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Determining Mixing and Compaction Temperatures of Evotherm® Warm Mix Asphalt Using 100% Reclaimed Asphalt Pavement

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Abstract: Laboratory viscosity testing of asphalt binder and compaction testing of asphalt mixture were performed to develop a rational method for determining mixing and compaction temperatures of warm mix asphalt (WMA) using 100% reclaimed asphalt pavement (RAP), RAP-WMA, with Evotherm® DAT technology. Results of laboratory tests and analyses of the results indicate that traditional equiviscous principle is not applicable to the RAP-WMA. Compared with RAP hot mix asphalt (HMA), RAP-HMA, the reductions in mixing and compaction temperatures of RAP-WMA determined using the equiviscous principle are only less than 1°C. An equivolumetric principle can be used for determining average compaction temperature of RAP-WMA, which is defined as the temperature corresponding to a prescribed value of air voids of asphalt mixture. A method, termed "equi-viscous-volumetric principle," developed in this study, can be used for determining mixing and compaction temperatures of RAP-WMA, which is a combination of the equiviscous principle and the equivolumetric principle. Compared with RAP-HMA, the reductions in mixing and compaction temperatures of RAP-WMA determined using this method are around 25°C. These reductions are close to the values recommended by the Evotherm® DAT additive manufacturer and used in paving practice.

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***Key words**: Equi-viscous-volumetric principle; Mixing and compaction temperatures; Reclaimed asphalt pavement (RAP); Warm mix asphalt (WMA).*

Introduction

Due to rising energy prices and stricter environmental regulations since the 1990s, the asphalt paving industry has developed a number of technologies for warm mix asphalt (WMA). These technologies allow a reduction in the temperatures at which conventional hot mix asphalt (HMA) is mixed at the production plant and compacted at the construction site, without sacrificing the quality of the pavement. Reduced mixing and compaction temperatures can decrease the energy consumption required by burning fuels to heat asphalt binder and mineral aggregate to temperatures above 150°C. These high temperatures are needed to allow the asphalt binder to have sufficient flow during mixture production, the asphalt mixture to have good workability during pavement construction, and the asphalt pavement to have reasonable durability during traffic exposure. With the reduced temperature comes the additional benefit of decreased emissions, fumes, and odors generated at the plant and the paving site [1-3].

In general, WMA technologies reduce the viscosity of asphalt binder at elevated temperatures. The reduced viscosity allows the aggregate to be coated and the mixture to be densified at lower temperatures than what is conventionally required in HMA production and pavement construction. While some of the technologies require significant equipment modifications, others simply involve the use of additives, such as Aspha-min®, Sasobit®, and Evotherm® [4-6]. Evotherm® is a WMA technology developed by Asphalt Innovations, a division of MeadWestvaco. The first generation is ET, which is based on the use of asphalt emulsions. The second generation is DAT, which uses a chemical additive technology and a "Dispersed Asphalt Technology" delivery system. The latest third generation is 3G, which is a water-free technology offering new advantages for innovative warm mix solutions. The easy and ready-to-use formula provides comprehensive benefits that surpass conventional hot mix asphalt. It is claimed that Evotherm® WMA technology allows asphalt application at a temperature that is 33 to 50°C lower than conventional asphalt paving practice [7-8].

Reclaimed asphalt pavement (RAP) is the term for removed or processed materials containing asphalt binder and mineral aggregate. These materials are generated when asphalt pavements are removed for construction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregate coated by asphalt cement. The utilization of RAP has advantages such as reduced costs of construction, conservation of asphalt binder and mineral aggregate, preservation of the existing pavement geometrics, preservation of the environment, and conservation of energy. At the same time, recycling of existing material also helps to solve disposal problems. The percentage of RAP that can be utilized successfully in hot-mix recycling is primarily dictated by practical considerations, and technologies of recycling 100% RAP have been reported [9-10]. While mainly used in asphalt mixture of virgin materials, WMA technologies are also applied to asphalt mixture with RAP. In fact, RAP and WMA have become the primary methods for enhancing sustainability in the asphalt paving industry in recent years. To further enhance sustainability benefits, the asphalt paving contractors have begun using RAP and WMA in combination [11-14].

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The asphalt binder and mineral aggregate are usually mixed and compacted at elevated temperatures in producing asphalt mixture. The mixing temperature is the range of temperatures that can provide satisfactory aggregate coating during laboratory mixing, and the compaction temperature is the range of temperatures that may facilitate appropriate densification during laboratory compaction, without excessively degrading the asphalt binder. For conventional HMA, laboratory mixing and compaction temperatures are selected as the temperatures corresponding to prescribed viscosities of asphalt binder. Viscosities of 170±20 centistokes and 280±30 centistokes, or equivalently (assuming the density of asphalt binder to be 1 g/cm^3) 0.17±0.02 Pa·s and 0.28±0.03 Pa·s, have been adopted as in ASTM D6925-09 "Standard Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor" [15]. This is what is called equiviscous principle.

For WMA, a universal approach for selecting the mixing and compaction temperatures has not been established. These temperatures are estimated largely based on recommendations of the manufacturer or experiences of the practitioner. For the last decade, many research studies have been conducted on the performance of WMA [16-18]. Studies related to temperature mainly deal with the effects on the performance of WMA [19-21]. This research study attempts to develop a rational method for determining mixing and compaction temperatures of WMA.

In view of the trend that higher percentages of RAP are utilized in recycling asphalt pavement, 100% RAP is used. Evotherm® DAT is applied as a representative of the WMA technologies. In order to achieve the objective of the study, laboratory viscosity testing of asphalt binder and compaction testing of asphalt mixture are to be conducted to generate data for evaluating the variation of viscosity with temperature of asphalt binder and the variation of volumetric properties, particularly air voids, with temperature of asphalt mixture. The analyses on viscosity testing data of asphalt binder and compaction testing data of asphalt mixture are to be performed to examine the applicability of traditional equiviscous principle to WMA and develop the method for determining mixing and compaction temperatures of WMA.

Materials

The RAP for testing was taken from a pavement on Tan-Shao (Xiangtan to Shaoyang) Highway in Hunan Province, a section of G60 Highway, where rehabilitation was planned due to distresses. The asphalt mixture is a dense graded asphalt mixture with a nominal maximum aggregate size of 13.0 mm. The aggregate is crushed basalt and the original asphalt binder is a Penetration 70 petroleum asphalt with Penetration of 60-80 (0.1 mm) as specified in JTG F40-2004 "Technical Specifications for Construction of Highway Asphalt Pavements" [22].

For the RAP, tests were carried out in accordance with various procedures in JTG E20-2011 "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" [23]. The procedure in JTG E20 T0722-1993 "Test Method for Asphalt Content in Asphalt Mixture (Centrifugal Separation Method)", which is equivalent to ASTM D2172/D2172M-11 "Standard Test Methods for Quantitative Extraction of Bitumen From Bituminous Paving Mixtures" [15], was performed to determine the asphalt content and prepare trichloroethylene solution containing asphalt binder and mineral filler for recovering the aged asphalt binder. The test results indicate that the asphalt content is 4.1%. For the trichloroethylene solution containing asphalt binder and mineral filler from JTG E20 T0722 test, the procedure in JTG E20 T0727-2011 "Test Method for Recovery of Asphalt from Asphalt Mixture (Rotational Vaporizer Method)" [23], which is similar to ASTM D1856-09 "Standard Test Method for Recovery of Asphalt from Solution by Abson Method" [15], was performed to separate the asphalt binder from mineral filler and recover the asphalt binder for further testing.

For the recovered asphalt binder, properties such as penetration, softening point, and ductility were measured in accordance with various JTG E20 and ASTM test procedures. Table 1 shows the properties of the recovered asphalt binder from RAP and that the recovered asphalt binder has undergone a moderate degree of aging. A restoration process is required for reuse of the asphalt binder.

A rejuvenator, which was manufactured by Ningxia Institute of Transportation, was selected to restore the properties of the asphalt binder. The properties of the rejuvenator meet the requirements for RA-1 rejuvenator in JTG E41-2008 "Technical Specifications for Highway Asphalt Pavement Recycling" [24]. In preparing the rejuvenated asphalt binder, the asphalt binder was heated to approximately 120℃, the rejuvenator was added into the asphalt binder, and the blend of asphalt binder and rejuvenator was then stirred thoroughly. The amount of rejuvenator added is 2% by mass of asphalt binder for target Penetration 70 petroleum asphalt with Penetration of 60-80 (0.1 mm) as specified in JTG F40. For the rejuvenated asphalt binder, properties such as penetration, softening point, and ductility were measured in accordance with various JTG E20 and ASTM test procedures. Table 1 also shows the properties of the rejuvenated asphalt binder, as well as respective test procedures. It is seen, from the table, that the rejuvenated asphalt binder meets the requirements in the specification.

For the mineral aggregate from JTG E20 T0722 test, the procedure in JTG E42-2005 T0302-2005 "Test Method for Sieve Analysis of Coarse Aggregate and Aggregate Mixture" [25], which is equivalent to ASTM C136-06 "Standard Test Method for Sieve

Table 1. Properties of Recovered and Rejuvenated Asphalt Binder.

Property	Asphalt Binder			Test Procedure	
	Recovered	Rejuvenated	JTG F40 Specification	JTG E20	ASTM
Penetration at 25℃, 100 g, 5 s	48	63	60-80	T0604-2011	D5/D5M-13
Softening Point, ℃	49.5	48	≥46	T0606-2011	D36/D36M-14
Ductility at 10℃, 5 cm/min, cm	13	25	≥15	T0605-2011	D113-07

Table 2. Aggregate Gradation of RAP with Gradation Requirements for AC-13 and SP-12.5 Asphalt Mixtures.

Sieve Size	Percent Passing		
(mm)	RAP	AC-13	SP-12.5
16	100	100	
13.2	96.4	90-100	90-100
9.5	71.6	68-85	≤ 90
4.75	45.8	38-68	
2.36	36.6	24-50	28-58
1.18	27.2	15-38	
0.6	22.8	10-28	
0.3	17.6	7-20	
0.15	12.6	5-15	
0.075	8.4	4-8	2-10

Analysis of Fine and Coarse Aggregates" [15], was performed to determine the gradation of the aggregate. Table 2 shows the aggregate gradation of RAP, gradation requirements for AC-13asphalt mixture as specified in JTG F40, and gradation requirements for Superpave 12.5 mm (SP-12.5) asphalt mixture as specified in AASHTO M323-13 "Standard Specification for Superpave Volumetric Mix Design" [26]. It is seen, from the table, that the RAP aggregate gradation generally meets the requirements for AC-13 asphalt mixture (except that 8.4% passing 0.075 mm sieve is slightly higher than the 8.0% upper limit). It is also seen, from the table and figure, that the RAP aggregate gradation fully meets the requirements for Superpave 12.5 mm asphalt mixture.

Test results above indicate that properties of both rejuvenated asphalt binder and mineral aggregate meet the requirements of the specification. In view of the trend that higher percentage of RAP has been utilized in recycling asphalt pavement, 100% RAP is used in the present study.

Evotherm® DAT, the second generation of Evotherm® WMA technology, is applied as an additive, which uses a chemical additive technology and a "Dispersed Asphalt Technology" delivery system. By using the technology, a unique chemistry customized for aggregate compatibility is delivered into a dispersed asphalt phase, i.e., emulsion. During production, the asphalt emulsion with Evotherm® chemical package is used in place of conventional asphalt binder. The emulsion is then mixed with the aggregate in the plant. It is indicated that the chemistry provides aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required. Based on the recommendation of the manufacturer, the amount of Evotherm® DAT added is 5% by mass of asphalt binder and additive, or 5.3% by mass of asphalt binder.

Laboratory Testing

Laboratory testing includes viscosity testing of asphalt binder and compaction testing of asphalt mixture. The viscosity testing is to generate data for evaluating the variation of viscosity with temperature of asphalt binder, while the compaction testing is to generate data for evaluating the variation of air voids with temperature of asphalt mixture.

Table 3. Results of Viscosity Testing of Asphalt Binders.

Temperature (℃)	Asphalt Binder		
	Recovered	Rejuvenated	Rejuvenated+DAT
	Viscosity (Pa·s)		
75	92	30.2	25.5
90	16.2	7.321	6.873
105	7.12	2.185	2.065
120	2.321	0.83	0.801
135	0.889	0.367	0.351
150	0.391	0.175	0.168
165	0.189	0.102	0.098
180	0.103	0.062	0.06
195	0.065	0.041	0.041

Viscosity Testing of Asphalt Binder

Viscosity testing was performed on asphalt binders that are recovered, rejuvenated, and rejuvenated with Evotherm® DAT WMA additive (rejuvenated with DAT). In preparing the rejuvenated with DAT asphalt binder, the rejuvenated asphalt binder was heated to approximately 120℃, the additive was added into the rejuvenated asphalt binder, and the blend of rejuvenated asphalt binder and the additive was then stirred thoroughly.

In viscosity testing of asphalt binder, the procedure in JTG E20-2011 T0625-2011 "Test Method for Rotational Viscosity (Brookfield Viscometer Method)" [23], which is equivalent to ASTM D4402/D4402M-13 "Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer" [15], was performed. Nine test temperatures, i.e., 75, 90, 105, 120, 135, 150, 165, 180, and 195℃, were used for better defining the relationship between temperature and viscosity in analyzing the test results. Two replicates were tested for each combination of material and temperature. Table 3 summarizes the averaged viscosities at various temperatures of the asphalt binders.

Table 3 shows that both the type of the asphalt binder and temperature have significant effects on the viscosity of asphalt binder. For given type of asphalt binder, the viscosity decreases with increasing temperature. At given temperature, the recovered, rejuvenated, and rejuvenated with DAT asphalt binders have the highest, the intermediate, and the lowest viscosities, respectively.

Compaction Testing of Asphalt Mixture

Compaction testing was performed on asphalt mixtures using the aggregate and asphalt binders that are aged, rejuvenated, and rejuvenated with Evotherm® DAT WMA additive (rejuvenated with DAT). In preparing the asphalt mixture with the aged asphalt binder, the RAP was directly heated to the required temperature and remixed for compaction testing. In preparing the asphalt mixture with the rejuvenated asphalt binder, the rejuvenator was added into the heat RAP, and the blend was mixed for compaction testing. In preparing the asphalt mixture rejuvenated with DAT asphalt binder, the rejuvenator and the additive were added in order into the heated RAP, and the blend was then mixed for compaction testing.

Prior to compaction testing, verification tests were carried out on the HMA with rejuvenated asphalt binder in accordance with the requirements and Marshall procedure in JTG F40, which was similar to the procedure in Asphalt Institute MS-2 [27]. Seventy five (75) blows per side were applied in compacting the specimen, simulating heavy traffic. Results of the verification tests indicated that the asphalt mixture met all the volumetric and performance requirements when the RAP asphalt content 4.1% was selected as the optimum asphalt content. Particularly, the design air voids was 4.6%, which was within the range of 4-6% specified in JTG F40. Based on the results, a single asphalt content of 4.1% was then used for the three asphalt mixtures and design air voids of 4.6% was used as the reference value in evaluating the variation of air voids with temperature of the asphalt mixtures.

In compaction testing of asphalt mixture, the procedure in JTG E20 T0702-2011 "Test Method for Preparation of Asphalt Mixture Specimens (Compaction Method)" [23], which is equivalent to ASTM D6926-10 "Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus" [15], was performed with 75 blows per side in preparing the specimen for air voids measurements. Six test temperatures, i.e., 115, 125, 135, 145, 155, and 165℃, were used for better defining the relationship between temperature and air voids in analyzing the test results, which were average temperatures during test. Four replicates were tested for each combination of material and temperature. Table 4 summarizes the averaged air voids at various temperatures of the asphalt mixtures.

Table 4 shows that both the type of the asphalt binder in the asphalt mixture and temperature have significant effects on the air voids of asphalt mixture. For a given type of asphalt binder, the air voids decreases with increasing temperature. At a given temperature, the asphalt mixtures with the aged, rejuvenated, and rejuvenated with DAT asphalt binders have the highest, the intermediate, and the lowest values of air voids, respectively.

Table 4. Results of Compaction Testing of Asphalt Mixtures.

Temperature (℃)	Asphalt Binder in Mixture		
	Aged	Rejuvenated	Rejuvenated+DAT
	Air Voids (%)		
115	—	—	4.7
125	—	5.2	4.3
135	5.4	4.8	4
145	5.1	4.4	3.8
155	4.7	4.2	—
165	4.3	—	—

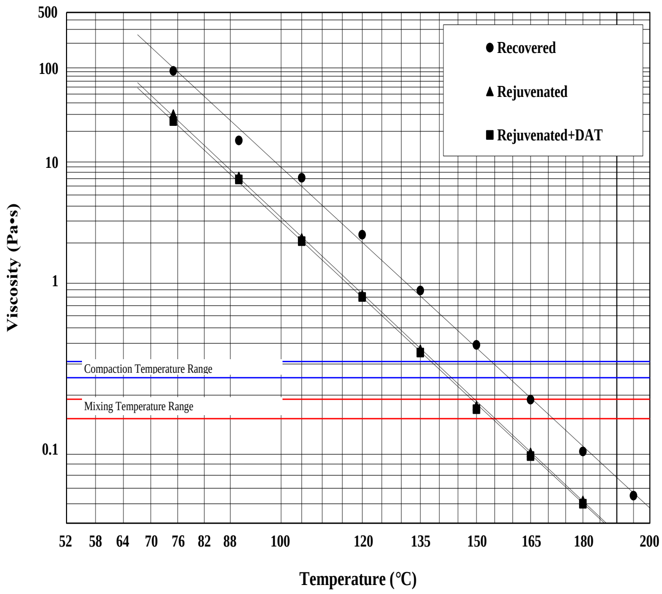

Fig. 1. Results of Viscosity Testing of Asphalt Binders.

Data Analyses

The data analyses include analysis on viscosity testing data of asphalt binder and analysis on compaction testing data of asphalt mixture. These analyses are to examine the applicability of traditional equiviscous principle to WMA and develop a rational method for determining mixing and compaction temperatures of WMA.

Analysis of Binder Viscosity Data

Fig. 1 graphically illustrates the results of viscosity testing of asphalt binders in Table 3. In plotting the data, the method in ASTM D2493/D2493M-09 "Standard Viscosity-Temperature Chart for Asphalts" [15] was adopted. The coordinates are logarithm of the viscosity in mPa·s as the ordinate, and logarithm of the absolute temperature in degrees Kelvin (degrees Celsius + 273.2) as the abscissa. However, the viscosity in Pa·s and the temperature in degrees Celsius are shown in the figure for convenience.

Fig. 1 shows that for all the three asphalt binders, the viscosity is a well defined linear function of temperature. In addition, these straight lines are nearly parallel to each other, or have close slope values. In order to examine the applicability of the equiviscous principle to the asphalt mixtures with the asphalt binders for determining the mixing and compaction temperatures, it is convenient to analytically express the relationship between temperature and viscosity as a first step. Assuming the viscosity is a linear function in the coordinates defined in ASTM D2493 for a given asphalt binder, the relationship between temperature and viscosity can be described using Eq. (1):

$$Y = \log[\log(V \times 1000)] = AX + B = A\log(T + 273.2) + B \qquad (1)$$

where
V = viscosity, Pa·s,
T = temperature, ℃,
A = slope of Y versus X linear function, and
B = intercept of Y versus X linear function.

Table 5 shows the values of parameters A and B, as well as the coefficients of determination R^2, for the relationships between temperature and viscosity of the asphalt binders from regression analyses.

With values of parameters A and B, the mixing and compaction temperatures of asphalt mixture can be found using Eq. (1) for given asphalt binder. For convenience, Eq. (1) can be rewritten as Eq. (2):

$$T_{\lim} = 10^{\frac{\log[\log(V_{\lim} \times 1000)] - B}{A}} - 273.2 \qquad (2)$$

Table 5. Values of Parameters from Regression Analyses and Mixing and Compaction Temperatures of Asphalt Mixture Calculated Using Equiviscous Principle.

Parameter		Asphalt Binder			Difference between HMA and WMA
		Recovered	Rejuvenated	Rejuvenated +DAT	
A		-3.404	-3.463	-3.436	
B		9.352	9.451	9.379	
R^2		0.9978	0.9997	0.9996	
Mixing Temperature (℃)	Lower Limit	165.4	149.4	148.6	0.8
	Average	168.4	152.3	151.5	0.8
	Upper Limit	171.4	155.1	154.3	0.8
Compaction Temperature (℃)	Lower Limit	154.1	138.7	137.8	0.9
	Average	156.5	141	140.1	0.9
	Upper Limit	158.9	143.3	142.4	0.8

where

T_{lim} = limit temperatures, i.e., lower or upper limits of mixing or compaction temperatures, ℃, and

V_{lim} = limit viscosities, i.e., 0.17±0.02 Pa·s and 0.28±0.03 Pa·s for mixing and compaction, respectively.

With Eq. (2), the lower and the upper limits of the mixing and the compaction temperatures of asphalt mixture can be calculated. Table 5 also shows these calculated mixing and compaction temperatures, as well as the average of the lower and upper limits. Of mixing temperatures, the lower limit is the temperature corresponding to viscosity of 0.17+0.02 = 0.19 Pa·s, the upper limit is the temperature corresponding to viscosity of 0.17-0.02 = 0.15 Pa·s, and the average is the mean of the lower and upper limits. Of compaction temperatures, the lower limit is the temperature corresponding to viscosity of 0.28+0.03 = 0.31 Pa·s, the upper limit is the temperature corresponding to viscosity of 0.28-0.03 = 0.25 Pa·s, and the average is the mean of the lower and upper limits.

Table 5 shows that the mixing temperature for asphalt mixture with the aged asphalt binder exceeds 165℃, which may cause excessive degradation of the already aged asphalt binder. It is also seen that for the rejuvenated asphalt binder, the mixing and compaction temperatures are decreased by at least 15℃, compared with those for the aged asphalt binder. However, for the rejuvenated asphalt binder with DAT, the mixing and compaction temperatures are essentially the same as those for the rejuvenated asphalt binder without the additive. The last column of Table 5 shows the differences between mixing or compaction temperatures of rejuvenated and rejuvenated with DAT asphalt binders (HMA and WMA). It is seen that there is only a temperature decrease of less than 1℃ with the addition of Evotherm® DAT, far below the value recommended by the additive manufacturer and used in paving practice. This indicates that traditional equiviscous principle is at least not applicable to Evotherm® DAT WMA for determining mixing and compaction temperatures. It is noted that the addition of Evotherm® DAT is in fact a modification to the asphalt binder. Modified binders exhibit a phenomenon known as pseudoplasticity. Viscosity measurements based on the current procedure are apparent values, which do not accurately match the viscosity values seen during mixing and compaction since they do not include the effects of shear rate [28].

Analysis of Mixture Compaction Data

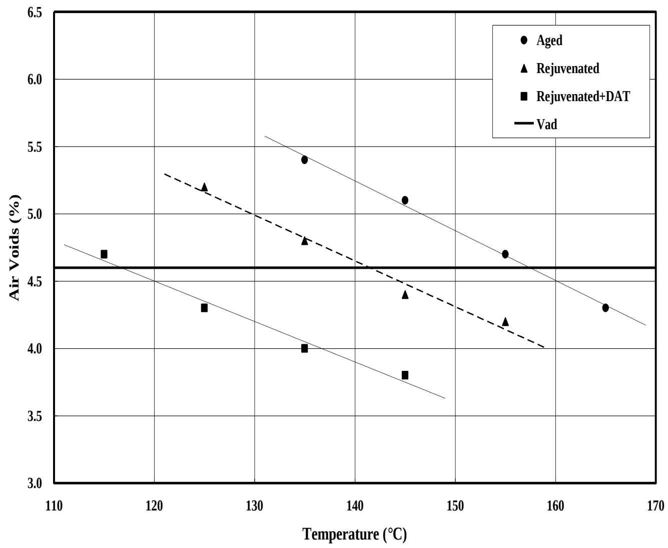

Fig. 2. Results of Compaction Testing of Asphalt Mixtures.

In view of the inapplicability of the equiviscous principle, data of compaction testing of asphalt mixture are analyzed for possible use in developing a method for determining the mixing and compaction temperatures of Evotherm® DAT WMA. Fig. 2 graphically illustrates the results of compaction testing of asphalt mixture in Table 4. In plotting the data of Table 4 in Fig. 2, regular arithmetic coordinates were used for air voids in percentage as the ordinate and temperature in degrees Celsius as the abscissa.

Fig. 2 shows that for all the three asphalt mixtures, the value of air voids is a well defined linear function of temperature. In addition, these straight lines are nearly parallel to each other, or have close slope values. In order to explore the use of the mixture compaction data in determining the mixing and compaction temperatures of asphalt mixture, it is convenient to analytically express the relationship between temperature and air voids as a first step. Assuming the air voids is a linear function for given asphalt mixture, the relationship between temperature and air voids can be described using Eq. (3):

$$V_a = A'T + B' \quad (3)$$

where

V_a = air voids, %,

T = temperature, ℃,

Table 6. Values of Parameters from Regression Analyses and Mixing and Compaction Temperatures of Asphalt Mixtures Calculated Using Equi-viscous-volumetric Principle.

Parameter		Asphalt Binder in Mixture			Difference between HMA and WMA
		Aged	Rejuvenated	Rejuvenated +DAT	
A'		-0.037	-0.034	-0.03	
B'		10.425	9.41	8.1	
R^2		0.9956	0.9797	0.9783	
Mixing Temperature (℃)	Lower Limit	166.4	149.9	125.2	24.8
	Average	169.4	152.8	128	24.7
	Upper Limit	172.3	155.6	130.9	24.7
Compaction Temperature (℃)	Lower Limit	155	139.2	114.4	24.8
	Average	157.4	141.5	116.7	24.8
	Upper Limit	159.8	143.8	119	24.8

A' = slope of V_a versus T linear function, and
B' = intercept of V_a versus T linear function.

Table 6 shows the values of parameters A' and B', as well as the coefficients of determination R^2, for the relationships between temperature and air voids of the asphalt mixtures from regression analyses.

Determination of Mixing and Compaction Temperatures

The value of air voids of asphalt mixture in compaction testing is related to properties of asphalt binder, mineral aggregate, compaction effort, and compaction temperature. For given asphalt binder, mineral aggregate, and compaction effort, the value of air voids is a function of compaction temperature. In other words, the compaction temperature can be selected as the temperature corresponding to a prescribed value of air voids of asphalt mixture in compaction testing. The air voids can be design value or the value corresponding to average compaction temperature determined using equiviscous principle with neat asphalt binder. This method for determining the compaction temperature is termed equivolumetric principle in this study.

The compaction temperature determined using the equivolumetric principle takes into account influencing factors not only of asphalt binder but also of mineral aggregate, i.e., the characteristics of asphalt mixture as a whole. At the compaction temperature, the asphalt binder provides appropriate lubrication for densification during compaction of asphalt mixture. In fact, the relationship between temperature and air voids reflects the true viscosity of asphalt binder in asphalt mixture. For given mineral aggregate and compaction effort, different asphalt binders have the same true viscosity at respective temperatures corresponding to any given air voids.

By rewriting Eq. (3), the compaction temperature can be expressed as Eq. (4):

$$\overline{T}_c = \frac{V_{ad} - B'}{A'} \tag{4}$$

where
V_{ad} = design or otherwise specified value of air voids, %.

The temperature determined using Eq. (4) is the average compaction temperature. To determine the mixing and compaction temperature ranges, appropriate approaches are required for estimating the average mixing temperature and limits of mixing and compaction temperatures of asphalt mixture.

Examination of Table 6 and observation of Fig. 2 indicate that an assumption can be made that the straight lines representing the relationship between temperature and air voids in Fig. 2 are parallel, or have same slope values, for the asphalt mixtures with the asphalt binders that are aged, rejuvenated, and rejuvenated with Evotherm® DAT WMA additive (rejuvenated with DAT). With the assumption, the difference between the average mixing and compaction temperatures remains the same as that determined using the equiviscous principle, and the average mixing temperature can be determined using Eq. (5):

$$\overline{T}_m = \overline{T}_c + \left(\overline{T}_m - \overline{T}_c\right)_b \tag{5}$$

Also with the assumption, the differences between the upper and lower mixing and compaction temperatures remain the same as those determined using the equiviscous principle, i.e., Eqs. (6) and (7):

$$T_c = \overline{T}_c \mp \frac{\Delta T_c}{2} \tag{6}$$

$$T_m = \overline{T}_m \mp \frac{\Delta T_m}{2} \tag{7}$$

in Eqs. (5) through (7)
$\overline{T}_c$ and $\overline{T}_m$ = average compaction and mixing temperatures, respectively, ℃,
$(\overline{T}_m - \overline{T}_c)_b$ = difference between average mixing and compaction temperatures determined using the equiviscous principle, ℃,
T_c and T_m = compaction and mixing temperature ranges, respectively, ℃,
ΔT_c and ΔT_m = differences between upper and lower compaction and mixing temperature limits determined using the equiviscous principle, ℃.

The method in Eqs. (4) through (7) is a combination of traditional equiviscous principle and the equivolumetric principle for determining the mixing and compaction temperatures of WMA.

This method is termed equi-viscous-volumetric principle in this study.

Table 6 also shows the calculated mixing and compaction temperatures using the equi-viscous-volumetric principle in Eqs. (4) through (7). For convenience, the design air voids 4.6% was used for determining the compaction temperature with Eq. (4). It is seen, by comparing data in Tables 6 and 5, that the average compaction temperatures for asphalt mixtures with the aged asphalt binder and the rejuvenated asphalt binder using different methods have essentially same values. At 4.6% air voids, the average compaction temperatures for asphalt mixture with the aged asphalt binder are 157.4℃ using the equivolumetric principle and 156.5℃ using the equiviscous principle. The average compaction temperatures for asphalt mixture with the rejuvenated asphalt binder are 141.5℃ using the equivolumetric principle and 141.0℃ using the equiviscous principle. The fact that average compaction temperatures for asphalt mixtures with the aged asphalt binder and rejuvenated asphalt binders have essentially same values indicates that the equivolumetric principle and the equiviscous principle are equivalent for neat asphalt binders.

On the other hand, as shown in Table 6, the average compaction temperatures for asphalt mixtures with the rejuvenated asphalt binder with DAT are 116.7℃ using the equivolumetric principle and 140.1℃ using the equiviscous principle. The temperature reduction is increased from 0.9℃ to 24.8℃, which is close to the value recommended by the additive manufacturer and used in paving practice. This indicates that the equi-viscous-volumetric principle is applicable to Evotherm® DAT WMA for determining mixing and compaction temperatures.

It is noted that although the equi-viscous-volumetric principle was developed using Evotherm® DAT WMA of 100% RAP and Marshall compaction procedure, the method for determining mixing and compaction temperatures of WMA should not be considered to be applicable to the specific constituent materials and test procedure only. It is expected that the method should provide valuable reference for WMA with other percentages of RAP, other types of WMA additive, or other procedures of compaction, e.g., the procedure in ASTM D6925-09 “Standard Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor” [15]. It is also noted that there are many WMA technologies with varying mechanisms. Whether or not the method developed is applicable to a specific WMA in determining mixing and compaction temperatures requires case-by-case verification with results of tests and analyses of results.

Conclusions

Laboratory viscosity testing of asphalt binder and compaction testing of asphalt mixture were performed to develop a rational method for determining mixing and compaction temperatures of warm mix asphalt (WMA) using 100% reclaimed asphalt pavement (RAP), RAP-WMA, with Evotherm® DAT technology. Results of laboratory tests and analyses of the results indicate that following conclusions are appropriate:

(1) Traditional equiviscous principle is not applicable to the RAP-WMA. Compared with RAP hot mix asphalt (HMA), RAP-HMA, the reductions in mixing and compaction temperatures of RAP-WMA determined using the equiviscous principle are only less than 1℃. These ignorable reductions are apparently against the original objective of developing WMA.

(2) An equivolumetric principle can be used for determining average compaction temperature of RAP-WMA, which is defined as the temperature corresponding to a prescribed value of air voids of asphalt mixture. The compaction temperature takes into account influencing factors not only of asphalt binder but also of mineral aggregate, i.e., the characteristics of asphalt mixture as a whole.

(3) A method, termed equi-viscous-volumetric principle, developed in this study can be used for determining mixing and compaction temperatures of RAP-WMA, which is a combination of the equiviscous principle and the equivolumetric principle. Compared with RAP-HMA, the reductions in mixing and compaction temperatures of RAP-WMA determined using this method are around 25℃. These reductions are close to values recommended by the additive manufacturer and used in paving practice.

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