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Evaluation for Application of Warm-mix Asphalt Concrete for Rural Road Pavement

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ABSTRACT

The asphalt pavement industry has introduced the warm-mix asphalt (WMA) as a mean of energy saving and environmentally safe technology, because the WMA mixture can be mixed and compacted at 30°C lower than conventional hot-mix asphalt (HMA) at 160°C or higher. The implementation of WMA can be a good option for paving operations for rural road in remote place, not only due to energy saving and environmental issues, but also lower working temperature. Using WMA technology, the cooled-down asphalt mixture can be still compacted to meet the quality requirement in narrow winding rural road in remote places. Therefore, this study is designed to evaluate engineering properties of WMA binders and concretes, which were prepared for rural road pavement. The objective of the study was to evaluate and suggest proper fundamental properties level of the WMA concrete for rural road pavement. The kinematic viscosity test result indicated that the WMA binders used in this study were effective for compaction at lower temperature, i.e., at 115°C, compared to the HMA binder. According to strength property analyses, it was found that the WMA concrete was acceptable for rural road pavement even though it was compacted at 30°C lower level. Since the deformation strength (S_D) of 3.2 MPa was found to satisfy rutting and cracking resistance minimum guidelines, this value was suggested as a minimum S_D value for rural road pavement, considering lack of maintenance program for rural area.

Keywords: Warm-mix asphalt (WMA); rural road; asphalt pavement; deformation strength (S_D); hot- mix asphalt (HMA)

Ⅰ. Introduction

The most popular road-paving material is asphalt concrete and approximately 90% of roadways (highways, streets and low-volume roads including rural roads) pavements are paved with the asphalt concrete in the world (NAPA and EAPA, 2009). The typical paving method is to use the asphalt concrete (as-con) mixture at hot-temperature. The warm-mix asphalt (WMA) is an asphalt concrete mixture produced at the temperature lower than the conventional hot-mix asphalt (HMA). The typical working temperature of WMA is at around 130°C, compared to the working temperature of 160°C or higher for HMA (AAPA, 2001; Choi et al., 2019).

The ‘World of Asphalt 2004’ featured a demonstration project on WMA, and since then, the major WMA additive companies have carried out several demonstration projects in the United States. The WMA has been gaining popularity in recent years around the country in Korea (Busan city, 2014) and in the world. Rising air pollution issues, global warming, energy-saving, and more stringent environmental regulations are the primary reasons for using WMA (Angelo et al., 2008). The WMA can be means of decreasing energy consumption and polluted gas emissions associated with conventional HMA production. Since the working temperature of asphalt concrete material can be reduced by 30°C on average, the WMA was proved to be an effective measure for energy saving and environmental issues (Angelo et al., 2008; Prowell and Hurrley, 2008; Newcomb, 2007).

The implementation of WMA can be a viable option for paving operations for remote place road in rural areas, not only due to environmental issues, but also due to lower working temperatures. Because of longer haul distance along with narrow and winding paths in many rural roads, a temperature drop of the paving mixture is inevitable when HMA is used. The cooled-down HMA mixture is a cause of poor compaction

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resulting in the low-quality pavement (Linden et al., 1989; Lee et al., 2012). In addition to the temperature drop problem, since many rural roads are one-way narrow paths, there are many limitations for paving operation using heavy-and-large equipments.

Therefore, the WMA concrete is appeared to be a good choice for rural road pavement construction, because the cooled-down mixture can be still compacted to meet the quality requirement (MLIT, 2017). However, even though the WMA is appeared to be a viable option for paving rural roadways, the WMA concrete quality level should be investigated before implementation. If the lower quality standard is applied for rural road pavement due to lower volume of traffic on it, the rural-road pavement may be susceptible to pothole and weathering, compared to the normal pavement, due to lack of official maintenance practices (Saarenketo and Aho, 2005).

The pavement for any normal traffic road is constructed on the proper foundation by layer thickness design using the asphalt concrete prepared by proper mix design (Kim and Yeon, 1992; MLIT, 2017; ScDOT, 2007). In addition, the pavement thickness design guide has not been established and the quality control for paved asphalt concrete density may not be applied during construction for rural road pavement (Na et al., 2018).

Therefore, if the rural road pavement is constructed using WMA concrete, the strength of the WMA should be strong enough to sustain environmental effects, including moisture damage and weathering, in addition to traffic loading on the pavement. This study is designed to evaluate the engineering properties of WMA binders and WMA concretes (including moisture resistance), which were prepared to use for rural road pavement. The objective of this study is to evaluate and suggest the proper fundamental property level of the WMA concrete for rural road pavement.

II. Materials and Methods

1. Materials

In this study, normal (unmodified) WMA concrete quality was investigated for application to the rural road pavement. Two maximum sizes (13 and 19 ㎜) of granite-based aggregates were used for dense-graded surface course mixtures. The screenings and limestone powder were used as the fine aggregate and mineral filler, respectively, for asphalt concrete mixture. Three binders were prepared using two WMA additives and a base asphalt (AP) which shows the performance grade (PG) of 64-22 (Asphalt Institute, 2002).

The two WMA additives (Fig. 1) include Evotherm (EV), the emulsion type additive, and K-Pearl (KP), the wax and oil-based pellet-type additive were used for producing WMA mixtures. EV was melted into the heated asphalt at 160°C and blended with a spatula for 3-5 minutes before use. However, KP was added to the mixer just before mixing with asphalt and aggregates in the mixing bowl. Designation, description and content by weight of each additive are shown in Table 1.

Since the rural road pavement is deteriorated due to

(a)

(b)

Fig. 1 Photographs showing (a) Evotherm (EV) and (b) K-Pearl (KP) environmental damage, in addition to traffic loading, the moisture resistance after freezing-and-thawing (F-T) was evaluated by tensile strength ratio (TSR). Since moisture resistance can be enhanced by using hydrated lime (Kim, 2015; Kim et al., 2019; Lesueur, 2010), a hydrated lime (HL) was added (by 1 wt. % of total mix) to a WMA mixture for moisture resistance test. Total 6 mixtures (2 aggregates × 1 gradations × 3 binders) were produced for the surface course.

Table 1 Binder designation and description

Type	Designation	Description	Note
HMA	AP (control)	AP (PG 64-22)	Without additive and modifier
WMA	EV	AP + EV (0.5wt% of binder)	Chemical emulsion type
	KP	AP + KP (1.7wt% of binder)	Wax base pellet type

2. Binder Test

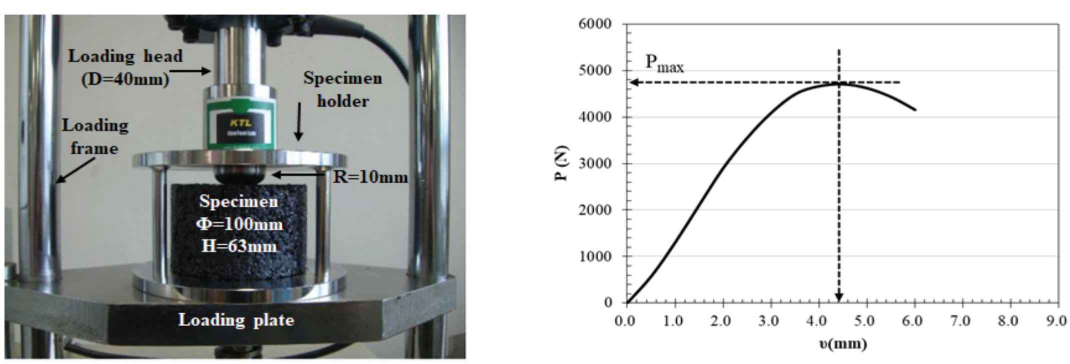
The kinematic viscosity (KS F 2392) of the asphalt binder sample was measured in two different temperatures, 135°C and 115°C, using a rotational viscometer. The PG grade of each binder was measured using the dynamic shear rheometer (DSR) and bending beam rheometer (BBR). The binder stiffness ($G^*/\sin\delta$) was measured from 64°C, which is high-temperature PG grade of base asphalt, up to the temperature where binder fails to pass the limit. Using BBR, beam stiffness and m-value were measured to estimate the low temperature PG of binder (Asphalt Institute, 2002).

3. Mix-Design

All WMA mixtures were short-term aged for 2 hours in a 130°C oven, while HMA mixture was short-term aged for 1 hour in a 160°C oven. For mix-design, the specimen was compacted by 75 gyrations using a Superpave gyratory compactor. The optimum asphalt content (OAC) of HMA was determined using the specification limits of four properties; the air-void ratio, void in mineral aggregate (VMA), voids filled with asphalt (VFA) and the deformation strength (S_D). The OAC was selected at the air-void ratio of 4%, as long as VFA and VMA satisfied specification limits by the Korean Guide (MLIT, 2017). Once the OAC of HMA was determined, the same OAC was used for the WMA mix with a minor adjustment by checking physical properties.

4. Deformation Strength (S_D)

The S_D is the strength property representing resistance against deformation at high-temperature (60°C) under a static-mode loading applied on top center of a briquette specimen of asphalt concrete (Doh et al., 2007; Kim et al., 2004(a); Kim et al., 2011). The specimen is soaked in 60°C water for 30 minutes and then placed in the specimen holder for measuring S_D, as shown in Fig. 2(a). Static loading is applied at the speed of 30 ㎜/min through the loading head (40 ㎜ diameter with a 10 ㎜ radius (r) of round cut at the bottom edge) until failure, as shown in Fig. 2(b) (Baek et al., 2009; Park et al., 2008). From the load (P) and deformation (v) curve of the test, designated as "Kim Test," the peak load, P and the vertical deformation, v at P were read and used in Eq. (1) for S_D calculation (Kim et al., 2004(a)).



(a) (b)

Fig. 2 (a) Kim Test setting and (b) P−v curve acquired from a Kim Test

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

where S_D is the strength against deformation (MPa), P is the maximum load (N), and v is the vertical deformation (㎜) at maximum load.

Since the S_D shows a good correlation with rut characteristics of dense grade asphalt concrete, it was adopted as a standard criterion in the Korean asphalt mix-design guide (Kim et al., 2006; Kim et al., 2011), in which the specific criteria of strength level are given. The criteria for S_D in Korean guide (MLIT, 2017) are $S_D \geq 3.20$ MPa and $S_D \geq 4.25$ MPa for the 2nd class road and 1st class highway pavements, respectively. Detailed Kim Test procedures are given elsewhere (Doh et al., 2007; Kim et al., 2004(a); 2004(b); 2011; MLIT, 2017).

5. Wheel Tracking Test

It is a widely held hypothesis that the wheel tracking (WT), used in much research, gives a reasonable prediction of rutting in the field (Kim et al., 2011, 2018). The rut depth data collected from wheel paths under the simulated conditions are assumed to indicate the rut characteristics of the asphalt concrete in the field (Brown and Gibb, 1996). The data used in this study were from a wheel tracker that consisted of a steel wheel (200 ㎜ in diameter and 50 ㎜ in width) rolling on top of a slab specimen on a base plate moving with a 200 ㎜ stroke back and forth. A WT test was performed for 7,200 passes at 60°C at a speed of 40 cycle/min for 90 minutes, with a pressure of 689.4 kPa (100 psi). The final rut depth data at 3,600 cycles were used for analysis.

6. Indirect Tensile Strength Test and Tensile Strength Ratio

The tensile strength (S_T) of asphalt concrete was measured by indirect tension test (KS F 2382) at 25°C on 100 ㎜ diameter, 63 ㎜ thickness specimen. A static loading is applied at the speed of 50 ㎜/min through loading strips on top and bottom of specimen (Fig. 3). The S_T was calculated using Eq. (2).

$$S_T = \frac{2{,}000P}{\pi D t} \tag{2}$$

where S_T is the indirect tensile strength (kPa), P is the peak load (N), D is the specimen diameter (㎜), and t is the specimen thickness (㎜).

Fig. 3 Indirect tensile strength test setting

In this study, to examine durability of asphalt concrete for rural road pavement, the tensile strength ratio (TSR) was evaluated after freezing-and-thawing (F-T) conditioning. Since the lower strength asphalt concrete shows, in general, lower durability during in service in the pavement, a WMA mixture, which showed the lower strength values (S_T and S_D) on average, was only selected to evaluate TSR. The specimens (diameter of 100 ㎜, heigh of 63 ㎜) were prepared with air void of 7±1% for a F-T cycle, for which a freezing at -18°C for 16 hours and then submerging at 60°C water for 24 hours for wet-conditioning by AASHTO T 283 (2014). The specimen, picked out from 60°C water, was submerged into the 25°C water bath for two hours before S_T testing. The dry specimen was kept in an environmental chamber controlled at 25°C for 48 hours. Three specimens were used for each conditioning and TSR was calculated by Eq. (3) using the average value for each condition.

$$TSR(\%) = \frac{S_{T_{wet}}}{S_{T_{dry}}} \times 100 \tag{3}$$

where TSR (%) is the tensile strength ratio, S_{Twet} is the indirect tensile strength (kPa) of wet-conditioned specimen, and S_{Tdry} is the indirect tensile strength (kPa) of dry specimen.

Ⅲ. Results and Discussions

1. Evaluation of Asphalt Binder

Table 2 shows binder test results. WMA binders, which showed PG 64-22, showed lower kinematic viscosity at 135 and 115°C than AP (base asphalt). The compaction temperatures of HMA and WMA are considered approximately 135 and 115°C, respectively. Those temperatures are the mixture temperatures, which were cooled down, when compacted by roller after wide spreading by the paver. Therefore, kinematic viscosity of two binders were tested at 135 and 115°C.

Comparing kinematic viscosity of HMA and WMA binders, as shown in Fig. 4, the WMA binder using EV were 27.4% and 13.6% lower than HMA binders at 115°C and 135°C, respectively. The WMA binder using KP was 23.0% lower than HMA binder at 115°C, but similar to each other at 135°C. The test result indicated that the WMA binders used in this study will be more effective for compaction at lower temperature, i.e., at 115°C, than the HMA binder.

Table 2 Test results of kinematic viscosity and PG for various binders

Type	Designation	Kin. viscosity (cP)		PG failure temp. (°C)		PG
		115°C	135°C	High	Low	
HMA	AP	1,550	450	68.2	-15	64-22
WMA	EV	1,125	389	69.7	-14	64-22
	KP	1,194	453	66.4	-16	64-22

All binders of HMA and WMA show similar failure temperature from 66 to 69°C. Therefore, WMA binders were not observed to be inferior to the HMA binders, even though WMA additives, which might cause softening of the binder at high service temperature, were contained. The low temperature grade was all measured to be -22°C, even though there were some differences in failure temperature to pass the maximum stiffness and minimum m-value.

2. Evaluation of Asphalt Concrete

Table 3 shows physical properties measured from the specimens prepared using the optimum asphalt content (OAC) and Table 4 shows three properties of HMA and WMA concretes. The values of S_D ≥ 3.20 MPa, WT rut depth ≤ 5 ㎜ and S_T ≥600 kPa are, in general, considered an acceptable level of engineering properties of asphalt concrete pavement for the 2nd class road pavement (ScDOT, 2007). The 2nd class road includes most of the two-lane roadways with daily traffic volume less than 1,000 ESAL (equivalent single axle loading). Therefore, WT rut depth of 5 ㎜ and S_T of 600 kPa were considered as guidelines of WMA concrete for rural roads.

All the HMA and WMA concretes satisfied the limits of S_D and S_T, although one HMA and one WMA mixes were slightly over the WT limit. However, those values are still very close to the 5 ㎜, which can be considered acceptable for rural roads pavement. Figs. 5~7 illustrated individual values of each test for more detailed analyses.

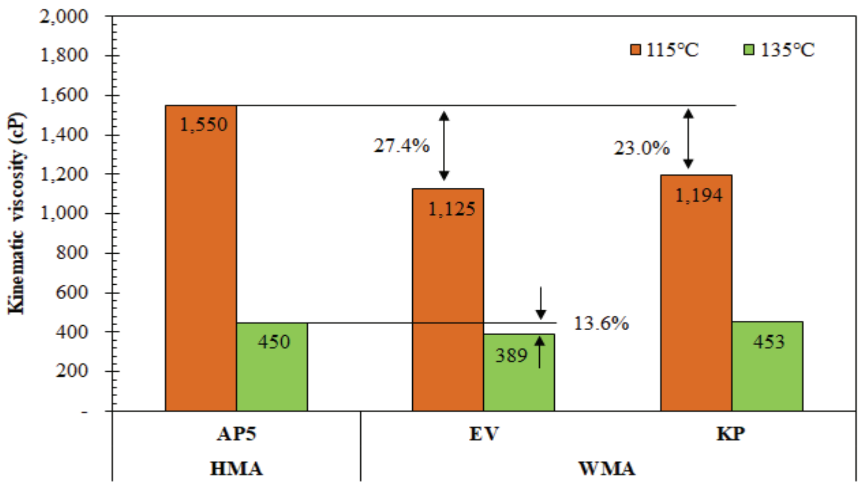


Fig. 4 Comparison of kinematic viscosity of HMA and WMA binders

Table 3 Mix-designed physical properties of various mixtures

Agg.	Mix type	Designation	Temp.[1] (°C)	No. of gyration	OAC (%)	Air Void (%)	VFA[2] (%)	VMA[3] (%)
13 ㎜	HMA	AP	160	75	5.6	3.93	65.25	17.01
	WMA	EV	130	75	5.5	3.82	74.21	16.97
		KP	130	75	5.7	3.81	75.22	17.30
19 ㎜	HMA	AP	160	75	4.7	3.79	75.66	17.63
	WMA	EV	130	75	4.7	3.72	72.20	16.95
		KP	130	75	4.7	3.88	70.24	17.62

[1]Short-term aging temperature, [2]Voids filled with asphalt, [3]Voids in mineral aggregate.

Table 4 Test results of asphalt concrete properties

Aggregate	Type	Designation	Property			
			PG	S_D* (MPa)	WT rut (㎜)	S_T (kPa)
13 ㎜	HMA	AP	64-22	3.37	5.45	630
	WMA	EV	64-22	3.34	5.23	759
		KP	64-22	3.62	4.89	845
19 ㎜	HMA	AP	64-22	3.69	4.56	795
	WMA	EV	64-22	3.61	4.98	817
		KP	64-22	3.47	4.97	743

*S_D ≥ 3.20 MPa for 2nd class road asphalt pavement.

In Fig. 5, S_D values of 19 ㎜ showed higher, on average, than those of 13 ㎜. In case of 13 ㎜, WMA concretes showed higher S_D, but for the case of 19 ㎜, WMA conversely showed lower S_D values. However, still all values satisfied the 3.2 MPa limit, indicating that WMA concretes have high enough strength for 2nd class roadways and rural roads. In general, the asphalt concrete made of the larger aggregate shows stronger resistance against rutting. But according to this result, the use of asphalt concrete with 13 ㎜ aggregate was found to be strong enough for rural road pavement.

The short-term aging temperatures of WMA and HMA were 130°C and 160°C, respectively. It is possible to state that the WMA additive performed properly at WMA temperatures (130°C) for mixing. Therefore, the WMA concrete appeared to be compacted properly at 30°C lower than the HMA temperature. This will be a good indication that the WMA will be workable properly at a cooled-down temperature for a rural working environment.

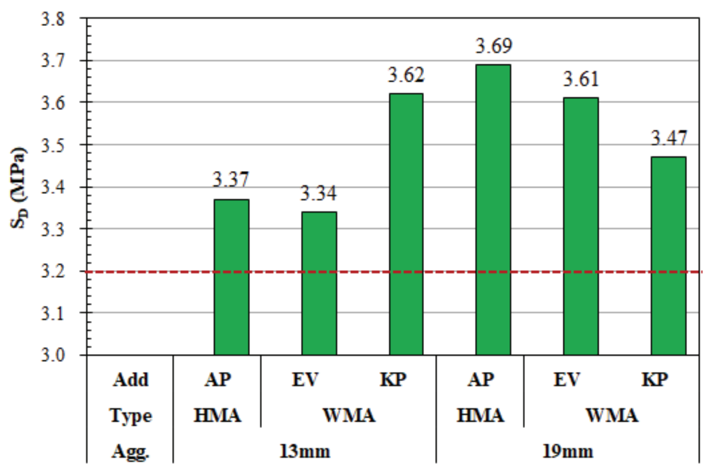


Fig. 5 Comparison of deformation strength (S_D) of HMA and WMA concretes

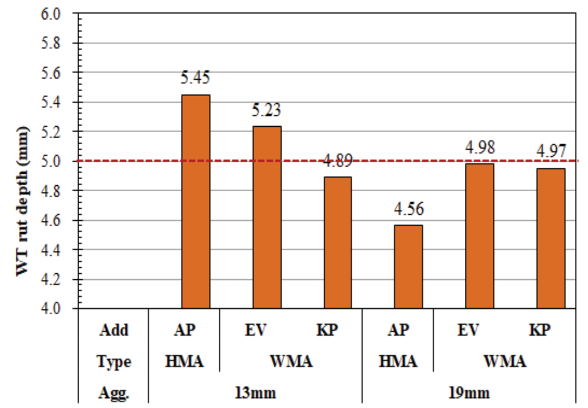


Fig. 6 Comparison of wheel tracking (WT) rut depth of HMA and WMA concretes

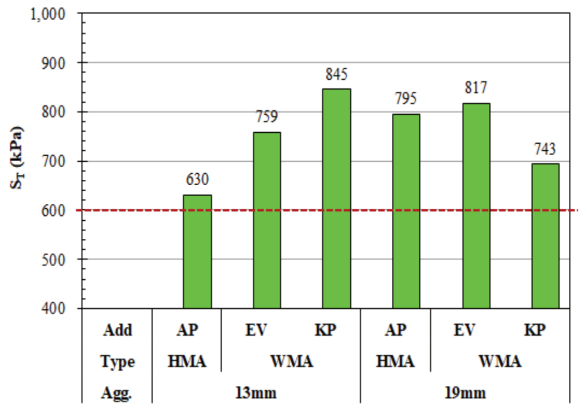


Fig. 7 Comparison of tensile strength (S_T) of HMA and WMA concretes

Fig. 6 shows wheel tracking test results. In general, as expected from S_D results, WT rut depths of 13 ㎜ were higher than those of 19 ㎜, indicating 19 ㎜ being better in rut resistance. However, it was difficult to see a pattern of difference between WMA and HMA concretes. The limit of 5 ㎜ rut depth is the guideline for the 2nd class roadway pavement (ScDOT, 2007), therefore, a somewhat higher limit, such as 6 ㎜ or less, might be allowable for rural road pavement. According to this test result, even though some mixes showed a little higher than 5 ㎜ rut depth, the rut resistance of WMA concrete with 13 ㎜ aggregate seems to be strong enough for rural road pavement.

The tensile strength (S_T) was measured at 25°C and illustrated in Fig. 7. According to S_T, WMA concretes revealed similar or somewhat higher strengths than HMA concretes. Therefore, in case of tensile strength, an ambient temperature property, basically no difference was observed between HMA and WMA concretes prepared using the same PG grade binders. Therefore, the normal (unmodified) WMA concretes seemed to be strong enough for rural road pavement because the ambient (25°C) and high (60°C) temperature performance were good enough when they were compared with those of HMA concretes.

Table 5 shows test results of tensile strength ratio (TSR) of rural road asphalt concretes. Since a HMA and a WMA were below 75%, which is the limit value of TSR by AASHTO (2014), those mixes were not satisfactory without hydrated lime (HL). However, by adding HL by 1 wt % of total mix, the TSR levels for both WMA mixes were improved to be superior levels, i.e., 97% or higher. If an asphalt concrete shows high TSR level, the pavement serviceability life will be extended with great durability under freezing weather condition. Therefore, it would be better to used HL in WMA mixtures for rural road pavement.

3. Correlation Analysis

The S_D is essential property used as one of the mix-design criteria of asphalt concrete in Korea mix-design guide (MLIT, 2017). Therefore, many studies evaluated the correlation of other properties with S_D for HMA concretes (Lee et al., 2004;

Table 5 Test results of tensile strength ratio (TSR) of HMA and WMA concretes

Hydrated lime (%)	Agg.	Type	Designation	ITS (kPa)		TSR (%)
				Dry	Wet	
0	13 mm	HMA	AP	697	624	75.2
		WMA	EV	486	348	71.6
	19 mm	HMA	AP	687	496	72.2
		WMA	EV	632	489	77.5
1.0	13 mm	WMA	EV	486	573	117.9
	19 mm	WMA	EV	632	614	97.2

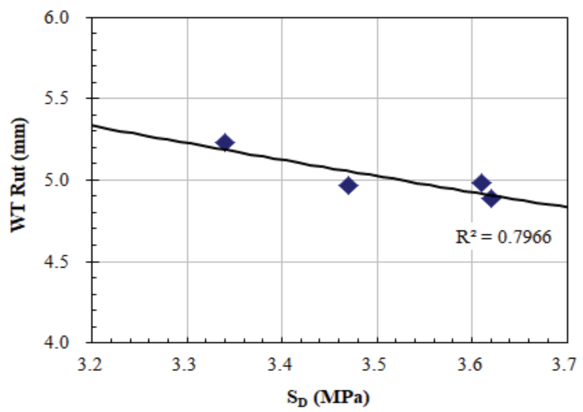


Fig. 8 Relation of WT rut depth and S_D of WMA concrete

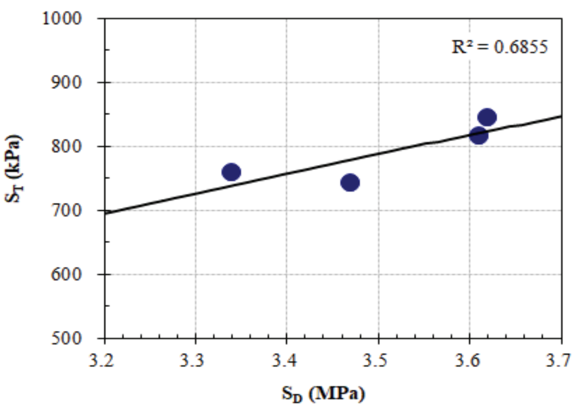


Fig. 9 Relation of S_T and S_D of WMA concrete

Kim et al., 2004(a); 2004(b)). This study examined correlation of WT rut depth and S_T with S_D using WMA concrete data only (Figs. 8 and 9).

The WT rut depth was reduced by S_D increase with $R^2 ≒ 0.80$, indicating that the asphalt concrete showing higher S_D would be stronger against rutting. The S_T was increased by S_D increase with $R^2 ≒ 0.70$, indicating that the asphalt concrete with higher S_D would be stronger against tensile stress. Since S_T is used as an index of cracking resistance for asphalt pavement, the asphalt concrete with higher S_D will be considered tougher against cracking.

According to these correlation analyses, the S_D, the most fundamental property measured during the mix-design stage, can be used as a criterion of WMA concrete for rural road pavement. The regression curve between WT rut depth and S_D in Fig. 8 showed that the WT rut depth of 5.3 ㎜ at S_D of 3.2 MPa was shown to decrease with S_D increase. Using the regression model in Fig. 8, the WT rut depth of 5.3 ㎜ can be estimated by S_D = 3.2 MPa. By getting rid of the decimal point from 5.3 ㎜ for practical use, therefore, the $S_D \geq 3.2$ MPa was considered as a reasonable level for satisfying 5 ㎜ of the rut depth guideline.

The relation of S_T with S_D showed that the regression line meets approximately 700 kPa at the S_D of 3.2 MPa. Since 700 kPa is higher than the previously mentioned S_T of 600 kPa guideline, the S_D of 3.2 MPa will be strong enough for satisfying the S_T performance.

Therefore, $S_D \geq 3.2$ MPa is suggested as a criterion of asphalt concrete for rural road pavement because the S_D level was observed to satisfy both rutting resistance (measured by WT) and cracking resistance (measured by S_T) guidelines. Although this level of S_D is the same as the 2nd class road pavement requirement, it is recommended for rural road pavement. If a lower level of S_D is applied, considering low level traffic volume, the pavement will be susceptible to environmental distresses and traffic loading, because there is no official maintenance program provided for the rural road in most cases.

Ⅳ. Conclusion

Characteristics of selected WMA concretes were examined for application to rural roadway pavement, in comparison with HMA concrete. The high-temperature properties (deformation strength: S_D and wheel tracking: WT) at 60°C and ambient-temperature properties (tensile strength: S_T) at 25°C were compared, and the data analyses reached the following conclusions.

1. The kinematic viscosity of PG 64-22 WMA binders can be drop as much as 27% than HMA binders at 115°C by the addition of warm-mix additives used in this study. This reduction can provide good compaction quality for WMA mixes at cooler temperature.
2. The S_D, WT and S_T test results of WMA concretes were found to be similar to or better than those of HMA concretes. Even though the mixture was produced at 30°C lower temperatures than HMA, the properties were equivalent to or better than those of HMA.
3. Therefore, it is concluded that WMA concretes evaluated

in this study is useful for rural road pavement, because they are compacted well at a much lower temperature than HMA in the rural working condition where the quality control (particularly for temperature control) is not often properly provided.

4. The S_D value of 3.2 MPa was suggested as the minimum strength guideline for rural road pavement. Considering the lack of an official maintenance program for rural roads in most cases, this level of S_D is considered as an initial strength value that can maintain the pavement serviceability without cracking and rutting.
5. For maintaining durable pavement, which can sustain longer serviceability life under severe weather condition, it was recommended to use a hydrated lime for WMA mixture for rural road pavement.
6. This recommend value, however, is tentative and as good as this study hypothesis reached because it is based on limited materials and properties evaluation. Therefore, further research on other properties using more materials are needed to be performed for a more generalized recommendation.

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REFERENCES

1. AASHTO T 283, 2014. Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage. American Association of State and Highway Transportation Officials, 444 North Capital Street N.W., Suite 249, Washington D.C.
2. Angelo, J. D., E. Harm, J. Bartoszek, G. Baumgardner, M. Corrigan, J. Cowsert, T. Harman, M. Jamshidi, W. Jones, D. Newcomb, B. Prowell, R. Sines, and B. Yeaton, 2008. Warm-mix asphalt: european practice. American Association of State Highway and Transportation Officials (AASHTO) and National Cooperative Highway Research Program (NCHRP).
3. Asphalt Institute, 2002. Performance graded asphalt binder specification and testing. *Superpave Series* No. 1, (SP-1), Lexington, KY, USA.
4. Australian Asphalt Pavement Association (AAPA), 2001. Warm mix asphalt–a state of the art review, Advisory Note #17. http://aapa.asn.au/content/aapa/download/advisorynote17.pdf, Accessed 10Jan. 2007.
5. Busan City, 2014. Press release-Warm mix asphalt mixture was fully implemented from 2015, https://www.busan.go.kr/nbtnews/157131, Accessed 4th Jan. 2021. (in Korean).
6. Brown, S. F., and J. M. Gibb, 1996. Validation of experiments for permanent deformation testing of bituminous mixtures. *Journal of the Association of Asphalt Paving Technologists* 65: 255-299.
7. Baek, S. H., J. C. Kim, Y. S. Doh, and K. W. Kim, 2009. Optimum loading speed for deformation strength test of bitumen mixtures. *Proceedings, 7th RILEM Symposium ACTBM09*, Rodos, Grees, May.
8. Choi, C. J., B. S. Dong, K. W. Kim, and S. Kim, 2019. Evaluation of impact energy absorption characteristics of flexible sand asphalt pavement for pedestrian way. *Journal of the Korean Society of Agricultural Engineers* 61(3): 31-41. doi:10.5389/KSAE.2019.61.3.031. (in Korean).
9. Doh, Y. S., K. K. Yun, S. N. Amirkhanian, and K. W. Kim, 2007. Framework for developing static strength test for measuring deformation resistance of asphalt concrete mixtures. *Construction and Building Materials* 21(12): 2047-2058. doi:10.1016/j.conbuildmat.2006.06.032.
10. Kim, B. I., M. S. Lee, and K. W. Kim, 2006. Methodology for developing HMA mix design taking into account performance-related mechanics properties. *Journal of the Korean Society of Road Engineers* 8(1): 15-23 (in Korean).
11. Kim, K. W, 2015. Benefits of using hydrated lime on asphalt mixtures. *Journal of the Korean Asphalt Institute* 5(1): 1-5 (in Korean).
12. Kim, K. W., Y. S. Doh, and S. N. Amirkhanian, 2004(a). Feasibility of deformation strength for estimation of rut resistance of asphalt concrete. *Road Materials and Pavement Design* 5(3): 303-322. doi:10.1080/14680629.2004.9689974.

13. Kim, K. W., S. J. Choi, G. H. Lee, and Y. S. Doh, 2004(b). Correlation analysis between deformation strength and rut parameters of asphalt concretes at different temperature. *Journal of the Korean Society of Civil Engineers* 24(5D): 743-748 (in Korean).
14. Kim, K. W., S. N. Amirkhanian, H. H. Kim, M. S. Lee, and Y. S. Doh, 2011. A new static strength test for characterization of rutting of dense-graded asphalt mixtures. *Journal of Testing and Evaluation* 39(1): 59-68. doi:10.1520/JTE102385.
15. Kim, K. W., and K. S. Yeon, 1992. Probabilistic thickness design of flexible pavement surface. *Journal of the Korean Society of Agricultural Engineers* 34(1): 66-77 (in Korean).
16. Kim, S., J. Shen, and M. M. Jeong, 2018. Effects of aggregate size on the rutting and stripping resistance of recycled asphalt mixtures. *Journal of Materials in Civil Engineering* 30(2): 04017280. doi:10.1061/(ASCE)MT. 1943-5533.0002139.
17. Kim, S., J. Shen, S. J. Lee, Y. S. Kim, and K. W. Kim, 2019. Examination of physical property degradation due to severe short-term aging and effect of hydrated lime as antioxidant in asphalt mixture. *Road Materials and Pavement Design* 20(7): 1638-1652. doi:10.1080/146806 29.2018.1473281.
18. KS F 2382, 2013. Standard test method for Indirect tension of asphalt mixtures, Korean Standard Association, https://www.ksa.or.kr/ksa_kr/index.do (in Korean).
19. KS F 2392, 2014. Standard test method for viscosity determination of asphalt binder using rotational viscometer. Korean Standard Association, https://www.ksa.or.kr/ksa_kr/index.do (in Korean).
20. Lee, M. S., S. J. Choi, Y. S. Doh, and K.W. Kim, 2004. Specimen size effect in estimation of rut resistance based on deformation strength. *Journal of the Korean Society of Road Engineers* 6(2): 1-13 (in Korean).
21. Lee, M. S., S. Kim, and K. W. Kim, 2012. Estimation of optimum compaction temperature for HMA and WMA mixtures by volumetric property evaluation. *Journal of Testing and Evaluation* 40(3): 463-475. doi:10.1520/JTE 103943.
22. Lesueur, D., 2010. Hydrated lime: A proven additive for durable asphalt pavements-Critical literature review. Brussels: European Lime Association (EuLA. Retrieved from http://www.eula.eu).
23. Linden, R. N., J. P. Mahoney, and N. C. Jackson, 1989. Effect of compaction on asphalt concrete performance. *Transportation Research Record* 1217: 20-28. http://onlinepubs.trb.org/Onlinepubs/trr/1989/1217/1217-003.pdf. Accessed 4Jan 2021.
24. Ministry of Land, Infrastructure and Transport (MLIT), 2017. Guideline for construction of asphalt concrete pavement (in Korean).
25. National Asphalt Pavement Association (NAPA) and European Asphalt Pavement Association (EAPA), 2009. The asphalt paving industry a global perspective-production, use, properties, and occupational exposure reduction technologies and trends. https://eapa.org/wp-content/uploads/2018/07/global_perspective.pdf. Accessed 4Jan. 2021.
26. Newcomb. D., 2007. Warm mix green asphalt technology 2007. Texas Department of Transportation (TDOT), http://www.warmmixasphalt.org/submissions/72_20080324_2007WarmMixGreenAsphaltTechnology_NAPA2008.pdf. Accessed 4Jan. 2021.
27. Na, I., S. J. Lee, J. H. Yoon, and K. W. Kim, 2018. Estimation of air voids of asphalt concrete using non-destructive density testing. *Journal of the Korean Society of Agricultural Engineers* 60(6): 109-117. doi: 10.5389/KSAE.2018.60.6.111. (in Korean).
28. Park, T. W., Y. S. Doh, and K. W. Kim, 2008. Determination of radius of edge round cut of loading head for deformation strength test. *Journal of the Korean Society of Road Engineers* 10(2): 183-192 (in Korean).
29. Prowell, B. D., and G. C. Hurley, 2008. Warm mix asphalt best practices. *Proceedings National Asphalt Pavement Association (NAPA) 53rd Annual Meeting,* Jan. 28.
30. Saarenketo, T., and S. Aho, 2005. Managing spring thaw weakening on low volume road-problem description, load restriction policies, monitoring and rehabilitation. ROADEX Ⅱ Northern Periphery. https://www.roadex.org/wp-content/uploads/2014/01/2_3-Spring_Thaw_Weakening_l.pdf. Accessed 4Jan. 2021.
31. South Caroline Department of Transportation (ScDOT), 2007. Standard specifications for highway construction. Columbia, SC, USA.
32. World of Asphalt, 2004. World of asphalt 2004 - march 15-18 (Equipment). https://www.equipmentworld.com/world-of-asphalt-2004-march-15-18/. Accessed 4 Jan 2021.