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Asphalt Binder Grading System by Indirectly Estimated Parameters and Relationship to Performance Related Properties of Asphalt Mixture

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Abstract: Nowadays, there have been initiative ideas to improve current use of grading system in Thailand by replacing with SUPERPAVE grading system. Unfortunately, such system requires complex and expensive equipment which is unavailable in Thailand. The knowledge in understanding the implementation of the system is also limited. Moreover, the SUPERPAVE specification is particularly based on the pavement conditions in USA. Therefore, a development of the performance grading system using indirectly estimated parameters related to pavement performance is proposed in this study. According to the existing pavement conditions in Thailand, the eligible performance related properties are examined and the acceptable limits for the acceptance of asphalt cement are determined. Additionally, the preparation of asphalt mixtures from the newly graded asphalt cement is investigated for their performance related properties in Thai traffic and climate conditions. After the validation of such developed system, it has been found that the proposed performance grading system can be satisfactorily used to classify the binders by its performance. Results of the proposed system are also comparable with the SUPERPAVE system. Finally, the proposed system can be used as a transition before obtaining the sufficient equipment and gaining sufficient understanding for SUPERPAVE implementation without using any complex and expensive equipment.

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Key words*: Asphalt cement; Asphalt binder; Classification; Performance grading system.*

Introduction

In Thailand, asphalt cement specifications have been developed for a long time by Thailand Industrial Standard Institute (TISI). Two types of grading systems: penetration and AC viscosity grading systems have been referred according to the Thai asphalt cement specifications [1]. However, only penetration grading system is specified as the asphalt cement standard by many highway agencies such as the Department of Highway (DOH), the Department of Rural Road (DOR), and the Department of Public Works and Town & Country Planning (DPT). Four penetration grades: AC40-50, AC60-70, AC85-100, and AC120-250, are included in the specification used in typical road projects. The penetration grading specification requires measurement and control of asphalt binder's physical properties including consistency, durability, purity and safety. The performance-related properties such as rutting, fatigue cracking and thermal cracking are not considered directly in this specification. Additionally, the rheological properties of asphalt cement during the long-term aging, which represent the condition of asphalt cement under further aging during a long term service period, are neglected. Other factors affecting pavement performance such as traffic volume, traffic speed, traffic load, temperature and moisture, are not considered in the current use of Thai specifications. For these reasons, the current specifications of the asphalt cement used in Thailand needs to be changed to include performance-related properties. These properties are more related to the performance of pavement layers subjected to various climatic and traffic conditions particularly in Thailand.

In the U.S.A., SUPERPAVE performance grading (PG) system, which was developed by the Strategic Highway Research Program (SHRP) in the early 1990s, has been used. The practice of building roads and the use of roads are quite similar between USA and Thailand. There is no doubt that the PG system can be sufficiently applied in Thailand. However, there are some difficulties to apply such system due to the lack of complex and expensive equipment in many provincial authorities. Moreover, the development of parameter criteria currently used in SUPERPAVE specification is based on the pavement conditions in the U.S.A, which is somewhat different from Thailand in terms of traffic and climate.

Bahia et al. [2] established the concept and protocol of the simple performance grading system for developing countries where the SUPERPAVE equipment is not available to grade the performance of asphalt cement. However, the relationship between asphalt cement performance grading and the performance related properties of asphalt mixtures produced by selected asphalt cement has not been investigated yet.

The purpose of this research is therefore to use similar concepts to develop a performance grading system based on indirectly estimated parameters that can be simply implemented in Thailand without using any complex and expensive equipment. In this proposed specification, the performance related properties are selected and the acceptable limits for the acceptance of asphalt cement are defined according to the existing pavement conditions in Thailand. In addition, the asphalt mixtures are prepared from the newly graded asphalt cements to investigate their performance related properties in Thai traffic and climate conditions.

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The Concept of Performance Grading System based on Indirectly Estimated Parameters

To develop a performance grading system based on indirectly estimated parameters, four performance related properties of asphalt binders are identified in this study including workability, permanent deformation (rutting) resistance, fatigue cracking resistance and thermal cracking resistance [2, 3].

Workability

For workability, the rotational viscometer (RV) has been adopted in SUPERPAVE specification for determining the asphalt viscosity at high temperature during the HMA production and construction process [4]. This is to ensure that the binder is sufficiently liquefied to be pumped and mixed during the construction process. Since such equipment is not affordable for many local pavement authorities in Thailand, a more affordable substitute is needed. Currently, the viscosity of asphalt binders is determined by using the kinematic viscosity tested at a temperature of 135°C which is the standard test method in Thailand [1]. This test method is used and the results are correlated to the RV results to determine if the substitution can be considered valid. Note that the current limits used in the TISI requirements for the kinematic viscosity should be changed to match the requirement in the SUPERPAVE system.

Permanent Deformation Resistance

The rutting resistance is normally increased by using stiffer asphalt binder with higher viscosity or lower penetration grade. The stiffness of asphalt binder is continuously increased during aging [5]. Therefore, the short-term aging of asphalt binder, which represents the production and construction process, should be considered. In addition, because the short term aging protocol of binder in the laboratory does not always indicate the actual aging during HMA production and placement in the field, additional control on the stiffness of original (un-aged) asphalt binder can be included as a safeguard. Consequently, the stiffness of the original and the short term aged asphalt binders at various high temperatures, depending on the climate, can be measured for control of rutting resistance.

The complex shear modulus (G*) and the phase angle (δ) of binder measured by using the dynamic shear rheometer (DSR) are used to determine the rutting parameter (G*/sinδ) for the control of the permanent deformation or rutting in the SUPERPAVE asphalt binder specification [4]. Due to the limited number of DSR equipment used in Thailand, the stiffness of asphalt binder, $S_b(t)$, is proposed to replace G*/sinδ in this study. The binder stiffness can be determined by using an indirect measurement which makes use of Van der poel nomograph [6]. The stiffness modulus can be determined from this nomograph based on the penetration and the softening point ($T_{R\&B}$) at a range of temperature and loading time using the penetration index (PI). Additionally, the estimated stiffness modulus after RTFO-aged can be determined by using the developed relationship between the stiffness values before and after Rolling Thin Film Oven (RTFO) short-term aging. This relationship is used to estimate the stiffness after the RTFO short-term aging without the need for the G* modulus measurement.

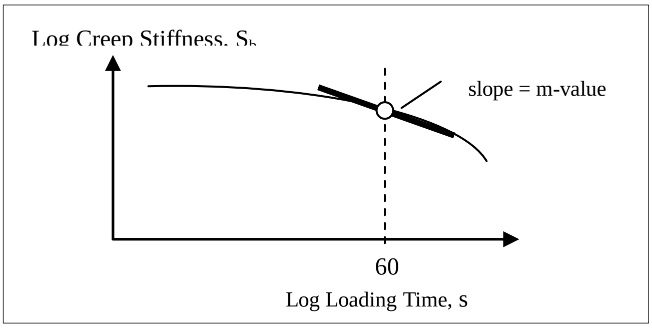

Fig. 1. Determining of m-value.

Generally, the asphalt binder becomes stiffer during its service life due to aging, which results in high potential of fatigue cracking susceptibility [5]. According to the SUPERPAVE specification, the fatigue parameter (G*sinδ) obtained from the DSR testing is chosen to limit fatigue cracking for long term aged binder. The pressure aging vessel (PAV) has been used to simulate the long term aged binder that occurs during 5-10 years of in-service HMA pavement [4]. For the proposed specification in this study, the estimated $S_b(t)$ after long term aging using the Van der poel nomograph is proposed to control fatigue cracking at intermediate service temperature. To represent long-term aging, adjustments for the $T_{R\&B}$ and PI are determined to simulate the long-term aged by PAV.

Thermal Cracking Resistance

High creep stiffness can result in greater potential of cracking when temperature drops rapidly [5]. The parameter of S_b and m-value measured by Bending Beam Rheometer (BBR) and Direct Tension Tester (DTT) tests are required to evaluate low temperature cracking in SUPERPAVE specification [4]. In the proposed system, the estimated S_b from the nomograph and the calculated m-value are proposed as substitutions. The calculated m-value is the slope of the plot of stiffness against time in log-log scale as shown in Fig. 1. Moreover, the breaking stress and/or tensile strain at break (λ) of binder are proposed to control brittleness of binders because the break normally occurs under condition of large stress and low temperature. The λ can be determined by using Heukolom's nomograph [7]. The effect of PAV aging is also considered for thermal cracking similar to the fatigue requirement, with the same adjustment factors.

Proposed Performance Grading System

Climate Data Analysis and Pavement Temperature Determination

Based on the concept of performance grading system, asphalt binders should be selected for the climate in where the binders will be used [4]. The pavement temperature is therefore needed for the selection of binder grading system. In this study, the pavement temperature in Thailand is incorporated into the proposed performance grading system.

The distribution of pavement temperatures, such as maximum and minimum design pavement temperature, can be determined from the relationship between pavement temperature and air temperature. The 30 years (1977 to 2007) of air temperature data in Thailand is obtained from the Thai Meteorological Department (TMD). For each year, the seven-day period with highest temperature is determined and the average maximum air temperature for those seven consecutive days is calculated. For the lowest temperature, it is identified from the lowest temperature day of each year. For all 30 years of record, a mean and standard deviation are computed.

To predict the maximum pavement temperature, the relationships between pavement temperature and air temperature were developed for all regions in Thailand. These relationships were obtained by observing air temperature and pavement temperature both at the pavement surface and at the depth of 50 mm below the surface. A linear relationship between air temperature and maximum pavement temperature was established. Note that other variables such as wind speed, sun radiation, and moisture in the atmosphere can also affect the pavement temperature. However, these variables are excluded from the pavement temperature prediction model in this study for the simplicity. The maximum pavement temperature models developed for all regions in Thailand are shown in Table 1.

Table 1 indicates that the maximum pavement temperature model at the pavement surface for northern, northeastern and southern regions achieves a goodness-of-fit R^2 of 0.944 0.818, and 0.899 respectively. For the maximum pavement temperature model at depth of 50 mm below surface, R^2 of northern and northeastern regions are 0.813 and 0.738, respectively.

According to SUPERPAVE [8], the average 7-day maximum pavement temperature ($T_{(Max)}$) defines the binder laboratory test temperature. A factor of safety can be associated into the performance grading system based on temperature reliability. The 50% reliability temperatures represent an average of the weather data. The 98 % reliability temperatures are determined based on the standard deviations of the high temperature ($\sigma_{High\ Temp}$) data. From statistics, 98 % reliability is two standard deviations from the average value, in which $T_{(Max)\ at\ 98\%} = T_{(Max)\ at\ 50\%}+2\sigma_{High\ Temp}$.

Based on the models in Table 1, the expected maximum pavement temperatures calculated at 50% and 98% reliability for each region are presented in Table 2.

As the minimum pavement temperature is not critical in Thailand, and the low pavement temperature has never been recorded, in this study, the minimum pavement temperature at surface was estimated from the air temperature data collected by TMD, and converted to minimum pavement temperature by using the SUPERPAVE low temperature model at the pavement surface. The low temperature model [9] is shown as Eq. (1):

$$T_{PAV@SURFACE(Min)} = 0.286+0.692T_{AIR(Min)} \quad (1)$$

The minimum pavement temperature at specified depth can be calculated using the following equation [9]:

$$\begin{aligned} T_{d(Min)} &= T_{PAV@6.4mm(Min)} \\ &- \left[0.00123T_{PAV@6.4mm(Min)}(d-6.4)\right]+0.0146(d-6.4) \end{aligned} \quad (2)$$

where, $T_{d(Min)}$ = minimum pavement temperature at depth d
d = depth from surface, mm
$T_{PAV@6.4mm(Min)}$ = minimum pavement temperature at 6.4 mm
= 2.27+0.778 $T_{AIR(Min)}$ for air temperature below 0°C
= 6.83+1.014 $T_{AIR(Min)}$ for air temperature above 0°C

Eqs. (1) and (2) were derived from Wisconsin, U.S. weather condition which had very low temperature compare to Thailand. However, these equations are assured to cover minimum temperature in Thailand.

Similar to the maximum pavement design temperature, the

Table 1. Maximum Pavement Temperature Model for all Regions in Thailand.

Region of Thailand	$T_{PAV@surface(Max)}$*	R^2	$T_{PAV@50mm(Max)}$†	R^2
NORTH	$-2.131+1.073T_{air(max)}$ ‡ Tair(Max)	0.944	$-0.186+1.087\ T_{air(Max)}$ ‡	0.813
NORTHEAST	$-3.561+1.221\ T_{air(Max)}$ ‡	0.818	$-1.042+1.197\ T_{air(Max)}$ ‡	0.738
CENTRAL	$-3.741+1.285\ T_{air(Max)}$ ‡	0.552	$-8.344+1.438\ T_{air(Max)}$ ‡	0.592
EAST	$0.019+1.227\ T_{air(Max)}$ ‡	0.48	$-2.577+1.315\ T_{air(Max)}$ ‡	0.522
SOUTH	$-1.936+1.086\ T_{air(Max)}$ ‡	0.899	$9.569+0.902\ T_{air(Max)}$ ‡	0.414

* $T_{PAV@surface(MAX)}$ = maximum pavement temperature at the pavement surface (°C)
† $T_{PAV@50mm(MAX)}$ = maximum pavement temperature at 50 mm below the surface (°C)
‡ $T_{air(MAX)}$ = maximum air temperature (°C)

Table 2. Maximum Pavement Design Temperatures for Thailand.

Region of Thailand	%Reliability	$T_{air(7days-Max)}$ ℃	$T_{PAV@surface(Max)}$ ℃	$T_{PAV@50mm(Max)}$ ℃
NORTH	50	41	42	44
	98	45	51	54
NORTHEAST	50	41	47	48
	98	43	55	57
CENTRAL	50	40	48	49
	98	44	57	59
EAST	50	38	47	47
	98	42	56	57
SOUTH	50	38	39	44
	98	40	47	53

Table 3. Minimum Pavement Design Temperatures for Thailand.

Region of Thailand	% Reliability	$T_{air(Min)}$ ℃	$T_{PAV@surface(Min)}$ ℃	$T_{PAV@50mm(Min)}$ ℃
NORTH	50	5	4	12
	98	-1	-2	6
NORTHEAST	50	6	4	13
	98	2	0	9
CENTRAL	50	10	7	17
	98	4	1	11
EAST	50	12	9	19
	98	8	4	15
SOUTH	50	16	11	22
	98	10	5	16

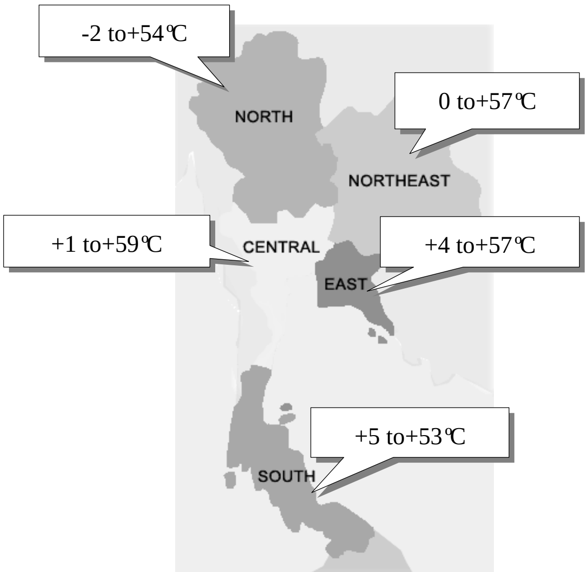

Fig. 2. Pavement Design Temperature for Thailand (at 98% Reliability)

expected minimum pavement temperature using the SUPERPAVE low temperature models for each region at 50% and 98% reliability in which $T_{(Min)\ at\ 98\%} = T_{(Min)\ at\ 50\%} + 2\sigma_{Low\ Temp}$ are calculated and represented in Table 3.

The performance grading system allows users to select binder grades for climate, which is specific to each paving project location. Thus, the performance grade number for the proposed grading system is based on existing temperature conditions that cover high and low pavement temperature as shown in Fig. 2. The set of binder grades can then be selected to cover the temperature conditions in all regions.

Based on Fig. 2, the high temperature grades of PG58 and PG64 are proposed to cover the range of high temperature for Thailand pavement. With the consideration of high traffic volume and/or slow moving traffic, PG70 grade is also included. For low temperatures ranging between -2℃ and +5℃, it is reasonable to use binder grades with low temperature of +8.0, +2.0, and -4.0℃. A total of 6 grades are therefore proposed in the new system as shown in Table 4.

Selection of Asphalt Binder for Testing and Development of Proposed Grading System

Five sources of asphalt binders which are commonly used in Thailand (Type I, II, III, IV, and V) are selected to perform traditional tests. These binders are the reference binders used for development of limits in the proposed grading system. The traditional tests include the penetration test at 25℃ and the softening point test ($T_{R\&B}$). These tests were conducted at three different aging stages, un-aged, RTFO-aged and PAV-aged. The test results are summarized in Table

Table 4. Proposed Performance Grading System for Thailand.

Proposed Grade		PG58		PG64		PG70	
High Temperature Grade (HT)		58		64		70	
Low Temperature Grade (LT)		2	-4	2	-4	8	2
Performance Related Property	Performance Criteria						
Part 1: For Workability							
Brookfield Viscosity	Max. 3 Pa.s (3,000 cP)	Temp=135°C					
Kinematic Viscosity	Max. 2,700 cSt.						
Part 2: For Rutting Resistance							
Estimated Creep Stiffness (Un-aged) @HT, kPa	S(0.0015) ≥ 27kPa	58		64		70	
Estimated Creep Stiffness (RTFO-aged) @HT, kPa	S(0.0015) ≥ 60kPa	58		64		70	
Part 3: For Fatigue Resistance							
Estimated Creep Stiffness (PAV-aged), kPa	S(0.015) ≤ 60,000 kPa	30	27	33	30	39	36
Part 4: For Thermal Cracking Resistance							
Estimated Creep Stiffness (PAV-aged), kPa	S(60) ≤ 300,000 kPa	12	6	12	6	18	12
Estimated Creep Rate (PAV-aged)	m(60) ≥ 0.3	12	6	12	6	18	12
Elongation at break	λ(60) ≥ 0.02	12	6	12	6	18	12

Table 5. Current Asphalt Binders Using in Thailand.

Source	Pen	PG	Pen@25°C (0.1mm)			$T_{R\&B}$ (°C)			PI		
			Original	RTFOT	PAV	Original	RTFOT	PAV	Original	RTFOT	PAV
I	60/70	64-22	63	38	23	47.1	52.3	58	-1.4	-1.2	-1
II	60/70	64-22	64	39	24	46.3	52.3	57.3	-1.6	-1.2	-1.1
III	60/70	64-22	70	43	29	45.6	50.1	54.6	-1.6	-1.5	-1.3
IV	60/70	64-22	69	42	28	46.7	50.7	55.9	-1.3	-1.4	-1.1
V	60/70	64-22	68	38	24	48.5	55	62	-0.8	-0.6	-0.2
Min			63	38	23	45.6	50.1	54.6	-1.6	-1.5	-1.3
Max			70	43	29	48.5	55	62	-0.8	-0.6	-0.2
Average			67	40	26	46.8	52.1	57.6	-1.3	-1.2	-0.9
STDEV			3	2	3	1.1	1.9	2.8	0.3	0.3	0.4
85^{th} Percentile			69	42	28	47.7	53.4	59.6	-1.1	-1	-0.7

5, which indicates that all reference binders can be classified as penetration grade of 60/70, and performance grade of PG 64-22 based on the SUPERPAVE specification.

From the test results, the penetration and the softening point for un-aged, RTFO-aged, and PAV-aged binders were used to determine the PI values. It can be observed that the binders become stiffer after short and long term aging as shown in the reduction of penetration value and the increase of $T_{R\&B}$. It can also be seen that the PI values increases with aging.

Determination of the Acceptance Limit for Proposed Grading System

The acceptance limits of the proposed PG system are derived based on experience of engineering experts and field performance of asphalt binders. The performance-related properties are also evaluated to determine the acceptable limits for the grading of asphalt binders. The following performance related properties are selected for this study.

Workability

The workability of asphalt mixture during the mixing and compaction is controlled by asphalt binder viscosity. In this study, the existing viscosity measurement method which is the kinematic viscosity was conducted at 135°C, and used as the alternative for viscosity measurement. According to the SUPERPAVE specification, the viscosity is set at 3 Pa.s (3000 cP) using the Brookfield rotational viscometer. Fig. 3 shows the results measured from the kinematic viscosity test and the Brookfield viscosity test. Results from both measurements correlate very well at high R^2 value of 0.87. Therefore, the equation relating the two viscosity measures can be used to determine such that the kinematic viscosity of 2,700 cSt, can be considered equivalent to the Brookfield viscosity of 3 Pa.s. This kinematic viscosity value is selected as the acceptance limit for workability in the proposed grading system, as indicated in Part 1 of Table 4.

Rutting Resistance

As mentioned above, S_b at typical speed in moderate climate is estimated using the PI value from the Van der poel nomograph. The

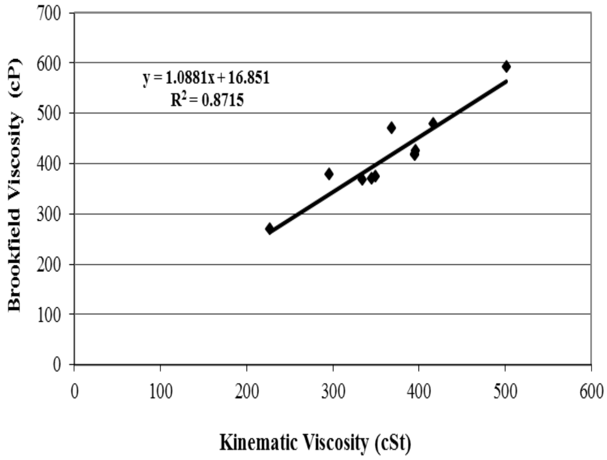

Fig. 3. Correlation between the Results Measured by the Brookfield Test and the Kinematic Viscosity Test.

speed of 60 km/hr is selected as typical speed based on the traffic condition in most highways in Thailand. In 1971 Barksdale and coworkers [10] had developed a chart of loading time as a function of vehicle speed and depth beneath the pavement surface. For the typical speed of 60 km/hr and a pavement surface thickness of 100 mm, the loading time is 0.015 seconds.

In this study, due to the unavailability of pavement performance data, the pavement engineers and experts were interviewed for their opinions on the performance of rutting resistance on Thailand highways. Based on their experience and the observation of field performance, it is determined that AC 60/70, which is normally used in Thailand, works well for the moderate traffic volume roads in the moderate climate zone. Since the maximum pavement design temperature of Thailand is close to 58°C; therefore, this temperature is proposed as the reference temperature to find the acceptance limit of S_b.

As explained earlier, the limit of S_b for rutting resistance is considered for un-aged and RTFO-aged binders. For all un-aged AC60/70 binders, the maximum PI of -0.8 (from Table 5) is used to represent the PI value for AC60/70. Moreover, $T_{R\&B}$ of 45°C is set to cover the minimum $T_{R\&B}$ of all five reference binders. The selection of PI and $T_{R\&B}$ is based on the assumption that all reference binders has performed well for rutting resistance. Using these values in the Van der poel nomograph, it shows that AC60/70 approximately gives

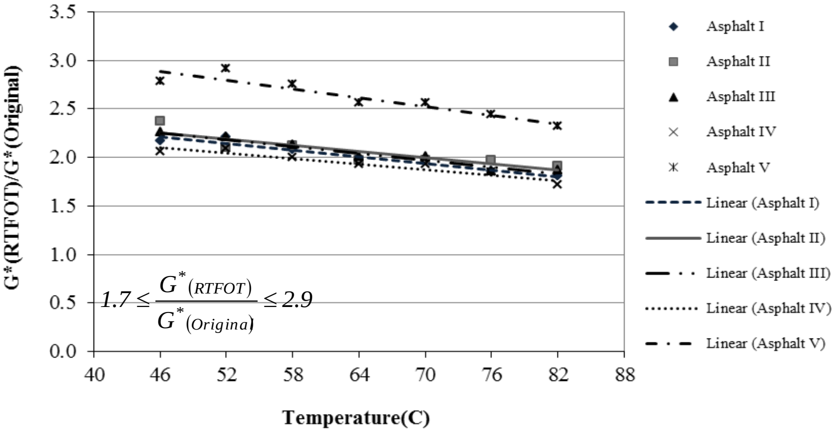

Fig. 4. Effect of RTFO Aging on G* at Varied Temperature.

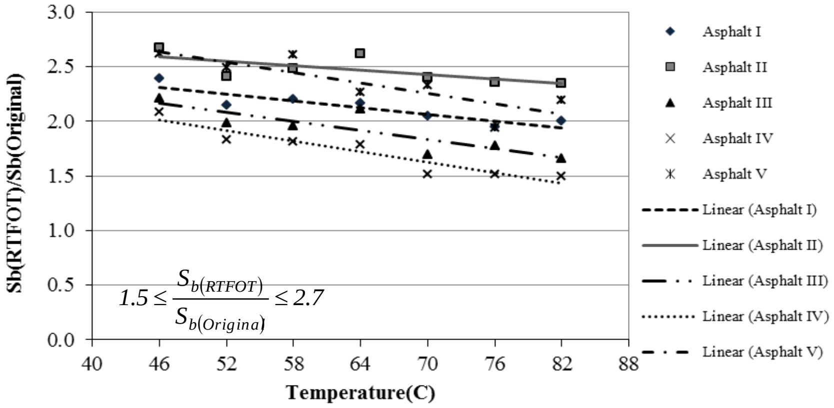

Fig. 5. Effect of RTFO Aging on S_b at Varied Temperature.

S_b(t = 0.015 sec) value of 27 kPa. This value is proposed in the new specification for all grades as shown in Table 4 (Part 2). This can be concluded that the S_b(t = 0.015 sec) of un-aged asphalt for all grades must be equal to or greater than 27 kPa at maximum design pavement temperature for the proposed system.

The effect of RTFO aging is considered using two parameters, G* and S_b. Based on DSR test results, as shown in Fig. 4, the G* values of RTFO-aged binders are 1.7 to 2.9 times higher than those of un-aged binders. Similarly, the estimated S_b of RTFO-aged binders are also, 1.5 to 2.7 times higher than those of un-aged binders as shown in Fig. 5. Therefore, the average value of 2.2 modulus ratio for the RTFO-aged to un-aged is proposed to achieve a minimum stiffness of RTFO-aged binders. As proposed in Table 4 (Part 2), the minimum S_b (t=0.015 sec) of RTFO-aged binders requires 2.2 times of 27 kPa which is approximately 60 kPa.

Fatigue Cracking Resistance

To identify stiffness limits for fatigue cracking resistance criterion, the field performance data was observed at the selected locations, and asphalt mixture samples were collected to determine the fatigue cracking parameter. Field cored samples from seven sites were collected based on the recorded fatigue performance within the pavement age of 5-10 years. Table 6 summarizes field performance data and the age of selected field cored samples in which sample C3 and C7 are in the top rank among all samples and show the best performance in resisting the fatigue cracking.

Asphalt binders were extracted from all samples, C1 to C7, and the G*sinδ parameter of all binders was measured, as the results shown in Table 7. Based on the SUPERPAVE specification, the G*sinδ parameter is chosen to limit the fatigue cracking with its maximum value of 5000 kPa. The decreasing amount of energy dissipated per load cycle by the lowering of G*sinδ value can minimize the chance of fatigue cracking occurrence. The results illustrate that the extracted binder of sample C3 shows the lowest G*sinδ value at all testing temperatures. It can be concluded that C3 binder performs the best in the resistance of fatigue cracking.

Due to the best performance in fatigue cracking resistance of C3, $T_{R\&B}$ and penetration were measured from the binder extracted from C3. The stiffness of C3 binder is estimated by using nomograph with $T_{R\&B}$, PI, and the intermediate pavement temperature in Thailand of 21℃. The binder stiffness obtained from the nomograph is 64.4 MPa (or 60 MPa). Thus, the S_b of 60 MPa is proposed as the maximum of S_b value for PAV-aged asphalt binder in the proposed specification, as shown in Table 4 (Part 3).

Low Temperature Cracking

Table 6. Field Performance Data of the Field Asphalt Mixture Samples.

Coring Sample	HW No.	Section	Province	Age	Pavement Thickness	Longitudinal Cracking		Transverse Cracking		Block Cracking		Rank
				(yr.)	(cm)	%Area	Severity	%Area	Severity	%Area	Severity	
C1	201	204+100 to 203+900	Loey	5	8	15%	2	0	0	5%	1	5
C2	36	42+700 to 42+500	Rayong	6	5	<5%	1	<5%	1	10%	2	4
C3	21	42+700 to 42+500	Saraburi	7	10	0	0	0	0	5%	2	2
C4	1	485+000 to 485+200	Lampang	7	7	0	0	5%	1	10%	2	3
C5	1	439+000 to 439+200	Tak	7	17	5%	1	35%	3	25%	3	6
C6	1	313+050 to 313+850	Kampang Petch	9	10	<10%	2	5%	3	15%	3	7
C7	101	415+500 to 415+300	Sokothai	10	5	5%	1	0	0	0	0	1

Table 7. SUPERPAVE Test Results of the Extracted Binders.

Coring Sample	Frequency Sweep, G*sin θ @T(℃) (kPa) < 5,000 kPa									Rank
	16	19	22	25	28	31	34	37	40	
C1	15,555	12,243	9,422	6,817	4,685	3,128	1,986	1,330	794	6
C2	9,028	6,684	4,731	3,450	2,224	1,344	834	489	293	3
C3	4,151	3,043	2,053	1,354	854	537	308	181	91	1
C4	7,241	5,301	3,771	2,417	1,542	906	529	304	107	2
C5	11,089	8,330	5,964	4,021	2,632	1,595	953	550	318	4
C6	11,599	8,732	6,272	4,385	2,848	1,750	1,089	663	391	5
C7	12,846	10,529	8,457	6,554	5,050	3,712	2,619	1,823	1,281	7

Thermal cracking is not a critical concern in Thailand due to the fact that the pavement temperature is not extremely low. Therefore, the criterion for low temperature cracking in SUPERPAVE specification is used as shown in Table 4 (Part 4). The S_b (t=60 sec) of PAV-aged binders must be equal to or less than 300 MPa, and the m-value must be equal to or greater than 0.3. The strain at break (λ) of PAV-aged binder is proposed to control binder brittleness at low temperature, using the Heukolom's nomograph. The minimum limit of λ of 0.02 is identified based on the $T_{R\&B}$ and PI of long term-aged binders with loading time of 60 seconds.

System Validation

The proposed performance grading system developed in this study was validated to classify asphalt binders currently used in Thailand, and to compare with the classification by the SUPERPAVE PG system. Four commercially available binders (A, B, C, and D) were graded based on the proposed specification and compared with the SUPERPAVE specification. The traditional measurements were conducted to measure fundamental properties and the results are shown in Table 8. It shows that the results of penetration test of all binders can be classified to two groups of penetration grade. Binder A and B are classified as grade 60/70, and binder C and D are classified as grade 40/50.

All binders were also graded using the SUPERPAVE grading system and performance grade of these binders are presented in Table 9. The results show that binder A and B are in the same PG grade, PG 64-22, while binder C and D are PG 70-16 and PG 64-16, respectively.

Parameter Validation

As described in the previous section, the estimated S_b parameter is proposed to substitute the G* parameter measured from DSR test. The creep stiffness (S_b) is plotted against complex shear modulus (G*) as presented in Fig. 6. It can be observed that both parameters show very high correlation for all performance aging stages which implies that the S_b parameter can be used to represent G*.

Comparison between Estimated S_b for RTFO-aged Binder and Measured S_b after RTFO-Aging

The comparison between estimated S_b(RTFO-aged) and Measured S_b(RTFO-aged) is plotted based on the test results of four binders as shown in Fig. 7. High correlation with R^2 value of 0.9507 was observed. This implies that the stiffness of asphalt binder after RTFO aging can be estimated based on the linear regression.

Comparison between Estimated Sb for PAV-aged Binder and Measured Sb after PAV-Aging

The estimation of S_b after PAV aging (S_b (PAV-aged)) is determined

Table 8. Traditional Properties of Four New Asphalt Binders.

Source	Pen.@25°C (0.1mm)			$T_{R\&B}$ (°C)			PI		
	Original	RTFO	PAV	Original	RTFO	PAV	Original	RTFO	PAV
A	67	42	26	46.8	50.1	55.7	-1.4	-1.5	-1.2
B	68	39	25	48.3	54.7	63.1	-0.9	-0.7	0.1
C	45	25	16	51.2	58.2	66.2	-1.1	-0.82	-0.2
D	44	29	20	50.2	54.2	59.2	-1.4	-1.4	-1
Min	44	25	16	46.8	54.6	55.7	-1.4	-1.4	-1.2
Max	68	42	26	51.2	62	66.2	-0.9	-0.9	0.1
Average	56	34	22	49.1	57.6	61.1	-1.2	-1.2	-0.6
STDEV	13	8	5	2	2.8	4.6	0.2	0.2	0.6
85th Percentile	68	41	26	50.8	59.6	64.8	-1	-1	0

Table 9. Classification of Asphalt Binders by Using SUPERPAVE Specification.

Asphalt	Pen	Original			RTFO			PAV			BBR			PG
		T (°C)	G* (kPa)	G*/sin θ (kPa) >1.0	T (°C)	G* (kPa)	G*/sin θ (kPa) >2.2	T (°C)	G* (MPa)	G*sin θ (MPa) <5.0	T (°C)	s (MPa) <300	m-value >0.3	
A	67	64	1.3	1.3	64	2.29	2.29	25	4.38	4.38	-12	276	0.344	64-22
B	68	64	1.51	1.5	64	3.35	3.37	22	5.81	4.02	-12	205	0.313	64-22
C	45	70	1.13	1.13	70	3.22	3.23	28	5.73	4.1	-6	178	0.316	70-16
D	44	64	2.22	2.22	64	4.23	4.24	28	4.23	3.61	-6	171	0.378	64-16

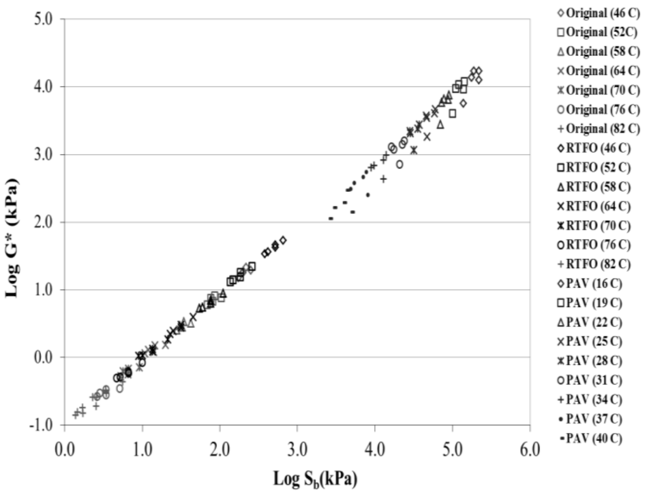

Fig. 6. Comparison between S_b and G* at Different Performance Stages.

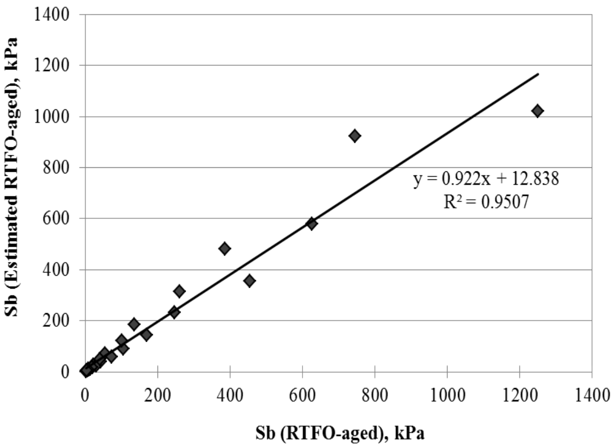

Fig. 7. Validation of Estimating S_b after RTFO Aging.

by using $T_{R\&B}$ and PI of PAV-aged binder. In this study, it is assumed that PAV aging leads to the increase of the softening point and PI by simulated factors. The simulated factors are obtained from traditional test results of five reference binders as presented in Table 5. The 85th percentile increasing values of both $T_{R\&B}$ (12°C) and PI (0.6) of binders after PAV aging are selected as simulated factors in order to cover most current binder sources in Thailand.

The simulated factors are verified by comparing measured binder stiffness after PAV-aging and estimated stiffness of PAV-aged binder. Fig. 8 shows high correlation between estimated S_b for PAV-aged and measured S_b after PAV-aging with R^2 of 0.9721. It can be seen that the stiffness of asphalt binder after PAV aging can be estimated by using the simulated factors in order to cover most asphalt binder sources in Thailand.

Binders Classification by using the Proposed Performance Grading System

Four binders (A, B, C and D) were classified based on the proposed performance grading system as presented in Table 10. From the results, the proposed system classifies these binders as PG grade of 58-4, 58-4, 64-4, and 58+2 for binder A, B, C, and D, respectively.

Comparison between Proposed Performance Grading System and SUPERPAVE Performance Grading System

The proposed PG system can be verified by comparing with the SUPERPAVE PG system. Table 11 shows the classification of four binders by using both systems. The SUPERPAVE system yields classification in the same grade of PG64-22 for binder A and B, and the grade of PG70-16 and 64-16 for binder C and D, respectively. Nevertheless, the proposed system gives the proposed PG grade of 58-4, 58-4, 64-4, and 58+2 for binder A, B, C, and D, respectively.

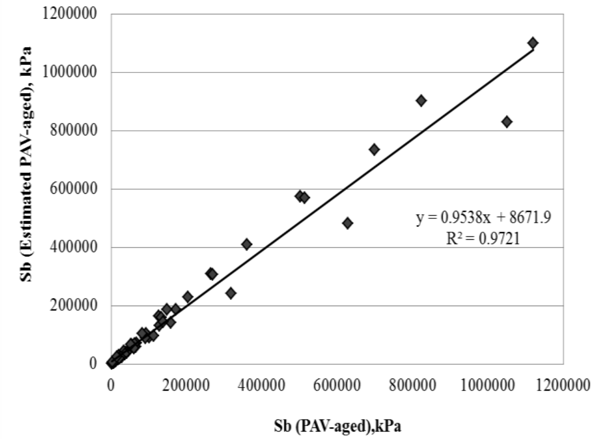

Fig. 8. Validation of Estimating S_b after PAV Aging.

From Table 11, the proposed system shows binder C (proposed PG64) has higher grade than binder A, B and D (proposed PG58) at higher temperature. Binder C tends to perform well in terms of rutting resistance at higher temperature when comparing to other binders. The result is similar to the results obtained from the classification by using the SUPERPAVE system.

It can also be observed that the proposed system and the SUPERPAVE system can differentiate between binder C and D, which are classified in the same grade by using the penetration grading system. Note that in this study, the proposed grading system is assumed to have the original stiffness limit value equal to or greater than 27 kPa ($S_b \geq 27$kPa), which is obtained from an average S_b of current asphalt binders used in Thailand. Moreover, it is assumed that these values have a satisfactory performance. On the contrary, criterion of the SUPERPAVE specifications is derived based on asphalt binder properties and pavement performance data in USA.

According to Table 11, the proposed PG system shows that binder B provides the best performance in the resistance of fatigue cracking comparing to other binders. This is because its stiffness parameter has met the limit at the lowest of intermediate pavement temperature of 24°C. Correspondingly, the SUPERPAVE system illustrates that the binder B has met the limit at lowest of intermediate pavement temperature (22°C). Furthermore, both the proposed system and the SUPERPAVE system similarly present the fact that binder A has lower fatigue cracking resistance in comparing with binder B. The property of binder A has reached the limit at intermediate pavement temperature of 25°C and 27°C for the SUPERPAVE system and the proposed system, respectively. In addition, both systems have shown that both binder C and D perform similarly to resist fatigue cracking. The property of both binders (C and D) has achieved the limit at 28°C and 30°C for the SUPERPAVE system and the proposed system respectively. It can be concluded that the proposed system are comparable with the SUPERPAVE system to classify the binders used in Thailand in terms of the fatigue cracking resistance.

Nevertheless, the intermediate temperatures of both systems are different because they are normally derived from high and low pavement temperatures. These temperatures are determined based on the climate in Thailand which is different from the climate in USA. This causes the difference of intermediate service temperature between the proposed system and SUPERPAVE system resulting in

Table 10. Classification of the Validation Binders by Using the Proposed PG System.

Asphalt	Pen	Original		Estimated RTFOT		Estimated PAV				Estimated PAV							Grade
		S_b(t=0.015 sec) ≥27 kPa		Sb(t=0.015 sec) ≥60 kPa		S_b(t=0.015 sec) ≤60 kPa				S_b(t=0.015 sec) ≤300 kPa			m(60)≥0.30		λ (60) ≥0.02		
		58℃	64℃	58℃	64℃	21℃	24℃	27℃	30℃	-12℃	-6℃	0℃	-12℃	-6℃	-12℃	-6℃	
A	60/70	33	14	72	29	91.6	60.2	40.2	24.8	242	96.8	34.5	0.397	0.521	0.02	0.05	Apr-58
B	40/70	41	19	90	41	70.1	47.7	31.9	20.3	159	69.8	24.9	0.347	0.501	0.05	0.08	Apr-58
C	40/50	65	28	145	60	133	90.5	61	39.5	300	145	55.1	0.3	0.391	0.015	0.05	Apr-64
D	40/50	55	23	122	50	164	104	67.9	45.3	409	187	66.7		0.373		0.05	58+2

Table 11. Classification of the Validation Binders by Using SUPERPAVE System and Proposed PG System.

SUPERPAVE System

Asphalt	Pen	Original			RTFO			PAV			BBR			PG
		T (℃)	G*(kPa)	G*/sin θ (kPa)>1.0	T (℃)	G*(kPa)	G*/sin θ (kPa) >2.2	T (℃)	G* (MPa)	G*/sin θ (MPa) >5.0	T (℃)	s (MPa) <300	m-value >0.3	
A	60/70	64	1.3	1.3	64	2.29	2.29	25	4.38	4.38	-12	276	0.344	64-22
B	40/70	64	1.51	1.5	64	3.35	3.37	22	5.81	4.02	-12	205	0.313	64-22
C	40/50	70	1.13	1.13	70	3.22	3.23	28	5.73	4.1	-6	178	0.316	70-16
D	40/50	64	2.22	2.22	64	4.23	4.24	28	4.23	3.61	-6	171	0.378	64-16

Proposed PG System

Asphalt	Pen	Original		Estimated RTFOT		Estimated PAV		Estimated PAV				Grade
		T (℃)	Sb (t=0.015 sec) ≥27 kPa	T (℃)	Sb(t=0.015 sec) ≥60 kPa	T (℃)	Sb (t=0.015 sec) ≤60 kPa	T (℃)	Sb(t=0.015 sec) ≤300 kPa	m(60) ≥0.30	λ(60) ≥0.02	
A	60/70	58	33	58	70	27	40.2	-12	242	0.379	0.02	Apr-58
B	40/70	58	41	58	90	24	47.7	-12	159	0.347	0.05	Apr-58
C	40/50	64	28	64	60	30	39.5	-6	145	0.391	0.05	Apr-64
D	40/50	58	55	58	122	30	45.3	-6	187	0.373	0.05	58+2

different grade numbers.

The result also shows that low temperature grade numbers of both systems are different. This can be related to the fact that the low grade numbers of the proposed system (e.g. -4, +2) are derived from the range of low pavement temperature in Thailand which differs from those used in USA (e.g. -22, -16). However, both systems depict that the stiffness of binder A and B pass the limit at lower pavement temperature (-12°C) which is better than binder C and D (-6°C). Both systems similarly indicate that the performance at low temperature of binder A and B are better than binder C and D. Based on the results, the proposed system is comparable with the SUPERPAVE system to classify asphalt binders in Thailand.

Investigation of Performance Related Properties of Asphalt Mixtures

Material and Testing Program

In order to ensure that the proposed performance grading system based on indirectly estimated parameters can be used to classify the performance of asphalt binder used in Thailand, the performance related properties of asphalt mixtures were measured in laboratory. The performance tests include two tests: dynamic creep test and indirect tensile fatigue test (ITFT). The dynamic creep test was performed to measure the resistance of asphalt mixture to permanent deformation under a repetitive loading. The test was conducted based on the Simple Performance Test (SPT) for SUPERPAVE Mix Design [11]. The indirect tensile fatigue test was carried out to estimate the resistance of asphalt mixtures to crack initiation. This test was conducted based on the British Standard Draft for Development [12]. Asphalt mixture specimens were produced by using other four asphalt binders (binder E, F, G, H) mixed with limestone aggregate, which is an aggregate type commonly used for pavement construction in Thailand.

Binder Properties and Classification

The properties of four binders were measured and classified based on the penetration grading system, as shown in Table 12. Based on the penetration grading system, four binders were classified as AC60/70 for binder E and F, and AC40/50 for binder G and H.

From the results of traditional tests, the four binders were also classified by using the proposed performance grading system in this study, as shown in Table 13. The classification shows that binders E and F are classified as PG 58-4, binder G as PG 58+2, and binder H as PG 58-4.

Table 12. Results from Traditional Tests Based on Penetration Grading System.

Sample	Penetration (0.01 mm)	$T_{R\&B}$ (°C)	PI	Pen. Grade
E	67	46.6	-1.4	60-70
F	66	48.8	-0.8	60-70
G	46	49.8	-1.4	40-50
H	45	50.8	-0.9	40-50

For the rutting performance based on Table 13, the proposed system shows that all binders meet the limits at the same high pavement temperature of 58°C. However, the results illustrate that binder F has greater resistance to rutting than binder E, which can be observed from higher stiffness of binder F at high pavement temperature of 58°C, for both under un-aged and RTFO-aged stage. Similarly, the stiffness of binder H is higher than the binder G at 58°C under both aging stages, which indicates greater resistance to rutting when comparing to binder G.

For the fatigue cracking resistance, Table 13 shows that the stiffness of PAV-aged binder E, F, G and H meet the criterion at intermediate pavement temperature of 27, 24, 30 and 27°C, respectively. It can be also implied that binder F shows greater fatigue cracking resistance than binder E, and binder H shows greater fatigue cracking resistance than binder G.

Finally, for the performance at low temperature, binder E, F, and H meet the acceptance limits at low temperature of -12°C, whereas binder G passes the limits at -6°C, as illustrated in Table 13. This implies that binder E, F, and H are more durable to low temperature cracking than binder G.

Asphalt Mixture Specimen Preparation

All mixture specimens were produced by using the SUPERPAVE Gyratory Compactor. The 12.5-mm nominal maximum size limestone aggregate was used to produce the asphalt mixture specimens in accordance with ASTM D3515. The selected gradation is illustrated in Fig. 9. The volumetric properties of all asphalt mixtures prepared by using asphalt binder E, F, G, and H are summarized in Table 14. It is found that the optimum asphalt contents of the mixtures, which are prepared by using all four types of asphalt binders, are not significantly different.

After the determination of optimum asphalt contents, 6800-gram mixture specimens were produced in a size of 150 mm-diameter and 165 mm-height. Then for the dynamic creep test, 100 mm-diameter specimens were cored using wet type coring bit. The end treatment

Table 13. Classification of Four Binders by Using the Proposed PG System.

		For Rutting Resistance				For Fatigue Resistance			For Low Temperature Cracking Resistance								
									Estimated PAV								
Asphalt	Pen	Original $S_b(0.015)$ ≥27 kPa		Estimated RTFOT $S_b(0.015)$ ≥60 kPa		Estimated PAV $S_b(t{=}0.015sec)$≤60 kPa			$S_b(t{=}60sec)$ ≤300MPa			m(60) ≥ 0.30		λ (60) ≥ 0.02			Grade
		58℃	64℃	58℃	64℃	24℃	27℃	30℃	-18℃	-12℃	-6℃	-18℃	-12℃	-18℃	-12℃	-6℃	
A	60/70	32	13	69	27	61	40	25	497	248	98	0.279	0.383	0.01	0.02		58-4
B	40/70	44	21	97	45	46	31	20	287	148	66	0.319	0.349	0.015	0.04		58-4
C	40/50	52	22	115	47	95	63	42	680	376	171	0.277	0.33	0.009	0.015	0.02	58+2
D	40/50	60	26	134	56	67	45	30	406	213	100	0.303	0.381	0.015	0.02		58-4

was also accomplished by cutting the top and bottom end of the specimen using a diamond saw blade. After cutting the end, the specimens of 100 mm-diameter and 150 mm-length were ready for the dynamic creep test using the Simple Performance Test (SPT) [11]. For the indirect tensile fatigue test, 2400-gram mixture specimens were prepared in a size of 150 mm-diameter and 50 mm-height using the gyratory compactor.

Dynamic Creep Test

The dynamic creep test or the permanent deformation test was performed based on the protocol of the SPT for SUPERPAVE Mix Design. The variables such as testing temperature, cyclic stress, frequency, and number of cycles were controlled. The temperature of 50°C, which represents the average high pavement temperature in Thailand, was selected as the testing temperature. For setting up the test, the specimens were placed in the environmental chamber of the Universal Testing Machine (UTM) at 50°C for two hours to equilibrate the specimen's temperature prior to the test. The cyclic stress of 200 kPa and the loading frequency of 1 cycle/sec, which is a typical frequency for slow moving traffic, were chosen. The maximum load was applied for 0.1 sec and then released. The 10% of the maximum load was then applied for the remaining 0.9 sec. The harversine loading was then maintained until 20,000 cycles or until the specimen was failed. Two LVDTs were set to measure the vertical displacement of the specimens. The average vertical displacement was calculated by averaging the LVDTs' readings and then converted to the permanent strain rate. Finally, the permanent strain rate was plotted against the number of cycles.

According to the SPT procedure [11], two parameters, which are the flow number (FN) and permanent deformation rate, are recommended to analyze the dynamic creep test results. The FN is defined as the number of cycles at which the rate of permanent strain reaches the minimum. The FN usually occurs before the tertiary creep stage begins. The permanent deformation rate is determined from the slope of the tangent line which is fitted to the linear region in the secondary stage of the permanent strain curve.

The dynamic creep test results of this study are shown in Table 15. Additionally, the permanent strain rate is plotted against the number of cycles as shown in Fig. 10. The results clearly show that the mixture F provides greater rutting resistance than mixture E, as can be seen from higher FN and lower permanent strain rate. Similarly, mixture H has greater rutting resistance than mixture G. Obviously, the performance test results of asphalt mixtures show similar trend as the performance test results from the binder classification using the proposed simplified performance grading system.

Indirect Tensile Fatigue Test (ITFT)

The indirect tensile fatigue test was conducted to investigate the resistance of asphalt mixture to the crack initiation. For the ITFT test, five specimens for each mixture were prepared in a size of 150 mm-diameter and 50 mm-height. Testing temperature was controlled at 20°C ± 0.5°C to represent intermediate temperature. The load at rate 40 pulses per minute or the pulse repetition period of 1.5±0.1 sec were applied. According to the British Standards Institution [12], the target stress level of 500 kPa is recommended for the first specimen.

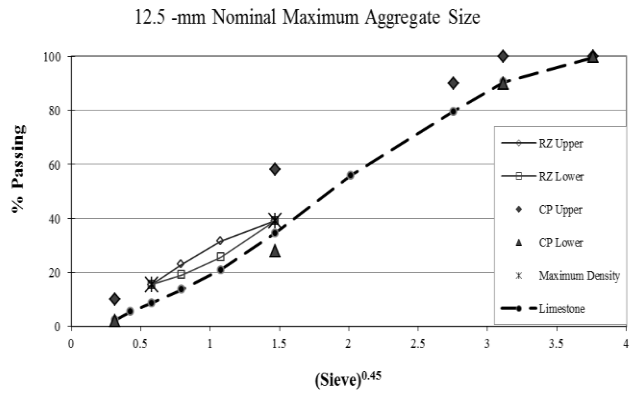

Fig. 9. Gradation Chart of Aggregate Used in This Study.

Table 14. Volumetric Properties of Four Mixtures.

Mix Type	% Opt AC	G_{mm}	VMA (%)	VFA (%)
E	5.7	2.533	16.61	77.75
F	5.5	2.547	16.23	75.23
G	5.8	2.526	16.67	79.29
H	5.6	2.538	16.69	75.51

Table 15. Dynamic Creep Test Results.

Mix Type	Average Flow Number (FN)	Average Permanent Strain Rate
E	376	2.826×10^{-3}
F	1775	8.291×10^{-4}
G	721	1.508×10^{-3}
H	985	1.158×10^{-3}

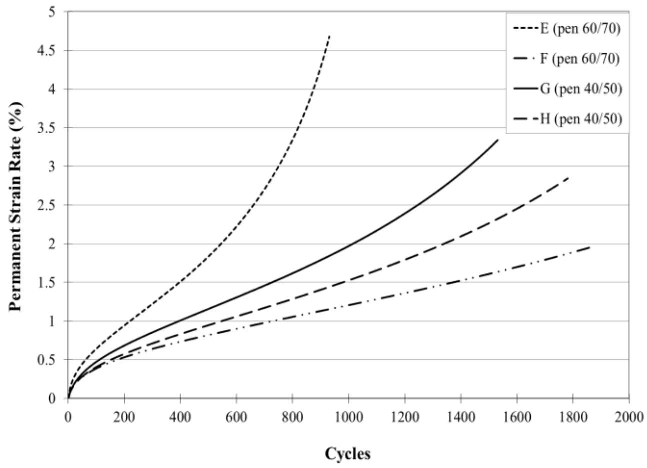

Fig. 10. Permanent Strain rate vs. Number of Cycles.

If the number of cycle to failure of the first specimen test is less than or equal to 200, the target stress levels for the second, third, fourth and fifth specimens of 400, 300, 250 and 200 kPa must be selected, respectively. The relationship between the maximum tensile horizontal strain ($\varepsilon_{x,max}$) and the number of cycles to failure (N_f) was plotted on logarithm scale to analyze the ITFT test.

The ITFT test results and the plot between $\varepsilon_{x,max}$ and N_f on logarithm scale are illustrated in Fig. 11, respectively. When comparing the slope between $\log(\varepsilon_{x,max})$ and $\log(N_f)$ of the mixture

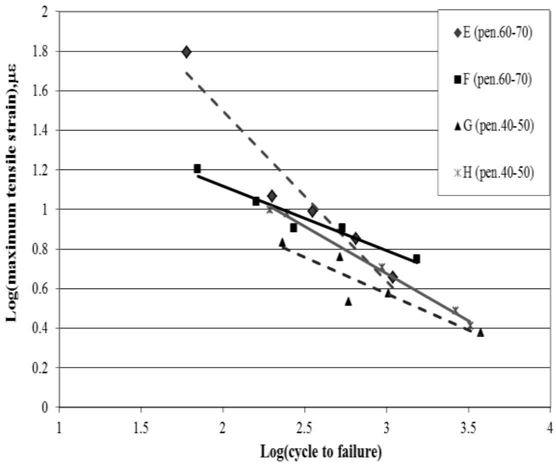

Fig. 11. Maximum Tensile Strain vs. Cycle to Failure.

specimen produced by binders with the same penetration grade ,the results show that mixture F has longer fatigue life than mixture E especially when the number of cycles are greater than 560 cycles. This can be also explained based on the binder test results from the proposed binder grading system that binder F performs better than binder E in terms of fatigue cracking resistance. Similarly, mixture H has greater fatigue resistance than mixture G which shows the same trend as the binder performance test based on the proposed system.

Conclusions and Recommendations

In this study, a proposed performance grading system was developed based on indirectly estimated parameters related to pavement performance for asphalt binders used in Thailand. The proposed parameters and criteria were also derived based on the existing pavement performance and pavement conditions in Thailand. Mixture testing was used to verify that the binder grading system relates to the mixture performance measured in the laboratory. The main findings from the study can be summarized as follows:

– The creep stiffness (S_b) parameter in the proposed system can be sufficiently used as the substitute of G* parameter measured by the Dynamic Shear Rheometer (DSR) test in SUPERPAVE system.
– The simulation of aging effect by average changes in softening point and penetration in the proposed system has been effectively used as a substitution for RTFO and PAV equipment in SUPERPAVE system.
– The proposed performance grading system can classify binders in Thailand which have different performance characteristics even within the same penetration grade.
– The proposed system is desirably comparable with the SUPERPAVE system to classify the existing binders used in Thailand.
– The proposed system can be adequately used to classify performance of asphalt binders used in Thailand while the SUPERPAVE testing devices are not available. This classification allows considering specific climate conditions directly and traffic conditions (speed and volume) indirectly by grade shift, as recommended by the SUPERPAVE system.
– The performance related properties of binder grade classified by using the proposed system correlate well with the performance properties of asphalt mixtures for both field cored and laboratory prepared specimens tested in this study.

Based on the conclusion from this study, it is recommended that the proposed simplified system can be very effective for the transition to the full implementation of the SUPERPAVE system in the future. Countries that have adapted this system based on their local climate and traffic conditions show significant improvement in the road performance, and better return on the investment.

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