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Original research article

Comparative Study of Fatigue of Asphalt Concrete Mixed with AC 60-70 and Polymer Modified Asphalt Binder

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ABSTRACT

Asphalt concrete pavement in Thailand is very important and accounts for 94 % of all roads. Over time, these roads become damaged with repeating loading being an important concern. This study used the Indirect Tensile Fatigue Test (ITFT) to investigate the engineering properties of asphalt concrete at 40 ºC to quantify the fatigue life of asphalt concrete mixed with the AC 60-70 binder and polymer modified asphalt (PMA) binder. Two types of gradation for aggregate in this study were tested: Upper Limit gradation and Lower Limit gradation. Based on the ITFT, the results of fatigue resistance of asphalt concrete depended on the type of asphalt binder and the gradation of aggregate. Asphalt concrete mixed with the PMA binder had a better fatigue life than asphalt concrete mixed with the AC 60-70 binder. In addition, specimens with the Lower Limit gradation had better fatigue life than those with the Upper Limit gradation.

Keywords: Fatigue life; Indirect tensile fatigue test; Limestone; PMA

1. Introduction

Thailand's 99,881.19 kilometers of roads are an important transportation component that is supervised by the Department of Highways and the Department of Rural Roads. Most of these roads are asphalt concrete pavements. There are 2 main types; a rigid, concrete pavement and a flexible, asphalt concrete pavement with most roads 94.69 % being asphalt concrete pavements, 4.56 % concrete pavements and the balance being non-asphalt roads [1].

In Thailand, asphalt concrete pavement consists of aggregates and binders which are important in carrying traffic load which depends on the selection of bonding materials [2-5].

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After bearing the traffic load for a period, the asphalt concrete becomes damaged as evidenced by cracks, distortion or deformation, surface defects and miscellaneous distress [6].

The two main damage characteristics in asphalt concrete pavement that are caused by the traffic load are permanent deformation or rutting and fatigue damage [7-10]. These result from the repeated loading until material fatigue occurs [11] and from an inadequate pavement thickness that causes damage at the base of asphalt concrete pavement under the traffic loading area [12]. Such damage affects the road surface and may be noticeable as cracks [13] and overall the damage results in a shorter pavement lifespan [14].

In the past, fatigue testing has been commonly applied on asphalt concrete and a crack was the main indicator of damage to the asphalt concrete [15-16]. Another factor is the asphalt concrete mixture [9, 17-18]. The current study investigated two mixed proportions of limestone aggregate and used two types of asphalt binder to compare asphalt concrete fatigue by testing the asphalt concrete at 40 ºC.

2. Materials and Methods

2.1 Asphalt mixture design using the superpave method

The Superpave involves laboratory compaction [19] using a Superpave Gyratory Compactor (SGC) and the method is shown in Fig. 1 [20-21]. Fig. 2 shows the design process that begins with the allocation of aggregate that complies with the Superpave criteria and the specifications of the Thailand Department of Highways to calculate the percentage of initial trial asphalt binder (P_{bi}) from the specific gravity of the aggregate for a 12.5 mm nominal maximum size that is then compacted using the SGC using a maximum number of gyrations (N_{max}) for compaction. Percent passing for aggregate gradation is shown in Table 1. There were 4 types (15 specimens for each type) of asphalt concrete specimens (2 for AC 60-70 binder and 2 for PMA binder), as shown in Fig. 3. Aggregate specimens with Upper Limit and Lower Limit gradations are presented in Fig. 4.

- PMA Upper is asphalt concrete mixed with PMA binder and Upper Limit aggregate.
- PMA Lower is asphalt concrete mixed with PMA binder and Lower Limit aggregate.
- AC 60-70 Upper is asphalt concrete mixed with AC 60-70 binder and Upper Limit aggregate.
- AC 60-70 Lower is asphalt concrete mixed with AC 60-70 binder and Lower Limit aggregate.

Fig. 1. Photo of Superpave Gyratory Compactor.

Table 1. Gradation for Limestone aggregate.

Sieve size		Passing		Criteria	Restricted zone
		Upper Limit	Lower Limit		
Number	(mm)	(%)	(%)	(%)	(%)
3/4"	19	100	100	100	-
1/2"	12.5	96.00	81.54	80-100	-
3/8"	9.5	90.00	74.13	-	-
#4	4.75	68.00	48.83	44-74	-
#8	2.36	52.00	29.86	28-58	39.1
#16	1.18	40.50	20.98	-	25.6-31.6
#30	0.6	30.00	14.67	-	19.1-23.1
#50	0.3	19.00	10.77	5-21	15.5
#100	0.15	14.00	8.25	-	-
#200	0.075	5.00	4.31	2-10	-

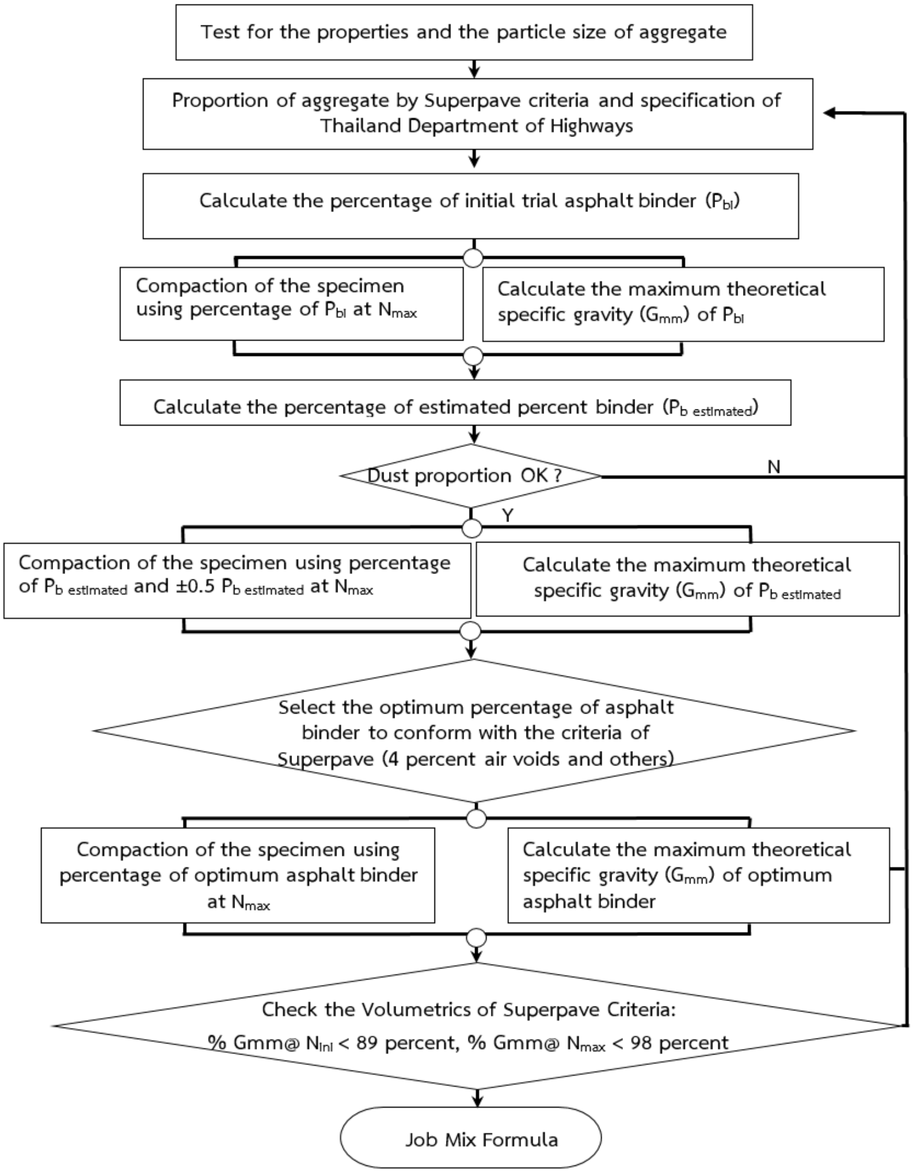
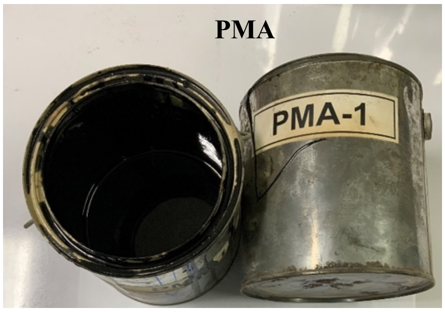


Fig. 2. Mixture flow chart designed using the Superpave method.



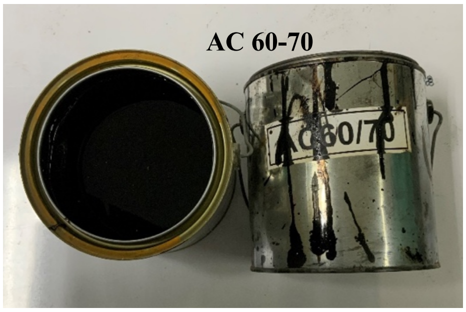


Fig. 3. Bitumen used in the research.

Fig. 4. Aggregate material used in the research.

In Thailand the temperature used for mixing is 160 ºC for AC 60-70 and 180 ºC for PMA. Afterwards the mixer temperature (for both AC 60-70 and PMA binder) becomes 165-170 ºC. Behavior of materials and their mixtures once laid hanks to more rational testing methods. However, both asphalt binder and asphalt-aggregate mixture show temperature and time-dependent behavior and have much better resistance to cracking [22-24]. To achieve exactly 4 % air voids (V_a), trials using different amounts of asphalt binder were carried out with 135 gyrations design compaction (N_{des}) 9 gyrations for initial compaction (N_{ini}) and 220 gyrations for N_{max} [25-26]. During compaction, the height was measured after each gyration and the number of gyrations was also recorded. The average design was based on a high air temperature of 44 ºC and 10-30 million cycles of an equivalent single axle load (ESAL).

2.2 Indirect Tensile Fatigue Test (ITFT)

Factors considered in the ITFT are temperature, frequency of repeated loading, characteristic of loading condition, and the type and shape of specimen [27]. For the initial stress, there is a direct correlation with the fatigue occurring in asphalt concrete, with the result depending on the loading and the test method [28]. There are two main types of fatigue test, with one involving controlled stress and the other controlled strain. In both types of fatigue test, the magnitudes of the applied stress pulse or of the strain are constant during the test. For this study, failure for controlled stress was defined as a horizontal deformation of 10 millimeters. The specimens were incubated in order to be 40 ºC for their temperature which closely approximated the 80^{th} percentile at temperature of the pavement [29]. Duration for curing was more than 3 hours and 40 minutes [30]. ITFT was used to determine the stress levels at which the fatigue tests were carried out on the limestone aggregate mixed with the AC 60-70 binder at 100, 200, 250, 300, 400 kPa. Additionally, ITFT was performed on the limestone aggregate mixed with the PMA binder at 200, 250, 300 350, 400 kPa with 0.1 sec loading followed by a 0.7 sec rest period that was repeated until the specimen failed. A compressive force applied along the vertical diameter of a cylindrical specimen results in an indirect tensile stress along the horizontal diameter. Repeated applications of the vertical force (as shown in Fig. 5) result in a crack along the vertical diameter. Fig. 6.

shows the installation of the ITFT. Failure due to fatigue was defined as a rapid increase in the rate of horizontal deformation, as shown in Fig. 7.

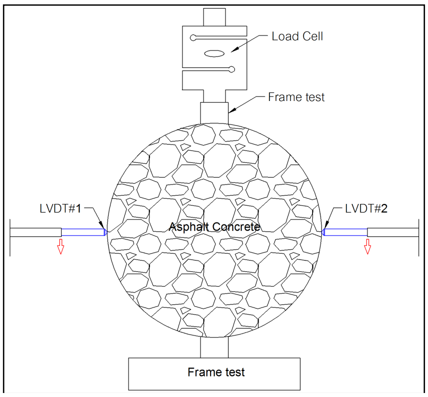


Fig. 5. Frame Test Indirect Tensile Fatigue.

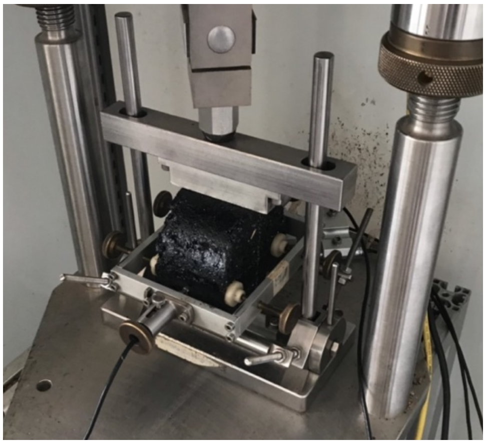


Fig. 6. Installation of Indirect Tensile Fatigue Test.

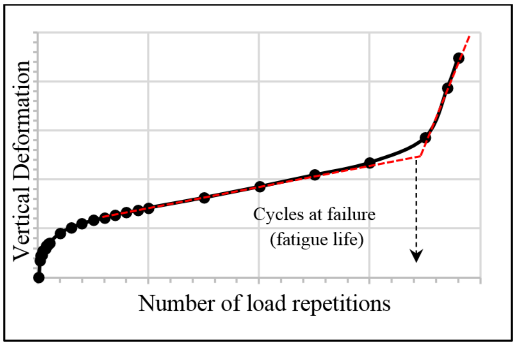


Fig. 7. Cycles at Failure.

3. Results

3.1 Properties of aggregate and asphalt binder mixes

The results of the physical properties of limestone aggregate are shown in Table 2. The proportion of limestone aggregate complied with the Superpave criteria and the asphalt mixture gradation requirements restricted the zone boundary, with the two types of mixed proportions (Upper Limit and Lower Limit) reflecting the controlled line to ensure the maximum aggregate size was not too large or too small. The particle size distribution of the aggregates is shown in Fig. 8, with the gradation set so that they could be compared. The preparation of gradation was in accordance with the standards of the Superpave criteria and specifications of the Thailand Department of Highways. AC 60-70 binder and the PMA binder were used as the binding materials. The results of physical properties measured are provided in Table 3. The test results showed conformation to the specifications of the Thailand Department of Highways.

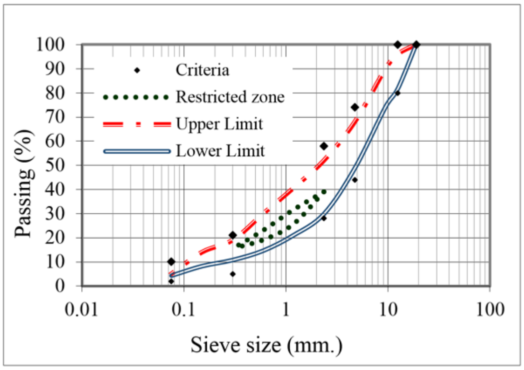


Fig. 8. Limestone Aggregate Particle Size distribution [31].

Table 2. Coarse and fine aggregate properties [31].

Property	Bin 1			Bin 2	Bin 3	Total	Criteria	Test method
	Pass #200	Retain #200	Total					
Apparent Specific Gravity, (G_A)	2.769	2.745	2.749	2.746	2.733	2.743	-	ASTM C 127, 128
Bulk Specific Gravity, (G_B)	-	2.719	2.728	2.703	2.684	2.707	-	
Absorption, (%)		0.74		0.58	0.57		-	
Uncompacted Void Content of Fine Aggregate, (%)			45.9				> 45	AASHTO TP 33
Sand Equivalent, (%)			73.0				> 50	ASTM D 2419
Flakiness Index, (%)					25		< 30	BS 812
Elongation Index, (%)					18		< 30	BS 812
Los Angeles Abrasion, (%)					32.55		< 40	ASTM C 131
Percentage of Crushed Fragments in Gravel, (%)				100	100		> 90	
Soundness Test of Aggregate, (Solution of sodium sulfate), (%)	Fine Aggregate = 2.90, Coarse Aggregate = 0.47						< 9	ASTM C 88
Flat of Elongated Particles in Coarse Aggregate, (%)				8	3		<10	ASTM D 479

Table 3. Physical properties of asphalt binder.

Property	Binder		Test method
	AC 60/70 (Criteria)	PMA (Criteria)	
Specific gravity (25 °C)	1.02 (-)	1.02 (-)	ASTM D 70
Penetration Test (25 °C), (0.1 mm)	67 (60-70)	61 (60-70)	ASTM D 5
Softening Point, (°C)	46.2 (>46)	71.1 (>70)	ASTM D 36
Viscosity (135 °C, 20 rpm, spindle 21), (cP)	394 (-)	1220 (1100)	ASTM D 4402
Ductility (25 °C), (cm)	> 100	> 100	ASTM D 113
Absorption of Asphalt (%)	0.236	0.237	ASTM D 2041

Note: Criteria of the Thailand Department of Highways

Considering the design results of the asphalt binder mixture, there were fewer voids filled with asphalt (VFA) for the Upper Limit gradation than for the Lower Limit gradation. The Upper Limit, in which the suitable estimated percent binder ($P_{b\ estimated}$) of asphalt concrete mixture was less than for the Lower Limit, had approximately 4 % V_a and a minimum void of 14 % in the mineral aggregate (VMA). These were in accordance with the Superpave criteria. The design results of the asphalt concrete mixtures are shown in Table 4.

Table 4. Results for asphalt binder mixture [31].

Property	PMA		AC 60-70		Criteria	Remark
	Upper[1]	Lower[2]	Upper[3]	Lower[4]		
$P_{b\ estimated}$, (%)	4.54	4.75	4.54	4.75	-	by mass of mix
V_a, (%)	4.03	3.98	4.00	4.05	4	Superpave criteria
VMA, (%)	14.73	14.67	14.72	14.79	>14	Nominal maximum size 12.5 mm.
VFA, (%)	71.61	72.75	72.78	72.95	65-75	ESALs 10-30 million cycles
Dust proportion	0.99	1.19	0.99	1.19	0.6-1.2	Superpave criteria
% G_{mm} @ N_{ini}	86.79	85.18	86.56	84.93	< 89	Average high temperature 44 ºC and
% G_{mm} @ N_{max}	97.29	97.44	97.25	97.78	< 98	ESALs 10-30 million cycles

Note:
* [1]PMA Upper - Asphalt concrete mixed with PMA binder and Upper Limit aggregate
* [2]PMA Lower - Asphalt concrete mixed with PMA binder and Lower Limit aggregate
* [3]AC 60-70 Upper - Asphalt concrete mixed with AC 60-70 binder and Upper Limit aggregate
* [4]AC 60-70 Lower – Asphalt concrete mixed with AC 60-70 binder and Lower Limit aggregate

3.2 Results of indirect tensile fatigue test

The fatigue performance of the asphalt mixtures was determined using the ITFT and based on the number of load repetition cycles on a specimen until it was damaged due to fatigue. The criteria for fatigue damage are presented in Fig. 7. Failure was considered to occur when the constant rate of increase of the horizontal deformations was replaced by a faster rate of increase of the deformations. In terms of the fatigue performance of the asphalt mixtures, fatigue functions (number of load repetitions to failure) in Figs. 9-10 (based on type) confirmed the superior fatigue performance of the asphalt concrete mixed with PMA binder and limestone at the Lower Limit which had the longest fatigue life followed by asphalt concrete mixed with PMA binder and limestone at the Upper Limit. Likewise, the asphalt concrete mixed with AC 60-70 binder and limestone at the Lower Limit had the longest fatigue life followed by the asphalt concrete mixed with AC 60-70 binder and limestone at the Upper Limit.

Table 5. Statistical parameters of stress and number of load repetitions.

Type	Subset for alpha = 0.05	
	Group 1	Group 2
PMA Upper	167.50	
PMA Lower	214.17	
AC 60-70 Upper		851.25
AC 60-70 Lower		922.25
Significant Level	**0.852**	**0.777**

Considering the asphalt binder as presented in Table 5, PMA Upper and PMA Lower were in the same group indicating there was no significant difference at the 95% confidence interval. Likewise, AC 60-70 Upper and AC 60-70 Lower were in the same group also indicating that there was no significant difference at the 95% confidence interval.

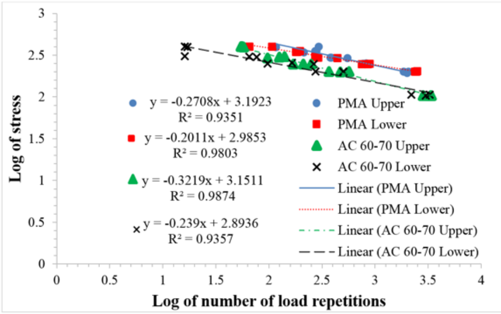


Fig. 9. Correlation between Log of number of load repetitions and Log of stress.

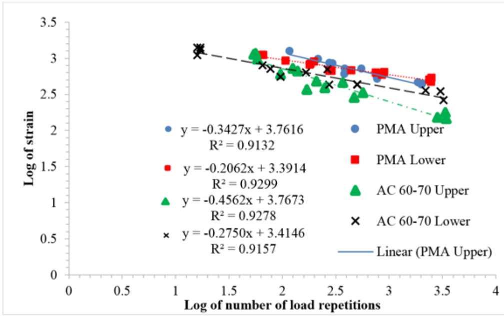


Fig. 10. Correlation between Log of number of load repetitions and Log of strain.

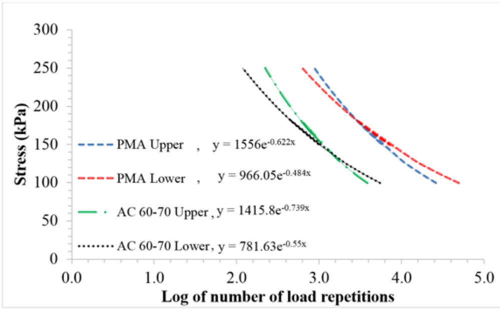


Fig. 11. Correlation between Log of number of load repetitions and Stress.

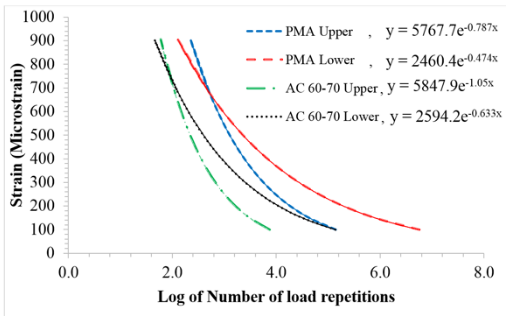


Fig. 12. Correlation between Log of number of load repetitions and Log of strain.

4. Discussion

The results in Fig. 11 show that the asphalt concrete with the mix of limestone aggregate and the PMA binder, with stress less than 182.2 kPa, performed better regarding fatigue resistance when the Lower Limit of aggregate was applied. Likewise, the asphalt concrete with the mix of limestone aggregate and the AC 60-70 binder had stress less than 138.4 kPa, using the Lower Limit of aggregate. The asphalt cement content has a direct effect on fatigue resistance. The Lower Limit mixed aggregates had a higher amount of asphalt cement in the mixture; therefore, the fatigue resistance was higher than for the Upper Limit aggregates. (4.75 % asphalt by mass of mix for Lower and 4.54 % asphalt by mass of mix for Upper).

The results in Fig. 12 show that the asphalt concrete with the mix of limestone aggregate and the PMA binder, with strain less than 677.0 microstrain, performed better regarding fatigue resistance when the lower Limit of aggregate was applied. Likewise, the asphalt concrete with the mix of limestone aggregate and the AC 60-70 binder had strain less than 754.5 microstrain using the Lower Limit of aggregate.

From Table 6, the cost of asphalt concrete with PMA Upper was 3.25 percent lower than the cost of asphalt concrete with PMA Lower. Thus, the fatigue life of PMA Upper was less than the fatigue life for PMA Lower. Likewise, the cost of asphalt concrete with AC 60-70 Upper was 2.82 percent lower than the cost of asphalt concrete with AC 60-70 Lower. Therefore, the fatigue life of AC 60-70 Upper was less than the fatigue life of AC 60-70 Lower.

Considering the criteria for fatigue resistance of 100 kPa stress [32], we found that PMA Lower had 1.9 times the PMA Upper fatigue life and AC 60-70 Lower had 1.4 times the AC 60-70 Upper fatigue life.

However, for fatigue resistance of 200 microstrain [32], PMA Lower had 10.5 times the PMA Upper fatigue life and AC 60-70 Lower had 6.8 times the AC 60-70 Upper fatigue life.

Comparing between PMA binder and AC 60-70 binder, the fatigue life of PMA was better than the fatigue life of AC 60-70 for both Upper and Lower Limit aggregate. PMA binder is the polymer modified asphalt that has shown that the presence of polymer in PMA improves the performance of asphalt pavements subject to heavy traffic

Table 6. Cost comparison and fatigue resistance of asphalt concrete.

Description	PMA		AC 60-70		Remark
	Upper	Lower	Upper	Lower	
Cost of asphalt binder	33,000	33,000	21,000	21,000	THB/Ton
Cost of limestone aggregate	554	554	554	554	THB/cubic meter
$P_{b\ estimated}$	4.54	4.75	4.54	4.75	% by mass of mix
Density of asphalt mixed	2.422				ton/cubic meter
Asphalt concrete pavement	1,330 cubic meters (4 lanes, 3.5 meters per lane, shoulder 5 meters, distance 1 kilometer, thickness 0.07 meters)				
Amount of asphalt binder	146.2	153.0	146.2	153.0	Ton
Amount of limestone Aggregate	30,750	30,683	30,750	30,683	Ton
Cost	6.530 [3]	6.749 [4]	4.775 [1]	4.913 [2]	million baht
Stress 100 kPa	25,991 [2]	49,032 [1]	3,852 [4]	5,450 [3]	fatigue life
Strain 200 microstrain	18,575 [2]	195,486 [1]	1,640 [4]	11,147 [3]	fatigue life

Note: 1-4 order from best to worst.

loading over a wide range of temperatures [24]. Therefore, it is more flexible than AC 60-70 binder.

5. Conclusion

The study of fatigue in asphalt concrete compared the fatigue life of asphalt concrete mixed with different type of binders (AC 60-70 and PMA) and different proportions of limestone aggregate (Upper Limit and Lower Limit).

The results showed that the fatigue resistance based on the ITFT of asphalt concrete depended on the type of asphalt binder and the gradation of aggregate. Asphalt concrete mixed with the PMA binder had better fatigue life than asphalt concrete mixed with the AC 60-70 binder. Furthermore, the specimen with the Lower Limit gradation has better fatigue life than that with the Upper Limit gradation.

The asphalt cement content affects fatigue resistance. The Lower Limit mixed aggregates had a higher amount of asphalt cement in the mixture; therefore, the fatigue resistance was higher than for the Upper Limit aggregates.

Among the four types of asphalt concrete, PMA Lower produced the best result for fatigue life but at the highest cost because PMA binder is more flexible and more expensive than AC 60-70 binder. And the asphalt cement content for Lower Limit is higher than the Upper Limit. However, the fatigue performance was not superior when the loading was extremely high (stress > 182 kPa, Strain > 677 microstrain) because an asphalt surface failed due to the compaction loading.

Acknowledgements

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