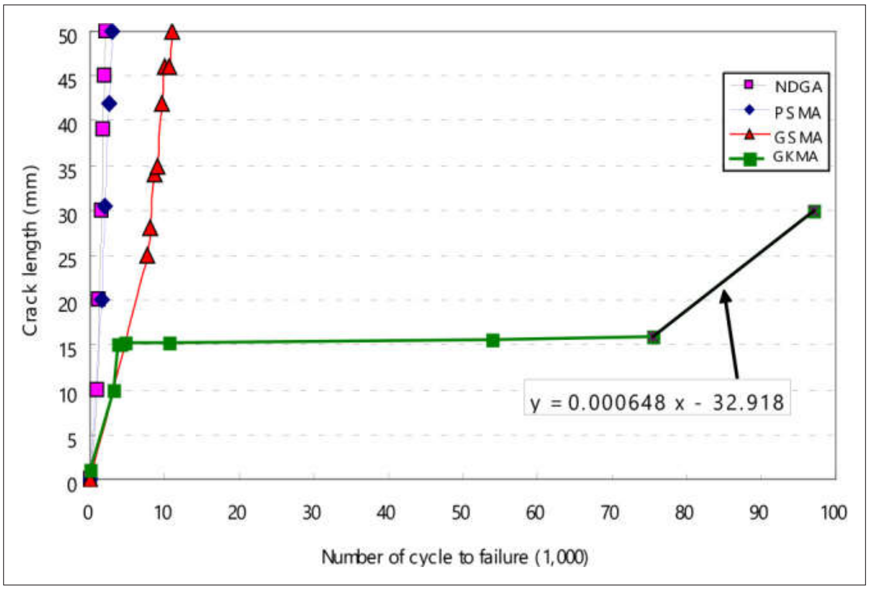

Figure 5 Crack length vs. number of cycle to failure for each mix

4 Conclusions

This study evaluated deformation resistance at a high-temperature (60 °C), fracture toughness at a low-temperature (-10 and -20 °C) and reflection cracking resistance at an ambient-temperature (25 °C) of the void-free asphalt concrete (AC) mix (designated as GKMA in this study) developed for heavy duty pavement. Based on experimental test results, following conclusions were drawn.

The near 0 air void of GKMA mix was achieved by modifying SMA aggregate gradation and using 9 % of PG82-34 binder content, without failing design criteria for the 1st class highway pavement mix, set forth by Korean Guide. The deformation strength (S_D) at 60 °C passed the limit value of 4.25 MPa, meaning the mix will have to perform satisfactorily against rutting.

The flexural strength (modulus of rupture: MR) and pseudo fracture toughness (the area under P-ν curve) of GKMA mix was the highest among the four mixes evaluated in this study. Therefore, the mix will have to show great strength against not only the bending stress, but also the stress intensity causing cracking.

The reflection cracking resistance was measured by simulated wheel moving on top of the asphalt pavement overlaid on concrete pavement joint (gap). The GKMA mix showed more than 30 time greater numbers of cycle before failure than normal (64-22) dense mix and PMA (76-22) SMA mix. Therefore, the GKMA mix was found to be the great performing AC mix against reflection cracking.

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