CHAPTER IV

TEST RESULTS AND ANALYSIS

4.1 Asphalt Cement

Several tests for asphalt cement were conducted to AASHTO and ASTM specification. There are two types of asphalt cement tested. In this study; original asphalt cement and oven-aged asphalt cement. Results are shown in Tables 4.1 and 4.2.

Table 4.1 Original asphalt cement properties

Objective	Test Results	AASHTO Required
Penetration (at 25°C, 100g, 5 sec, 1/10 min)	64	60 - 70
Flash Point, Cleveland open cup (°C)	317	Min 232
Ductility (at 25°C 50 mm per min)	>100	Min 100
Solubility (%)	99.2	Min 99
Softening Point (°C)	52	49-54

Table 4.2 Oven-aged asphalt cement properties

Objective	Test Result	AASHTO Required
Loss on heating (5 hours at 163°C) %	0.04	Max 0.8
Penetration after heating (% of original)	61	Min 54
Ductility after heating (at 25°C, 50mm/min) (cm)	> 100	Min 50

The engineering properties of asphalt cement obtained from laboratory tests were shown in the table 4.1 and 4.2. It can be seen that, all the properties satisfy AASHTO and ASTM specification. Hence, the asphalt cement could be used in this study.

4.2 Foamed Asphalt Characteristics

Foamed bitumen normally has two parameters, expansion ratio (ER) and half-life (HL). The ER is the ratio of maximum volume of foamed bitumen relative to the original volume of bitumen. After injecting water into hot bitumen. The HL is the time in seconds it takes for foamed bitumen to drop from its maximum volume to half of the maximum volume.

In this study, foamed asphalt was test at three temperatures, 160, 170 and 180°C with each temperature test having change in the percent of water of 1-5%. Test results for each temperature are shown in table 4.3 and Figures 4.3, 4.4 and 4.5.

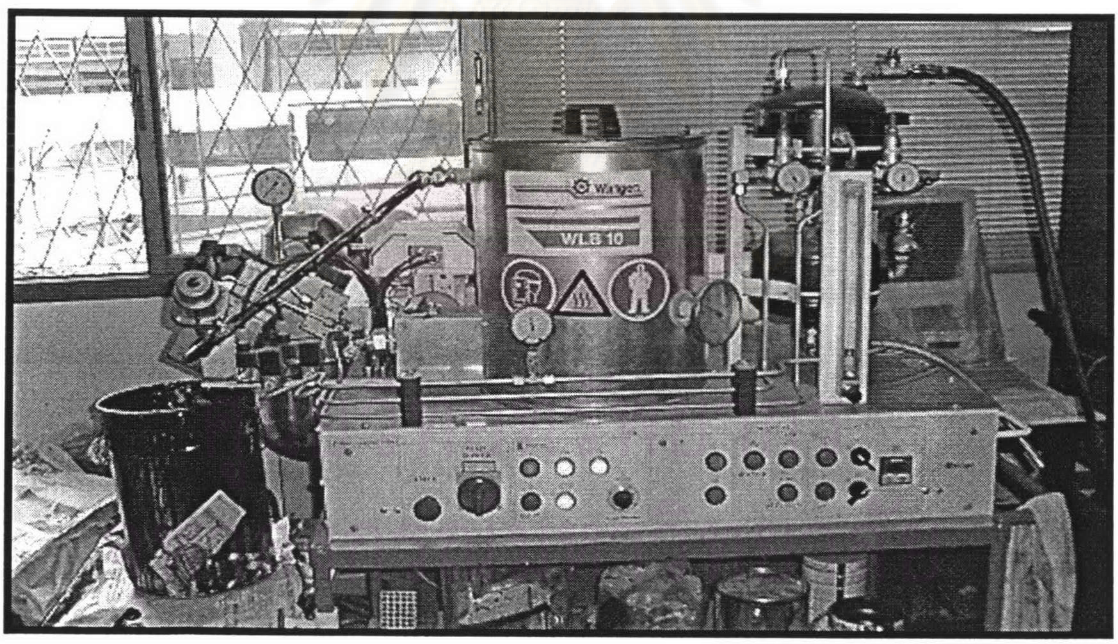

Figure 4.1 Foamed bitumen plan WLB 10

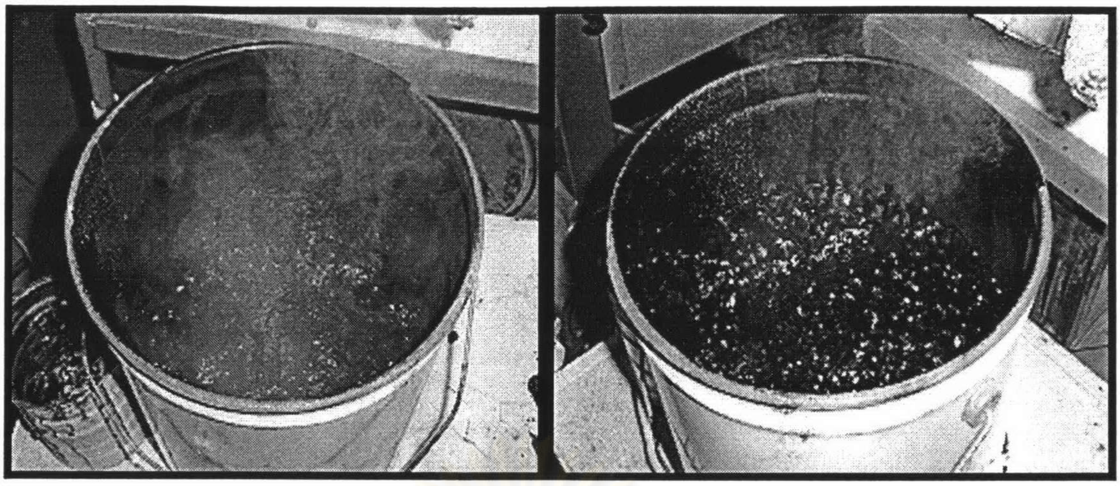

Figure 4.2 Foamed asphalt characteristics duration tested

Table 4.3 Foamed asphalt characteristics

Water Content (%)	Asphalt cement temperature					
	160 °C		170°C		180°C	
	ER	HL	ER	HL	ER	HL
1.0	9	14.14	9	14.33	9	13.85
1.5	10	13.03	11	13.43	11	13.61
2.0	12	11.79	13	12.21	13	12.95
2.5	13	11.27	14	10.92	14	11.49
3.0	14	9.42	16	8.21	17	10.29
3.5	15	8.29	17	7.41	18	9.51
4.0	17	7.12	19	6.74	19	6.20
5.0	18	5.27	22	4.33	20	3.85

ER: Expansion Ratio

HL: Half-Life

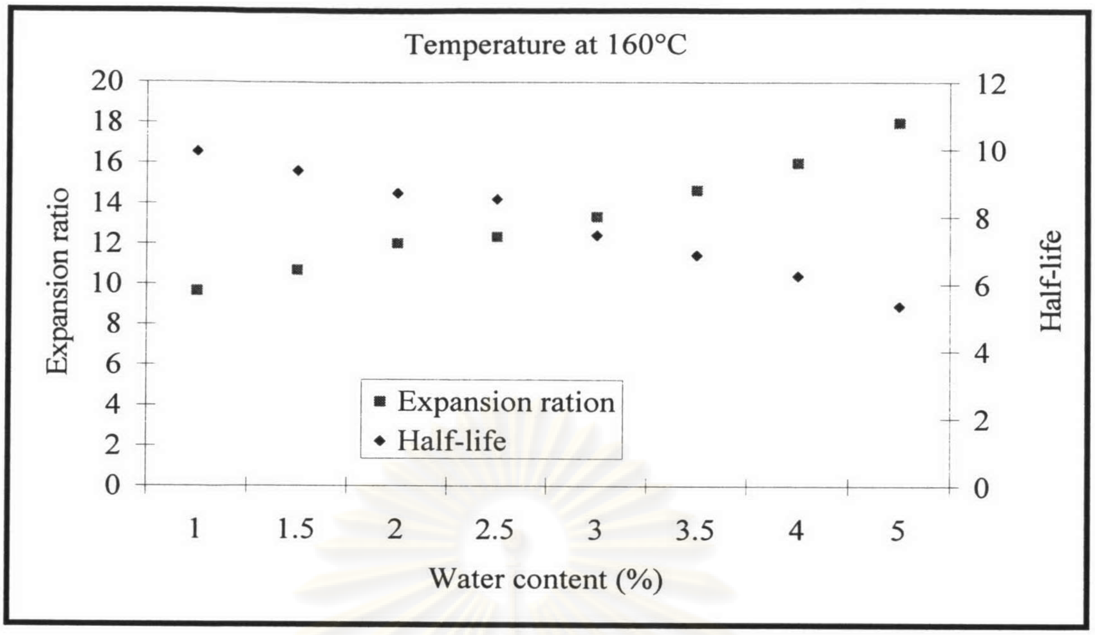

Figure 4.3 Foamed asphalt characteristics at 160°C

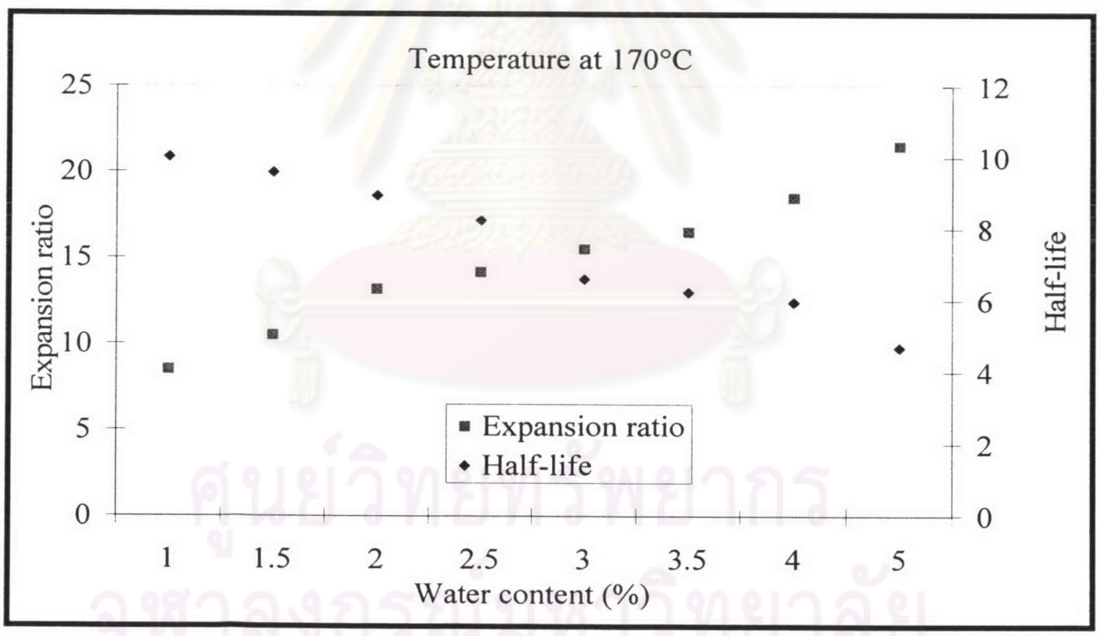

Figure 4.4 Foamed asphalt characteristics at 170°c

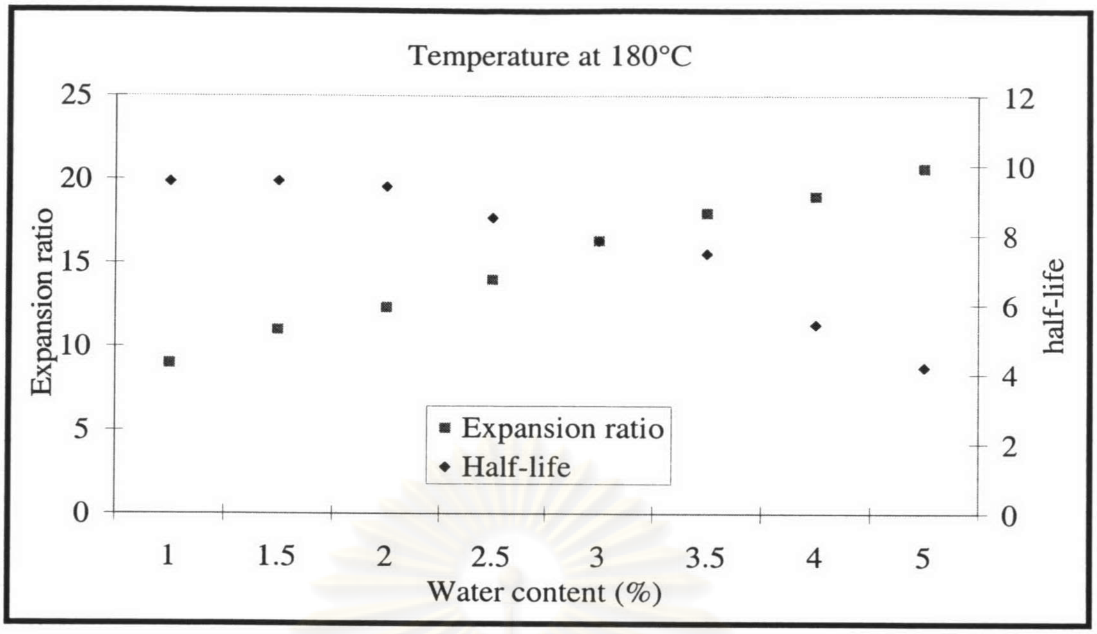

Figure 4.5 Foamed asphalt characteristic at 180°c

Base on the tests results, the optimum temperature and water content to procedure of foamed asphalt are 170°C and 2.5% water content which yield the expansion ratio of 14 and half life of 10.92 seconds. Both values fit in the ranges of the expansion ratio and half life of 10-15 and 5-10 seconds, respectively (Wirtgen cold recycling manual, 2001).

Table 4.4 Optimum foamed asphalt properties

Foamed Asphalt Characteristic	Test Results
Temperature (°C)	170
Water Content (%)	2.5
Expansion Ratio	14
Half-Life (second)	10.92

4.3 Aggregates Test Results

4.3.1 RAP and Virgin Aggregates for Foamed Asphalt Mixtures

Foamed asphalt mixtures consist of RAP and virgin aggregates. In this study, only reclaimed asphalt pavement aggregates of less than 19 mm was examined. Virgin aggregates came in three sizes, 3/4 “, 3/8 “and crushed stone aggregates. Aggregates test results are shown in Table 4.5, Figures 4.6, and 4.7 while specific gravity of both aggregates is shown in the Table 4.6.

Table 4.5 Gradation of RAP and virgin aggregates

Sieve Sized		Percentage Passing (%)			
		RAP	Dust	Normal Sized 3/8”	Normal Sized ¾”
(inch)	(mm)				
11/2 ″	37.50	100.00			
1 ″	25.00	88.98			100.00
3/4 ″	19.00	82.91			96.99
1/2 ″	12.50	75.32		100.00	62.96
3/8 ″	9.50	64.59		100.00	37.87
No. 4	4.75	40.55	99.11	53.69	1.64
No. 8	2.36	24.19	79.68	8.80	
No. 16	1.18	15.22	58.10	4.05	
No. 30	0.60	10.94	35.40		
No. 50	0.30	8.14	22.56		
No. 100	0.15	6.15	15.29		
No. 200	0.075	4.62	15.16		

Table 4.6 Specific gravity and asphalt content

Aggregates Type	Bulk Specific Gravity	Asphalt content (%)
3/4 " Sized	2.74	-
3/8 " Sized	2.73	-
Dust	2.68	-
100%RAP	2.67	4.03

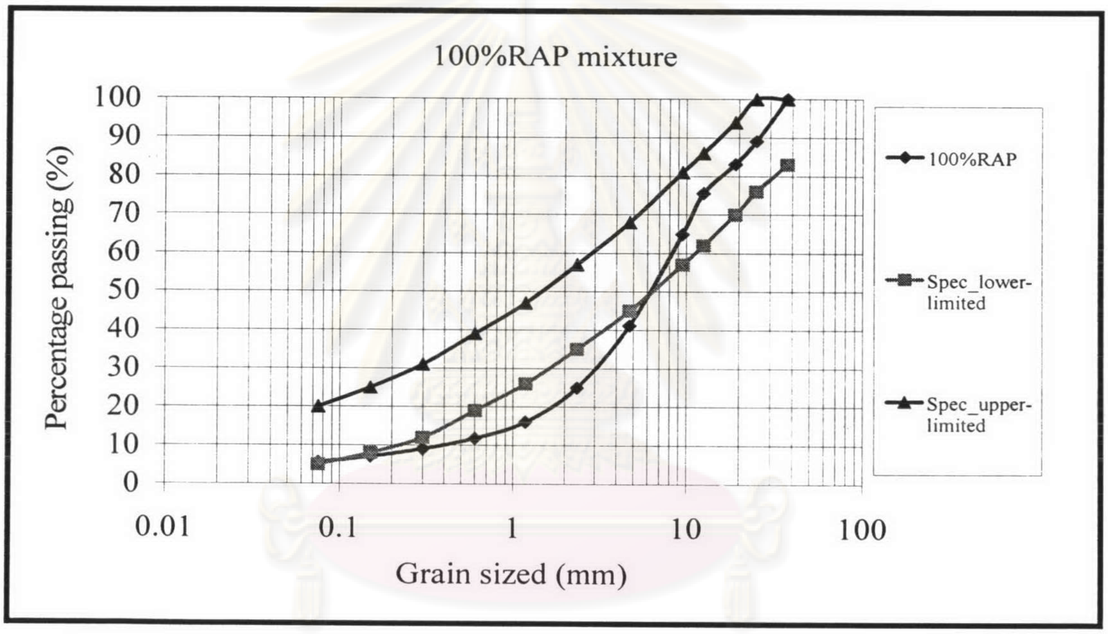

Figure 4.6 Gradation of 100%RAP aggregates

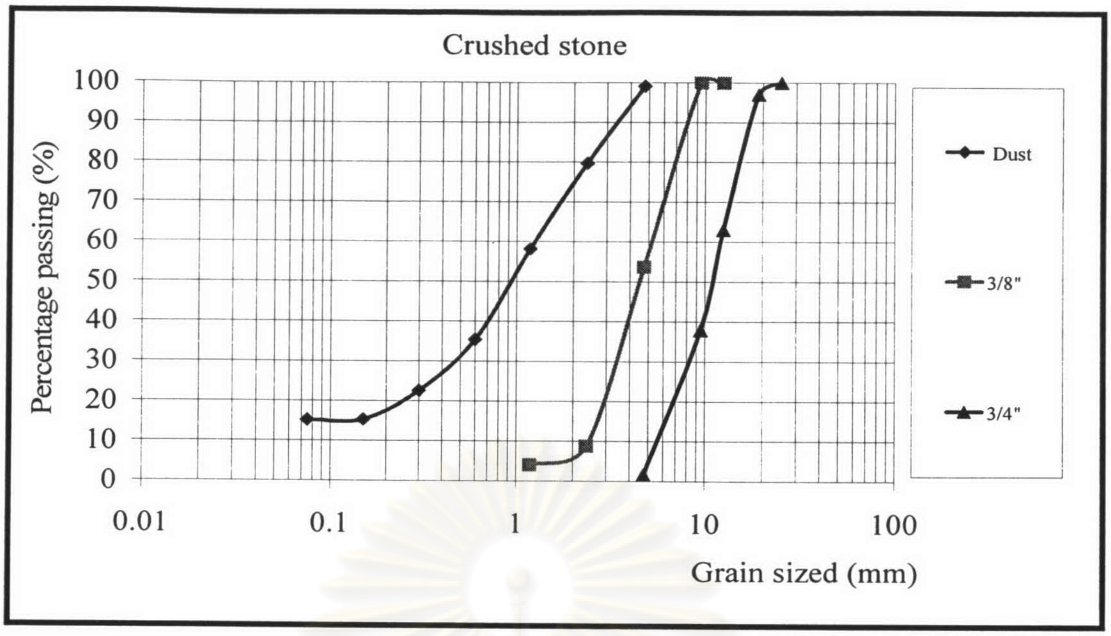

Figure 4.7 Gradations of virgin aggregates

Note that Portland cement (1% by weight of aggregates) was added to all three mixtures proportions with the propose to

1. Increase the amount of fine aggregates
2. Increase the density of mixtures
3. Increase the strength of mixtures.

Figure 4.6 that the gradation of 100% RAP aggregates does not match recommendation in Wirtgen cold recycling manual 2001. It was found that aggregates with 50% RAP aggregates and 50% virgin aggregates have gradation with 50%in the recommendation range.

Nevertheless, three mix proportions (100%RAP, 50%RAP and 0%RAP) were used in this study for comparison purpose aggregates are presented in tables. More details of the mix proportions are presented in Tables C-1 to C-3 of appendix C.

Table 4.7 RAP and virgin aggregates blend

Typed of Materials	Proportions		
	Proportion 1 100%RAP	Proportion 2 50%RAP	Proportion 3 0%RAP
RAP	99	50	-
Dust	-	30	60
Normal Sized 3/8 ″	-	-	19
Normal Sized 3/4 ″	-	19	20
Portland cement	1	1	1
Total	100	100	100

RAP: Reclaimed Asphalt Pavement

Table 4.8 Combination of RAP and virgin aggregates

Sieve sized		Percentage passing (%)			
(inch)	(mm)	100%RAP	50%RAP	0%RAP	Specification
11/2 ″	37.50	100.00	100.00	100.00	83-100
1 ″	25.00	88.09	98.00	100.00	76-100
3/4 ″	19.00	83.08	95.90	100.00	70-94
1/2 ″	12.50	75.57	85.40	91.33	62-86
3/8 ″	9.50	64.95	76.46	84.24	57-81
No. 4	4.75	41.15	58.97	65.66	45-68
No. 8	2.36	24.95	42.95	49.02	35.57
No. 16	1.18	16.07	29.84	33.88	26-47
No. 30	0.60	11.83	19.07	23.66	19-39
No. 50	0.30	9.05	12.32	16.78	12-31
No. 100	0.15	7.09	8.61	12.25	8-25
No. 200	0.075	5.58	7.83	9.50	5-20

Materials lacking fine particles will not mix well with foamed bitumen. The minimum requirement of aggregates passing 0.075 is 5% by weight. Material with low fine particles can be improved by the addition of cement, lime or other materials with 100% passing a 0.075 mm sieve.

Figure 4.8 shows the gradations of the three mix proportions and the recommendation gradations by Wirtgen.

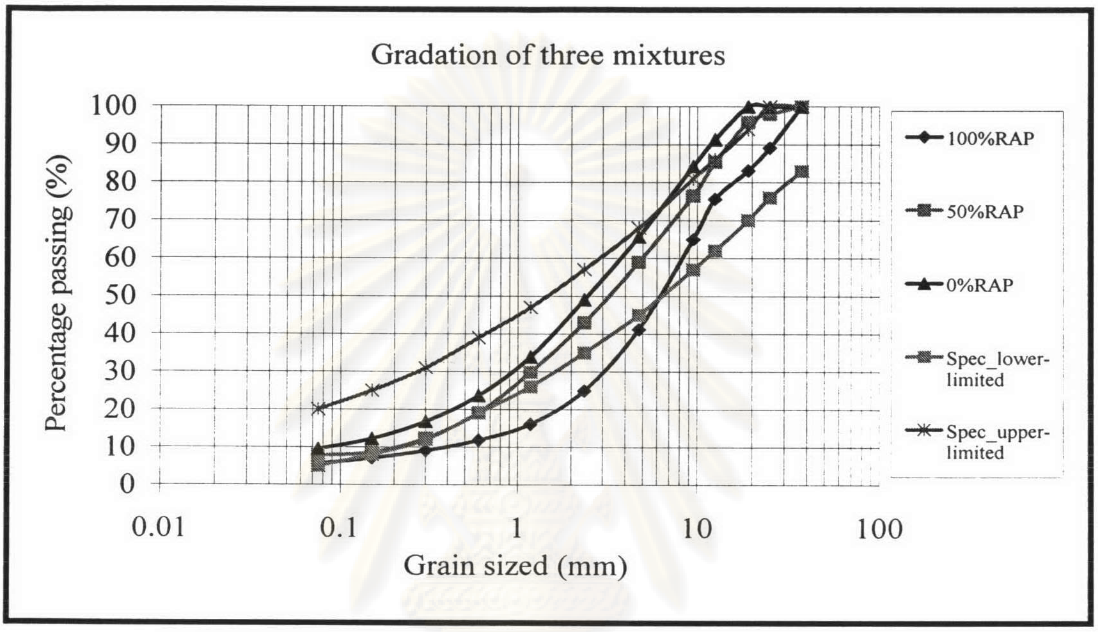

Figure 4.8 Gradations of three mixtures

4.3.2 Aggregates for Stabilized Portland Cement Mixtures

The gradation test was performed according to the same RAP aggregates used for foamed asphalt were also used for Portland cement stabilized mixtures to AASHTO T 27. Results indicated that the percentage of RAP materials was minimal, or 4.62% through a 0.074 mm (No. 200) sieve.

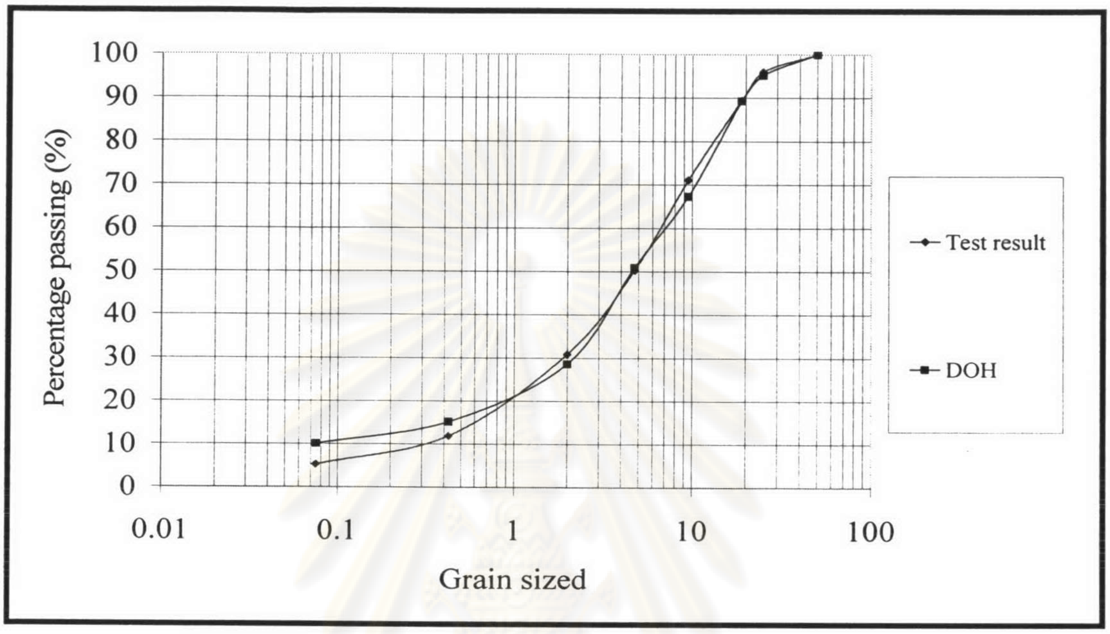

Figure 4.9 Gradation of portland cement mixtures

Table 4.9 Specific gravity of 100%RAP aggregates

Articles	RAP Aggregates
Bulk Specific Gravity (G_B)	2.667
Bulk Specific Gravity SSD (G_S)	2.698
Apparent Specific Gravity (G_A)	2.753
Absorption	1.179
Asphalt content (%)	4.03%

SSD: Saturate surface-dry weight of aggregates

4.4 Optimum Moisture contents (OMC)

4.4.1 OMC of Aggregates for Foamed Asphalt Mixtures

The optimum moisture contents (OMC) and maximum dry densities (MDD) of the three mixtures of aggregates were determined using AASHTO T-180 test method (Figure 4.10) and presented in Figures 4.11-4.13. The importance of OMC is that this amount of water will be added to the aggregates prior to the mixing with foamed asphalt to achieve required density.

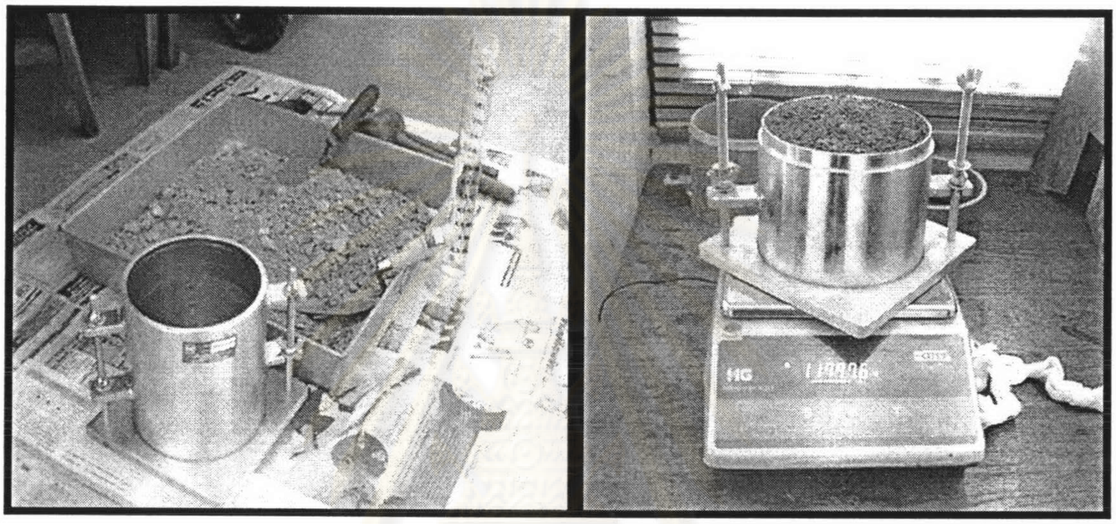

Figure 4.10 The optimum moisture content

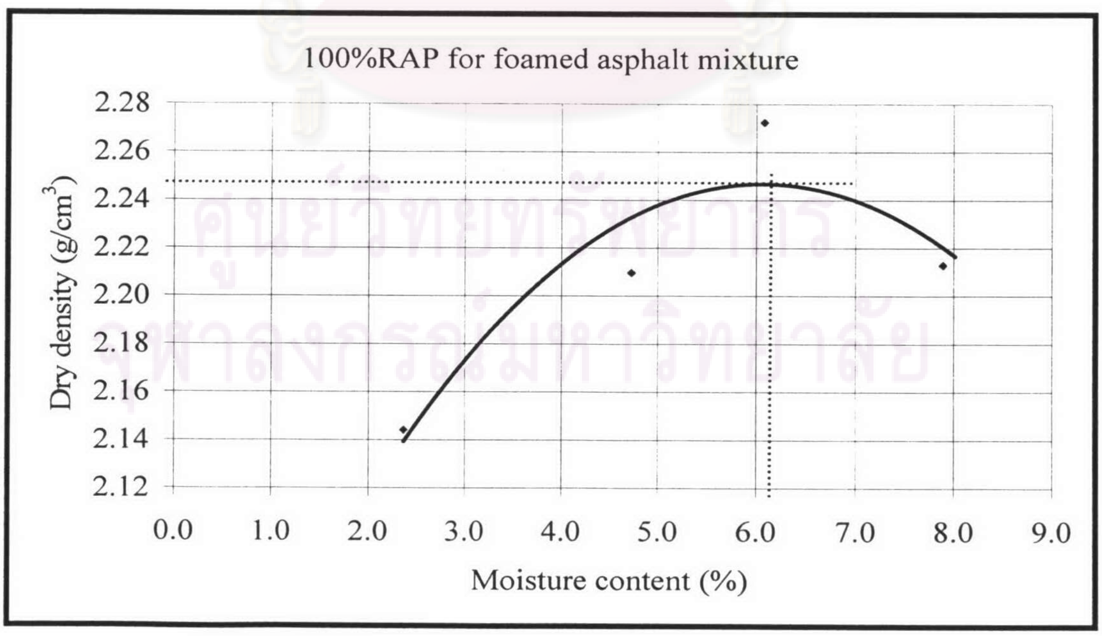

Figure 4.11 OMC and MDD relationship at 100%RAP

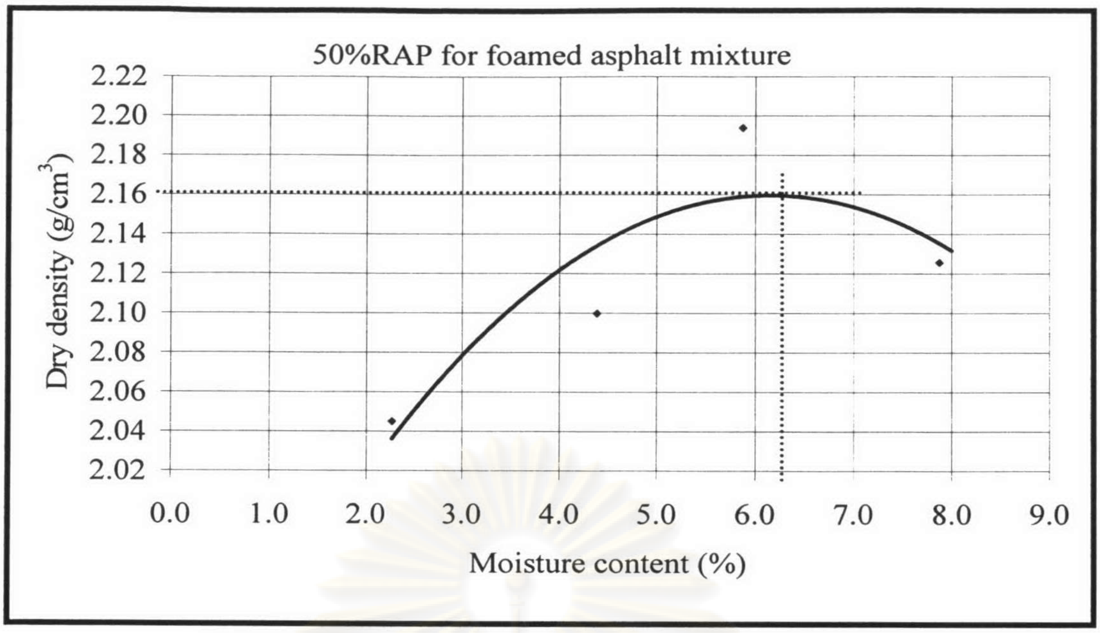

Figure 4.12 OMC and MDD relationship at 50%RAP

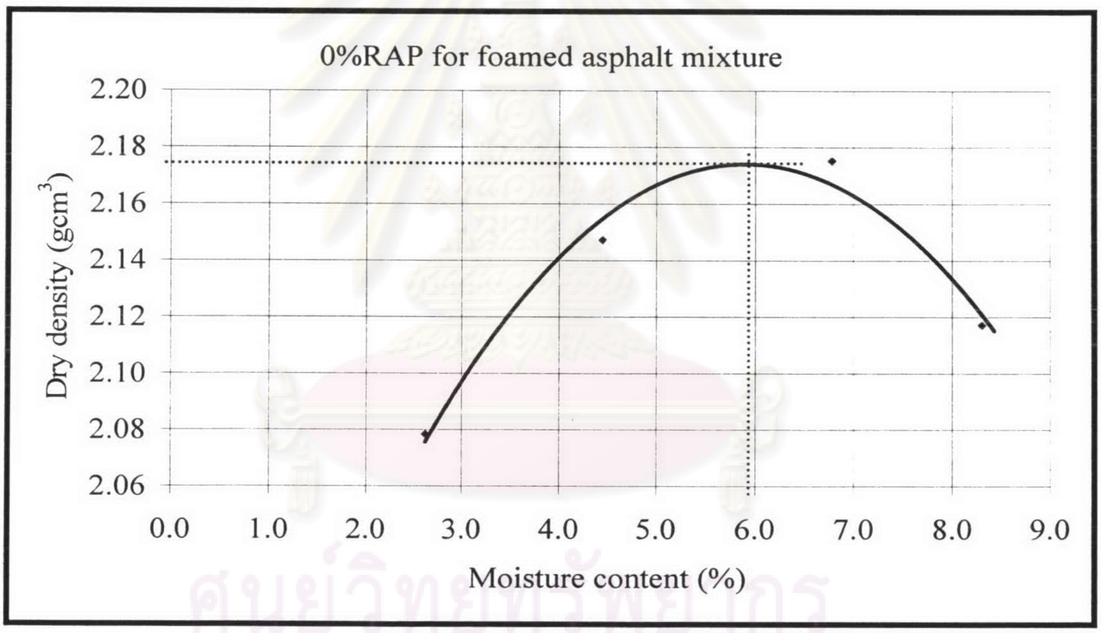

Figure 4.13 OMC and MDD relationship at 0%RAP

OMC: Optimum Moisture Content. MDD: Maximum Dry Density.

Table 4.10 Summary of OMC and MDD

Test Results	Proportion 1 100%RAP	Proportion 2 50%RAP	Proportion 3 0%RAP
OMC (%)	6.20	6.35	5.90
MDD (g/cm^3)	2.25	2.16	2.17

Table 4.10 shows the optimum moisture content and maximum dry densities of the three foamed asphalt mixtures

4.4.2 Optimum Moisture Content for Portland Cement Mixtures

The Portland cement mixtures compaction is similar to that of foamed asphalt mixtures according to tests following AASHTO designation T180. Test results show optimum moisture content (OMC) and maximum dry density (MDD) are 6.45% and 2.28 g/cm^3, respectively, as shown in Figure 4.14.

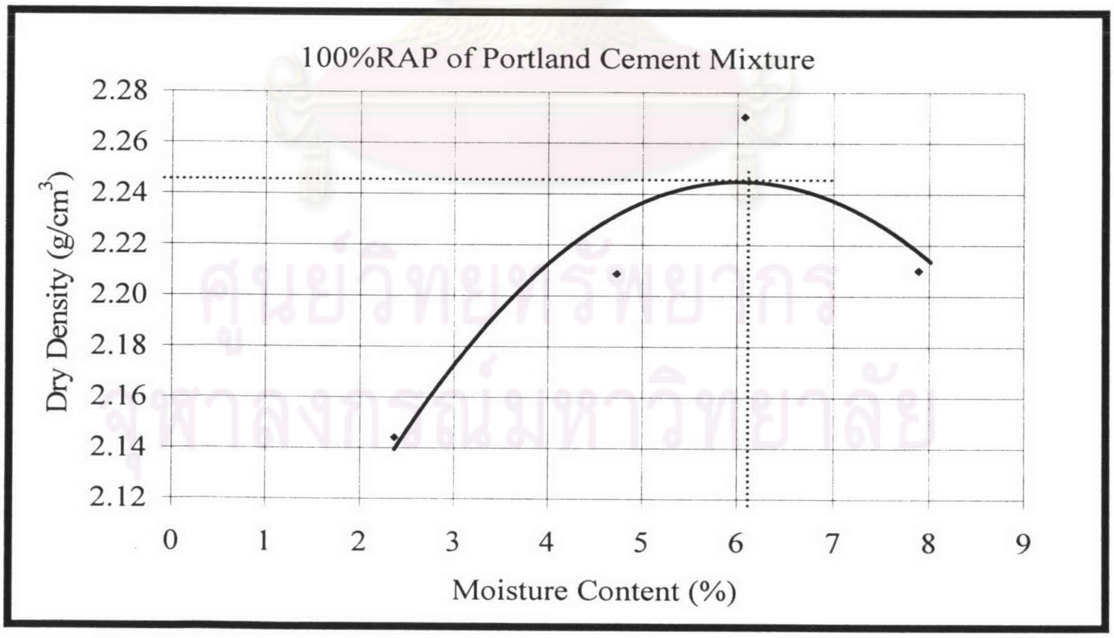

Figure 4.14 OMC and MDD relationship at 100%rap of portland cement mixtures

Similar test procedure (AASHTO T180) was conducted to OMC and MDD of aggregates for Portland cement mixtures. The test results are shown in the Figure 4.14.

4.5 Mix Designs

4.5.1 Foamed Asphalt Mix Design

There are four parameters to be obtained in the procedure for foamed asphalt mix design.

1. Dry density
2. Soaked indirect tensile strength
3. Unsoaked indirect tensile strength
4. Soaked and unsoaked indirect tensile strength ratio (retain ITS)

Figure 4.15-4.17 present the test results of the three mixtures. Note that, since the soaked ITS is the typically less than the unsoaked ITS, the foamed asphalt was selected based on this value. The soaked ITS, the selected foamed asphalt contents and the values of unsoaked ITS, retained ITS and dry density corresponding to the selected to the foamed asphalt contents are presented in the Table 4.11.

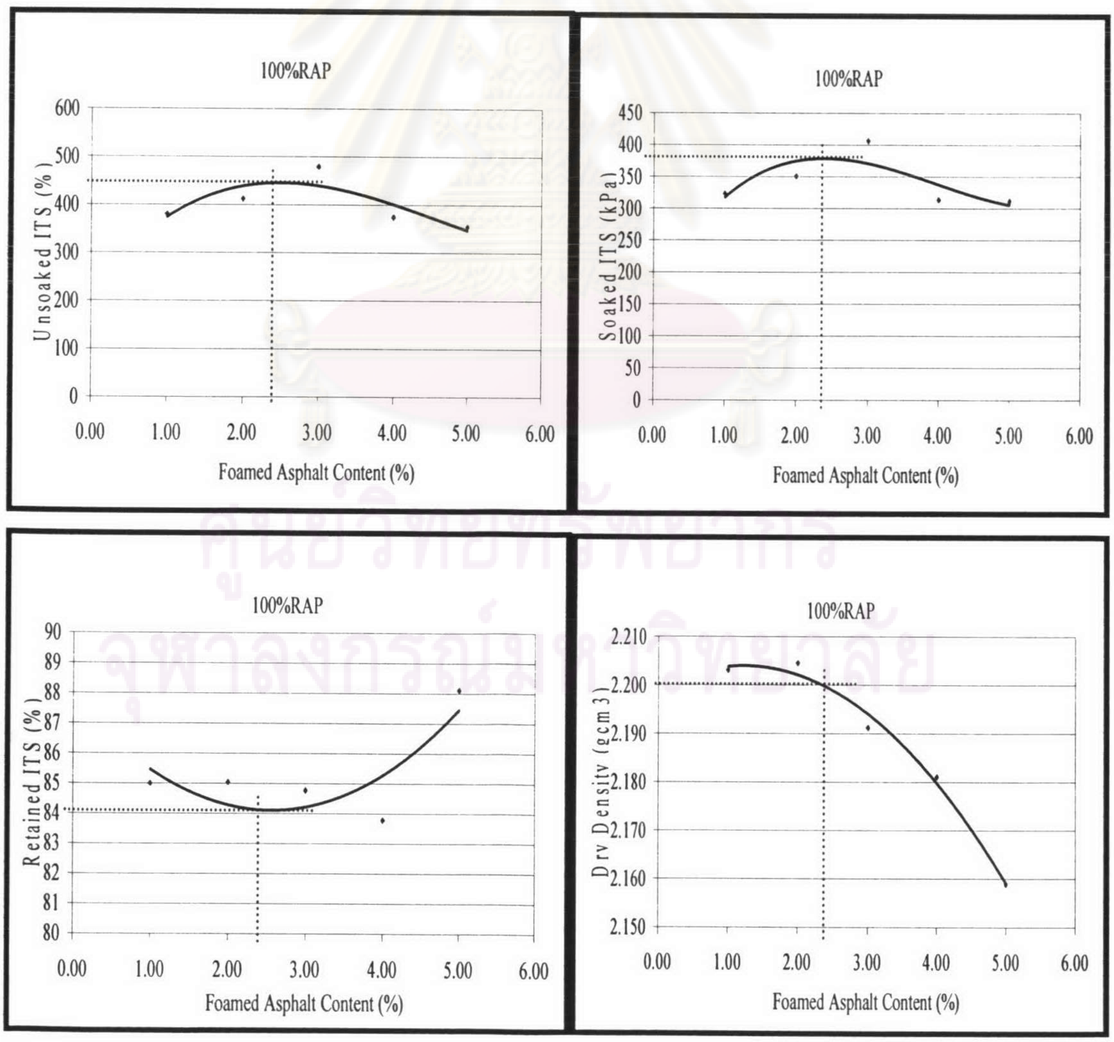

Figure 4.15 100%RAP for foamed asphalt mixtures

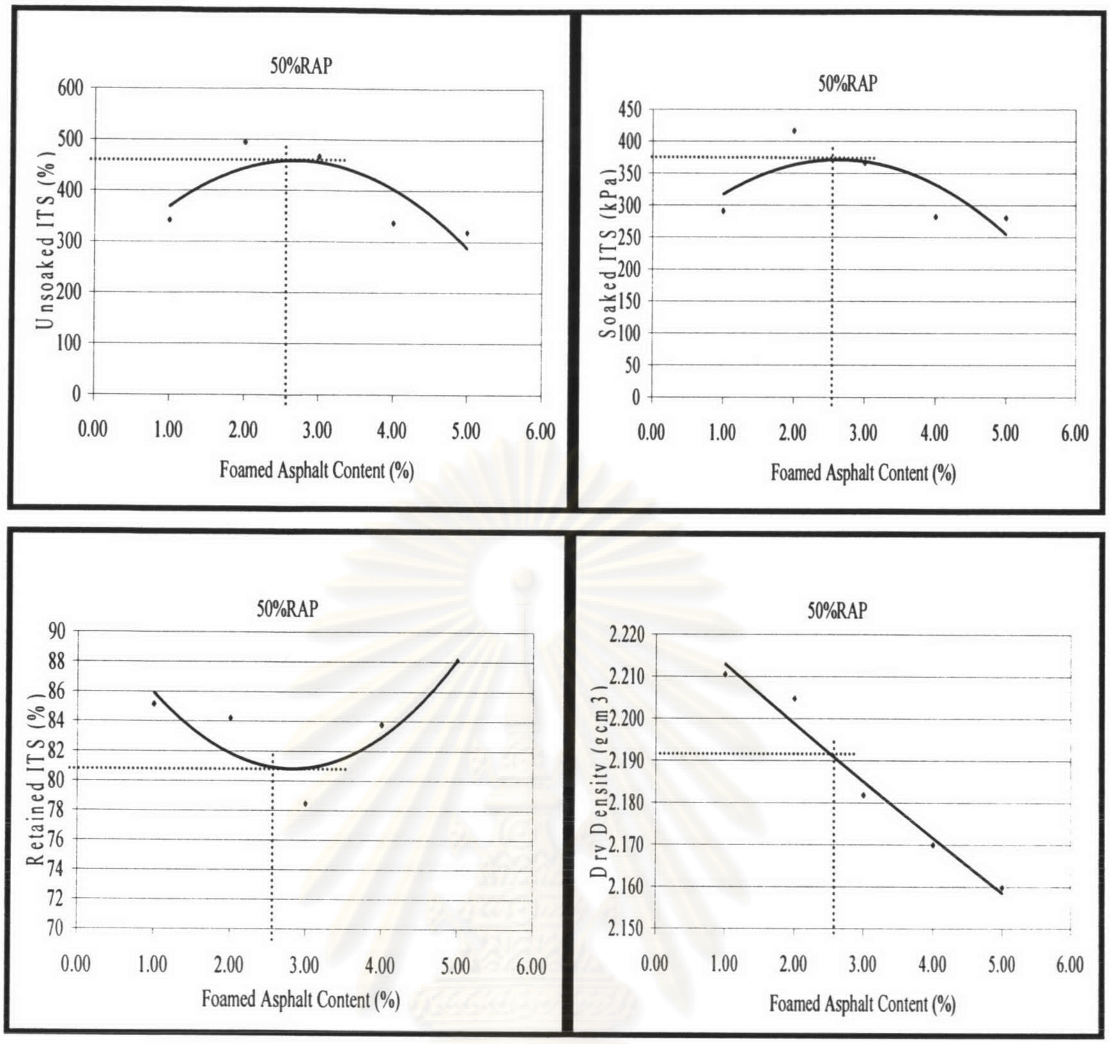

Figure 4.16 50%RAP of foamed asphalt mixtures

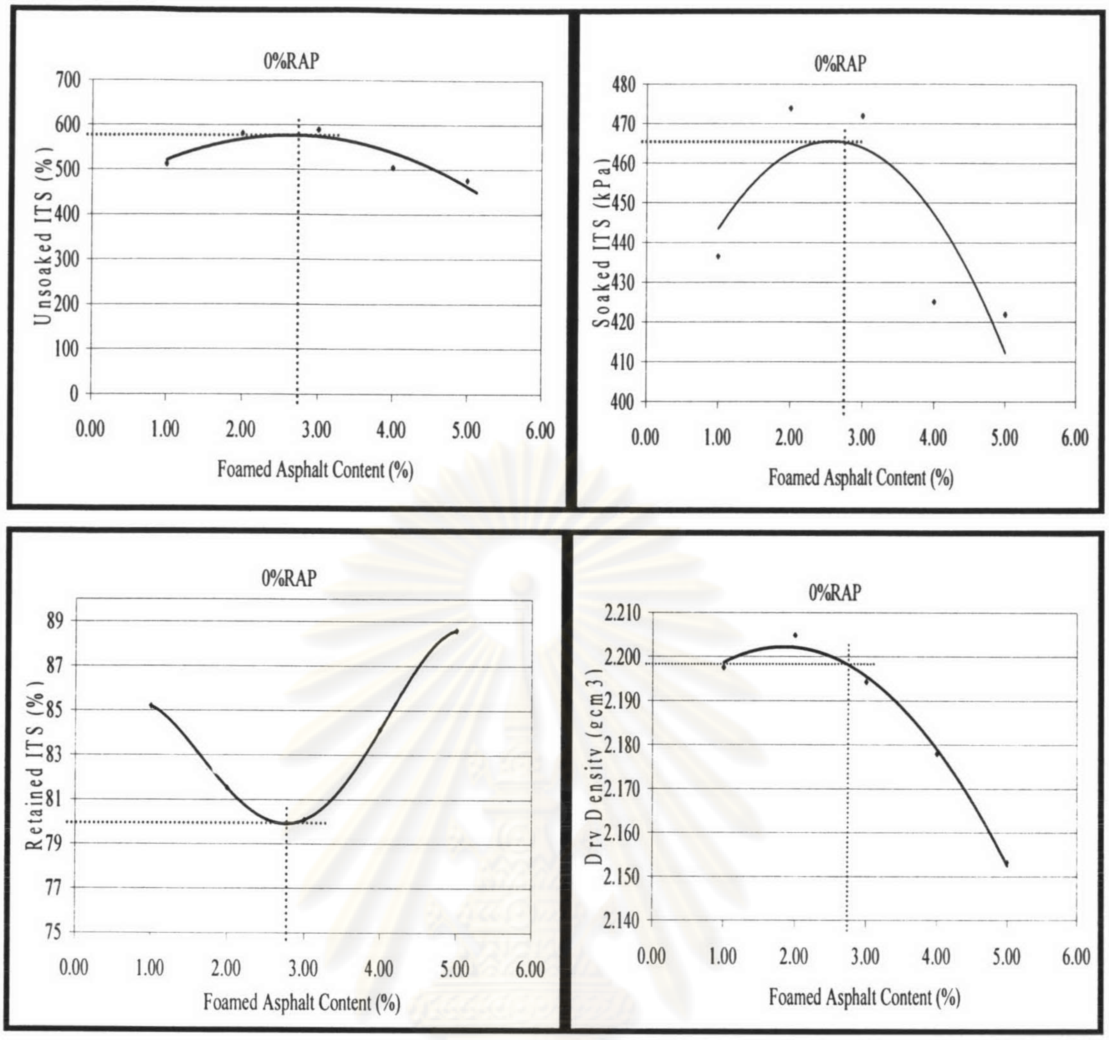

Figure 4.17 0%RAP of foamed asphalt mixtures

Table 4.11 Test result of foamed asphalt mixtures

Test Result	Proportion 1 100%RAP	Proportion 2 50%RAP	Proportion 3 0%RAP
Selected Binder Content (%)	2.35	2.55	2.90
Soaked ITS (kPa)	365	380	470
Unsoaked ITTS (kPa)	450	475	585
Retain ITS (%)	84	81	79
Dry Density (g/cm^3)	2.190	2.192	2.199

ITS: Indirect Tensile Strength

As can be see in table 4.11 as expected foamed asphalt mixtures with 100%RAP, 50%RAP and 0%RAP need foamed asphalt contents of 2.35%, 2.55% and 2.90%, respectively.

The higher percentage of RAP is the lower the percentage of foamed asphalt required. This is because the virgin aggregates absorb asphalt more than RAP. It can also be seen that the higher foamed asphalt content and lower percentage of RAP is the higher the soaked and unsoaked ITS

Table 4.12 Foamed asphalt mixtures of recommendations

Reference	Testing	Proportions		
		100%RAP	50%RAP	0%RAP
Wirtgen Cold Recycling Manual	Optimum content (%)	-	1.5-3.0%	2.5-4%
	Soaked ITS (kPa)	-	-	-
	Unsoaked ITS (kPa)	-	350-800	400-900
	Retain ITS (%)	-	>75	>60
Maccarrone 1994	Soaked ITS (kPa)	>100		
	Unsoaked ITS (kPa)	>200		
	Retain ITS (%)	>50		

Table 4.12 presents the recommended specification of foamed asphalt mixtures by Wirtgen cold recycling manual 2001and Maccarone 1994.

By comparing the values in Tables 4.11 and 4.12, it can be seen that the properties of three foamed asphalt mixtures meet both specifications.

4.6 Test Results

4.6.1 Foamed Asphalt Mixtures

Foamed asphalt mixtures of 100%RAP, 50%RAP and 0%RAP were tested for soaked and unsoaked ITS, resilient modulus (M_R),and fatigue resistance and permanent deformation characteristic.

4.6.1.1 Indirect Tensile Strength (ITS)

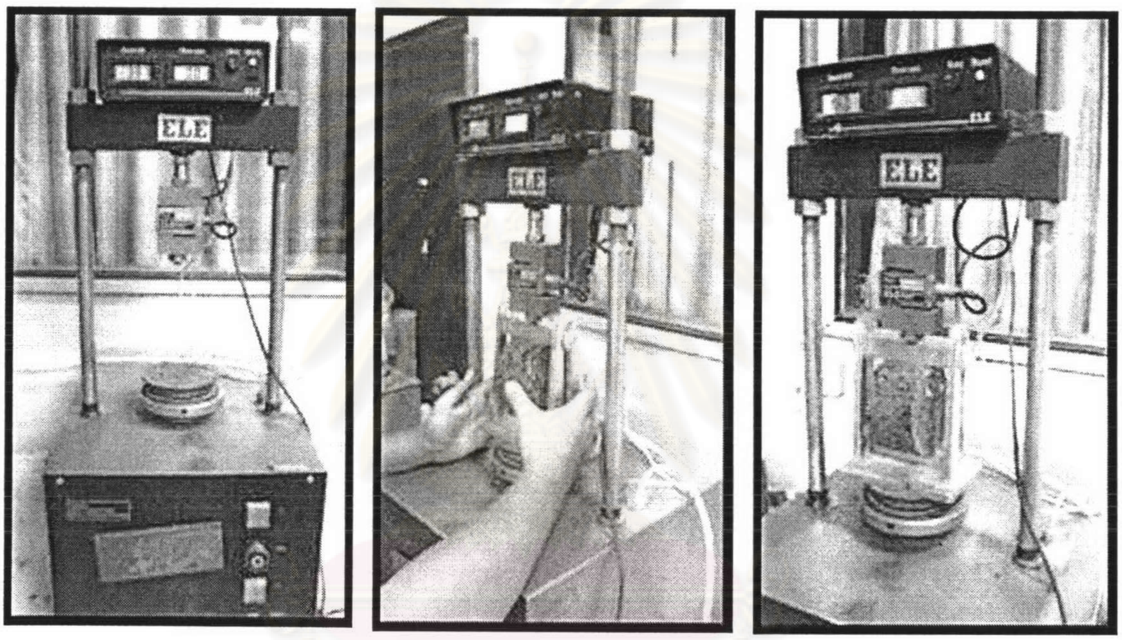

Figure 4.18 ITS of foamed asphalt mixtures test with ELE Marshall test 25

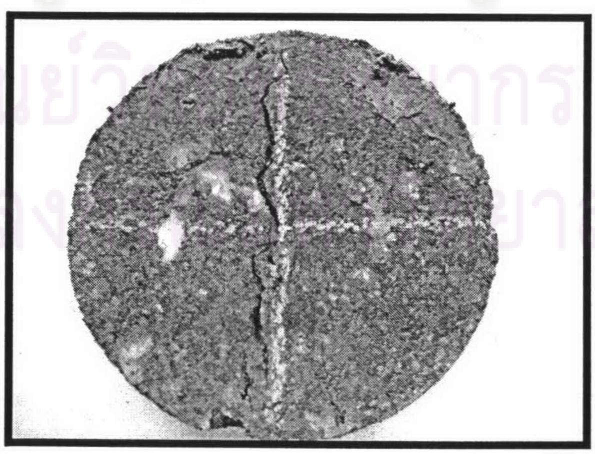

Figure 4.19 ITS characteristics failure

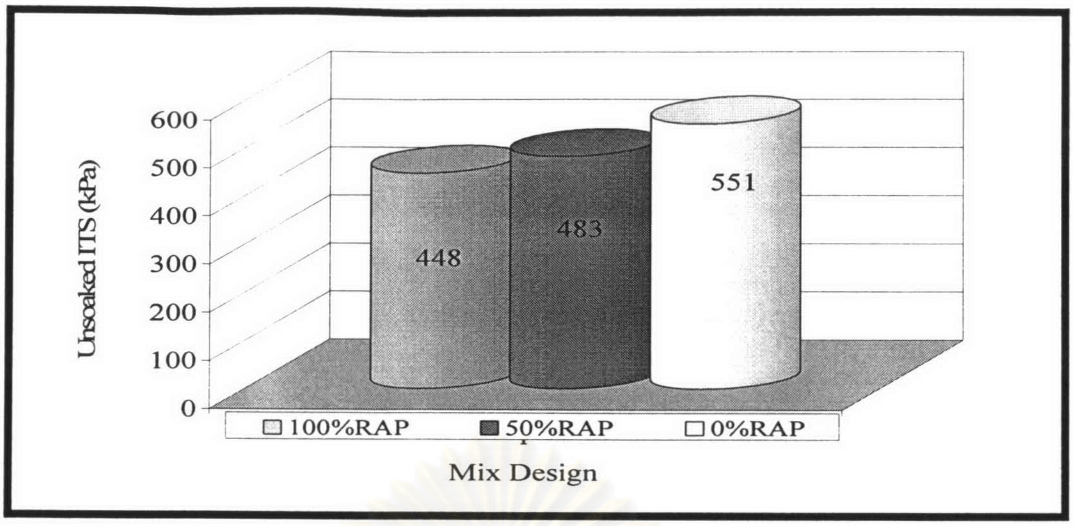

Figure 4.20 ITS test result of three proportions

Table 4.13 ITS of foamed asphalt mixtures comparison

Mix Design	Average unsoaked indirect tensile strength (kPa)			
	Test Result	Wirtgen Cold Recycling Manual 2001	Maccarrone 1994	Interim Technical Guideline 2002
100%RAP	448	-	>200	100-500
50%RAP	483	350-800	>200	100-500
0%RAP	551	400-900	>200	100-500

The ITS of 100%RAP, 50%RAP and 0%RAP were determined following AASHTO T283 test method and shown in figure 4.20, respectively. They were then compared with Wirtgen cold recycling manual 2001, Maccarone 1994 and Interim Technical Guideline as shown in Table 4.13.

Figure 4.20 illustrates, ITS of 100%RAP, 50%RAP and 0%RAP for foamed asphalt mixtures. The ITS values are compared with the recommended values from various source and tabulated in Table 4.13. It can been seen that the ITS of the three foamed asphalt mixtures are very well within or beyond the recommendation ranges.

4.6.1.2 Resilient Modulus

Table 4.14 Resilient modulus of foamed asphalt mixtures

Mix Design		Temperature Tested			
		15 °C	25°C	35°C	45°C
		25%ITS	20%ITS	15%ITS	10%ITS
100%RAP	Applied Load (kPa)	112	90	67	45
	Average Resilient Modulus (MPa)	3731	3625	2199	2060
50%RAP	Applied Load (kPa)	121	97	72	48
	Average Resilient Modulus (MPa)	8920	8018	5449	5289
0%RAP	Applied Load (kPa)	138	110	83	55
	Average Resilient Modulus (MPa)	7836	6472	5189	4993

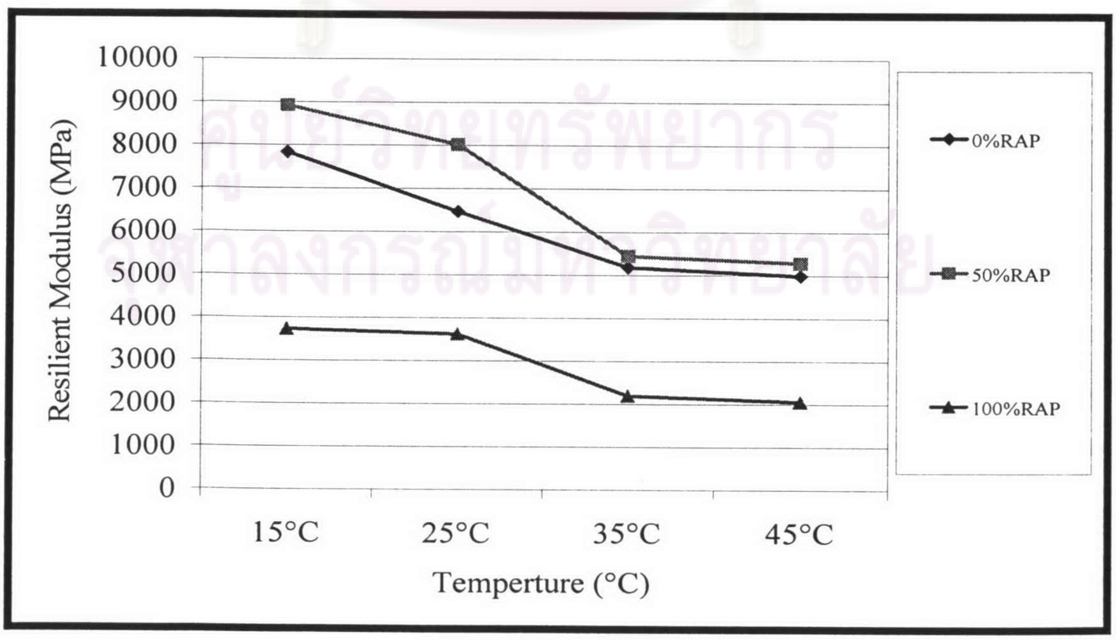

Figure 4.21 Resilient modulus test result

The average resilient modulus of triplicate samples. Which the result of each sample are reported in Tables E-3 to E-6 of appendix E

The results of the resilient modulus tests of foamed asphalt mixtures are shown in Table 4.14 and Figure 4.21. As can be seen the resilient modulus of 100%RAP foamed asphalt mixtures are much lower than those of 50%RAP and 0%RAP foamed asphalt mixtures. While the moduli of the latter two mixtures are relatively close to each other. Note that, the resilient moduli of 50%RAP and 0%RAP of foamed asphalt mixtures are higher than the ranges specified in Wirtgen cold recycling manual 2001, 2500-5000 Mpa for 50%RAP and 300-6000 Mpa for 0%RAP (no reference temperature specified in the manual).

The possible reasons that the ITS and resilient modulus of the 50%ARP and 0%RAP foamed asphalt mixtures are on the high ends of the specified ranges could be:

1. Differences raw materials
2. A difference in compaction efforts between 75 Marshall blows specified in the manual and is cycles of gyratory compactor used in this study.

4.6.1.3 Fatigue Resistance

Fatigue resistance of 100%RAP, 50%RAP and 0%RAP foamed asphalt mixtures were tested using repeated load of 40% ITS at 25°C until resilient modulus was reduced to 50% of the initial resilient modulus. The data recorded for fatigue was in cycles, with test results shown in Figure 4.22.

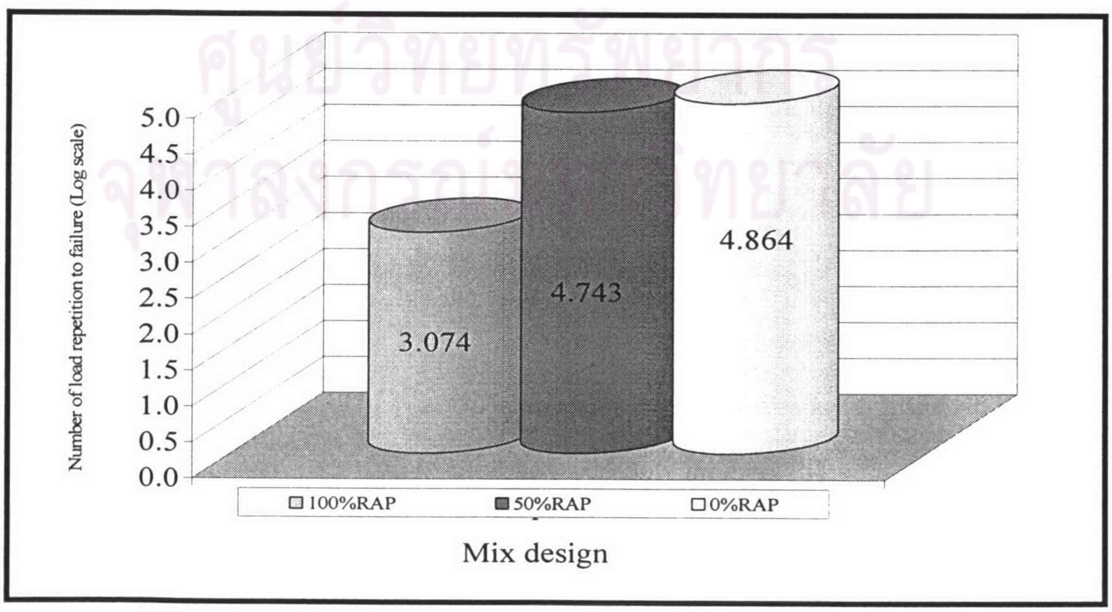

Figure 4.22 Fatigue resistance test results

The 100%RAP mixtures of foamed asphalt had the lowest log (N_f), showing that the mixtures were fail more easily when compared to 50%RAP and 0%RAP mixtures, 50%RAP mixtures had a log (N_f) = 4.743 0%RAP had 4.8664, had a similar.

Figure 4.22 shows the results of fatigue resistance tests. Note that, the fatigue failure is determined when the resilient modulus of sample drops to 50% of its initial value. Similar to the resilient modulus test results, the number of load repetition to failure of 50%RAP and 0%RAP are much higher than that of 100%RAP.

4.6.1.4 Permanent Deformation Test

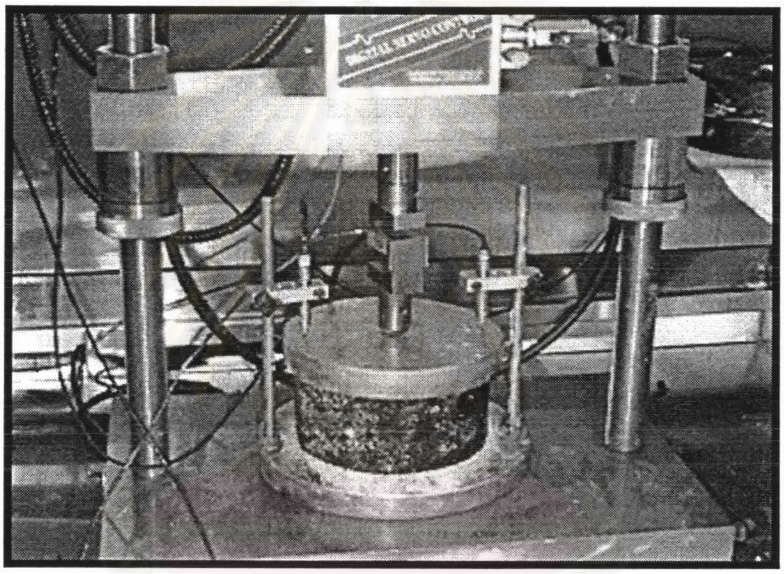

Figure 4.23 Repeated load deformation

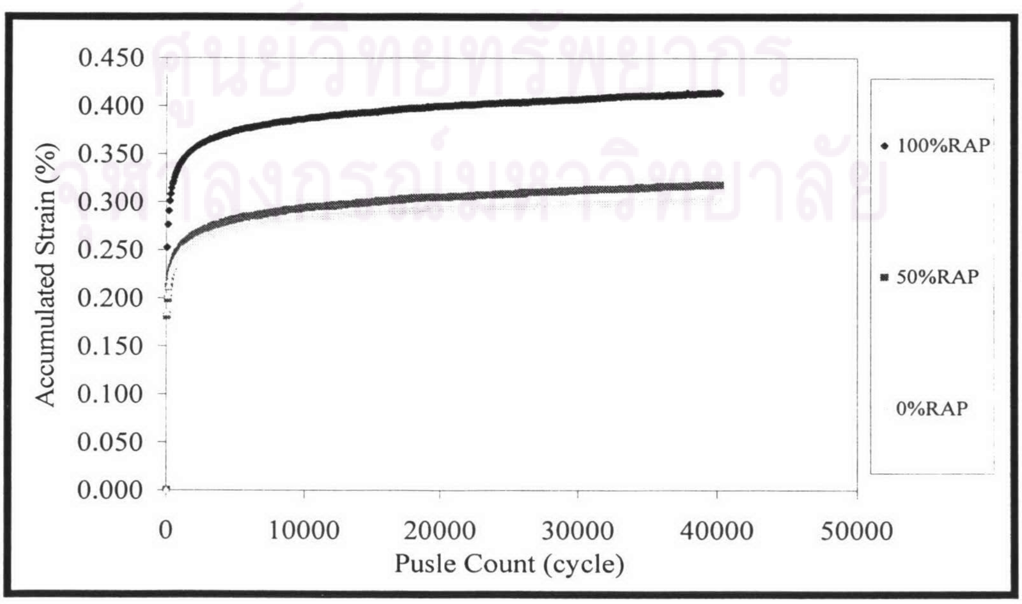

Figure 4.24 Accumulated strained of loading pulses count

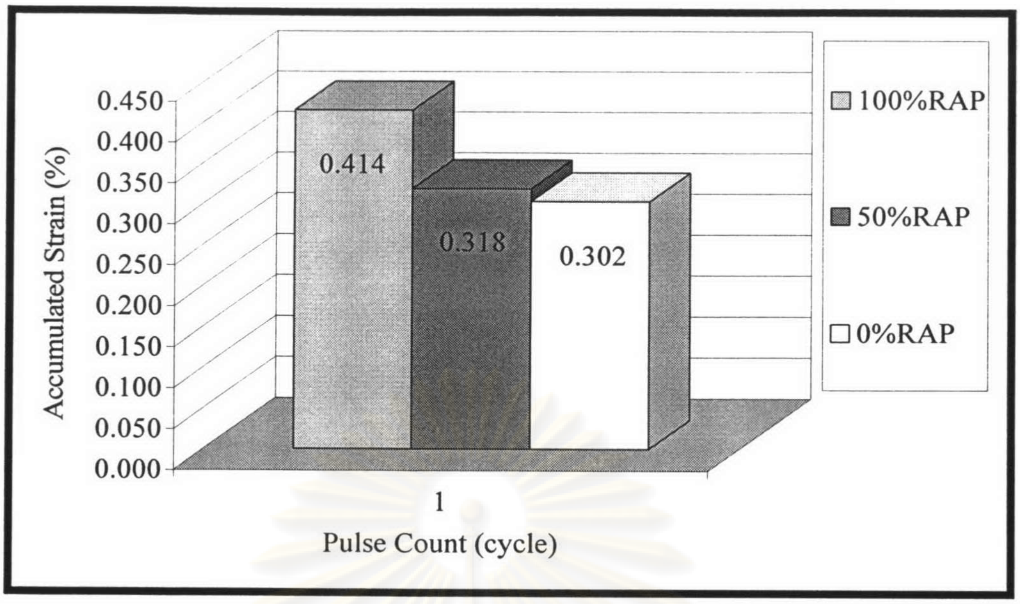

Figure 4.25 Accumulated strained at 40,000 pulses

Figure 4.25 shows the results of the permanent deformation test of foamed asphalt mixtures. As can be seen, once again, 50%RAP and 0%RAP foamed asphalt mixtures show superior to 100%RAP foamed asphalt mixtures that are they experience lower accumulated strain than 100% RAP samples.

4.6.2 Portland Cement Mixtures

The laboratory tests of Portland cement stabilized mixtures having 2%, 3%, 4% and 5% cement content were conducted at 7, 14 and 28 days for the following properties.

1. Indirect tensile strength (ITS)
2. Resilient modulus (M_R)
3. Unconfined compressive strength (UCS)

4.6.2.1 Indirect Tensile Strength

The indirect tensile strength of Portland cement mixtures test also utilized UTM-5P, following AASHTO standard test method T283 with a loading rate of 0.8333 mm/s or 2 inches/min at 25°C.

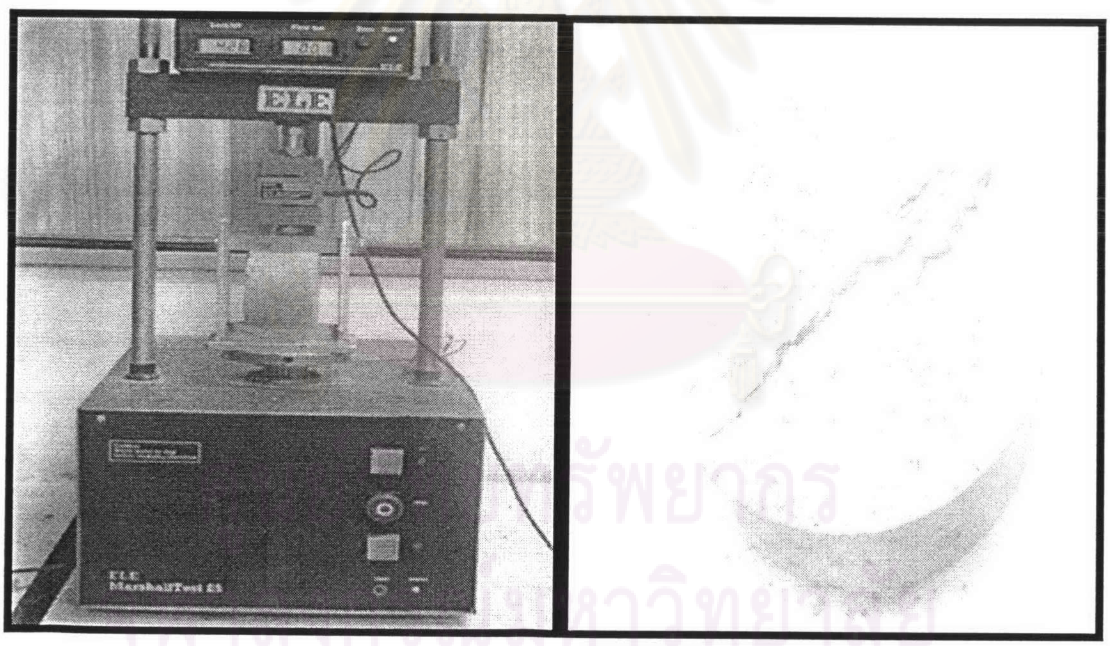

Figure 4.26 ITS Test with the ELE Marshall Test 25

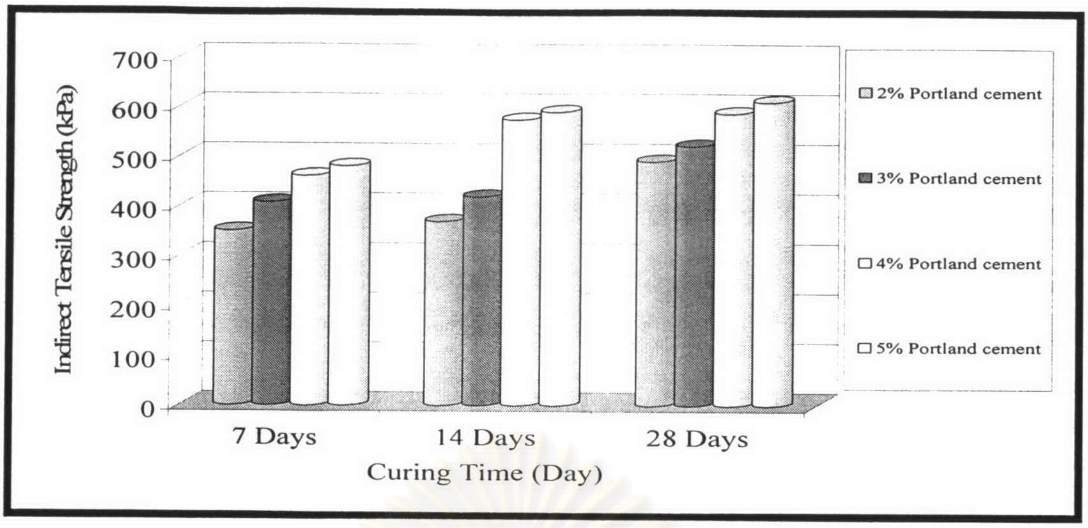

Figure 4.27 ITS of portland cement mixtures test result

Figure 4.27 shows the ITS test results Portland cement stabilized mixtures. As can be seen from the Figure, the higher the cement content and longer the curing time is the higher the ITS of the samples.

4.6.2.2 Resilient Modulus of Portland Cement Mixtures

Resilient modulus test of Portland cement mixtures with 2%, 3%, 4% and 5% cement at 7, 14 and 28 days curing time, were conducted using the UTM-5P, following the ASTM standard test method D4123. Two hundred repetitions cycles were applied by using Haversine shaped load pulse with 0.1 seconds of load duration, 0.9 seconds of rest period. The Poisson ratio of 0.35. Then, the average recovered deformations for each LVDT were recoded separately for the last five cycles.

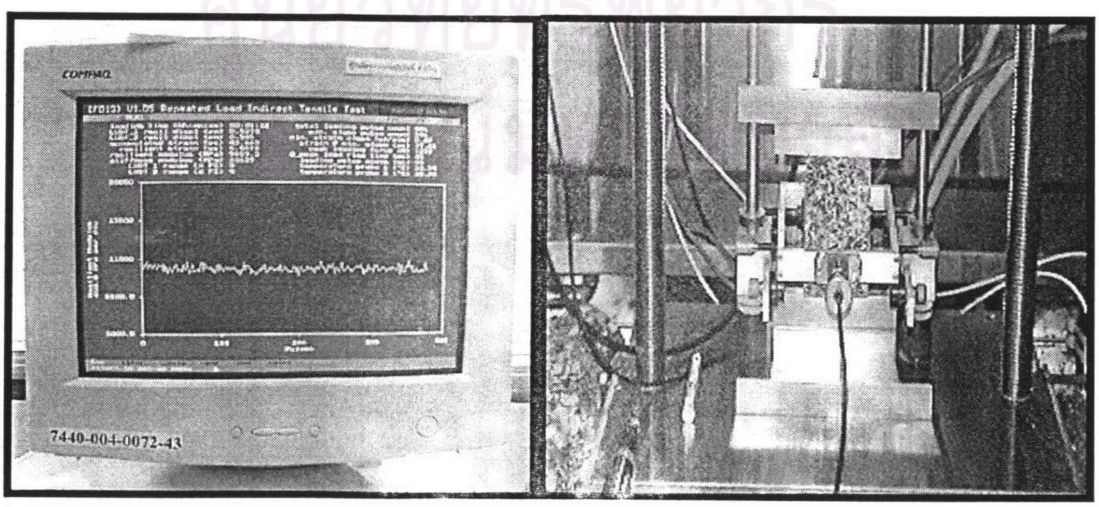

Figure 4.28 Resilient modulus of portland cement mixtures test with UTM-5P

Table 4.15 Resilient modulus of Portland cement mixtures

Mix Design	Resilient Modulus (MPa)		
Cement Content (%)	Curing Time (Day)		
	7 days	14 Days	28 Days
2 %	4833	6464	8100
3%	7332	8809	10989
4%	7879	10068	12327
5%	9476	10377	14401

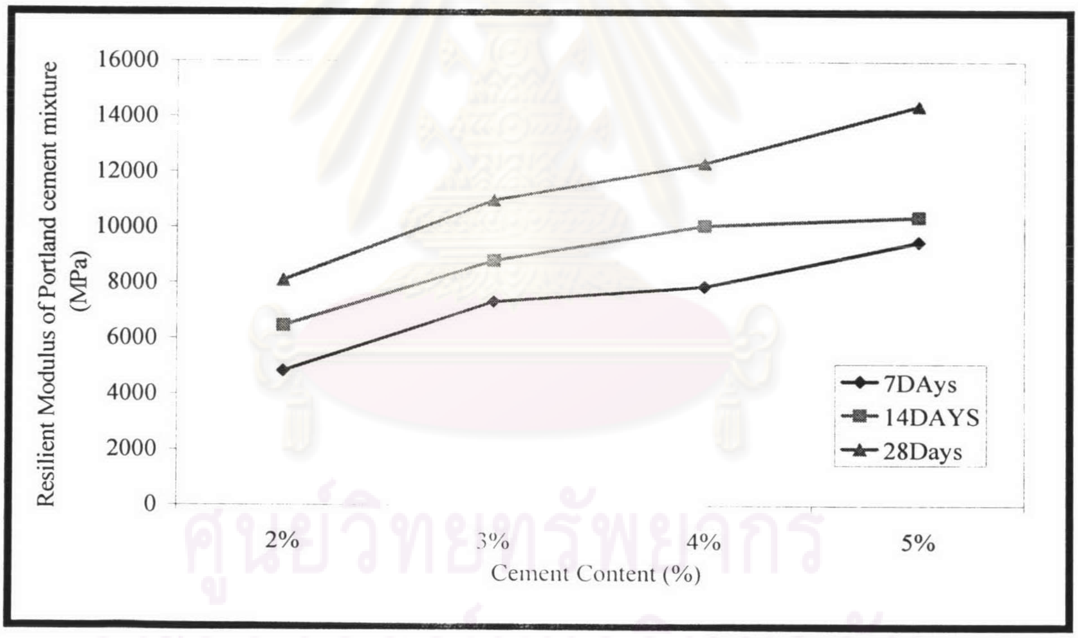

Figure 4.29 Resilient modulus of portland cement mixtures test result at temperature of 25 degree Celsius

Table 4.15 and Figure 4.29 show the results of resilient modulus tests of Portland cement stabilized mixtures. Similar to the ITS test results, the higher cement contents and longer the curing time result in higher resilient moduli of the samples. Similar results also reported by M. I. Pericleous, and J. B. Metcalf, 1996.

4.6.2.3 Unconfined Compressive Strength (UCS) Test Results

Unconfined Compressive Strength (UCS) test performed in accordance with using 30,000 lb, Soil test VERSATER 30 M machine, following the AASHTO standard test method T209-96. The test axial compressive loads to sample at loading rate of 2.5 mm/min until failure, the test result shows in the Table 4.16 and Figure 4.30

Table 4.16 Average of unconfined compressive strength test results (kg/cm^2)

Cement Content %	Curing time (Days)		
	7 Days	14 days	28 Days
2	21	38	40
3	28	41	54
4	37	47	58
5	48	51	59

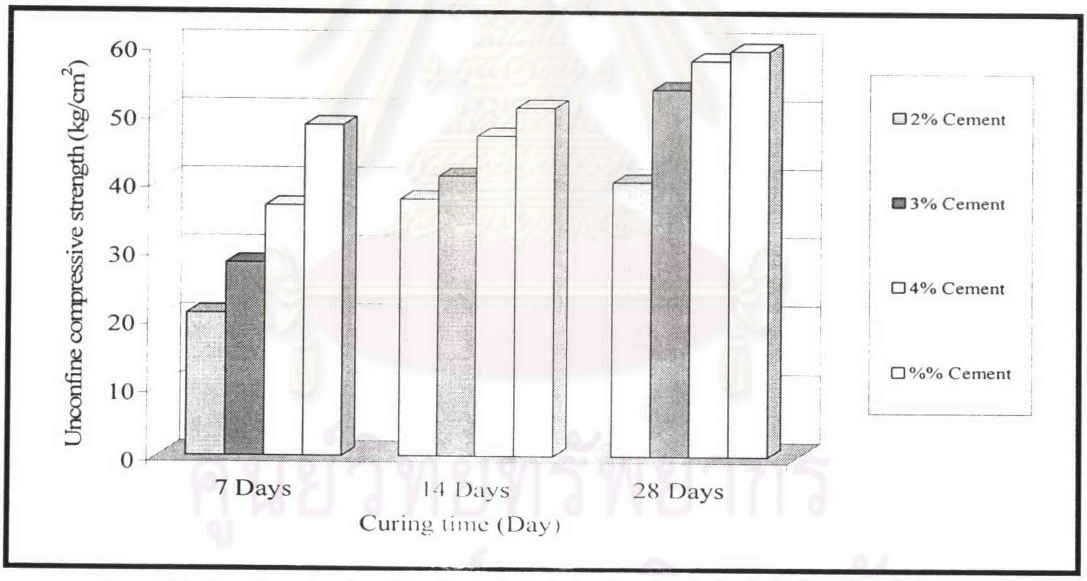

Figure 4.30 Unconfined compressive strength test results

Table 4.16 and Figure 4.31 show the results for UCS tests. This study found the optimal cement content per 100%RAP aggregates under required unconfined compressive strength of Department of Highways, which requires UCS values at 25 kg/cm^2 (for cement stabilized on crushed rock in Phisanulok-Uttradid section 1, 2 and 3 projects). When comparing the results in the laboratory to Department of Highways required UCS, the optimal percentage cement content was found to be 3% cement at 7 days curing time. However the results reflect highway materials used in road construction and RAP materials for future reconstruction.

As expected, the higher cement contents and the longer curing time result in higher UCS of the samples. Note that required UCS of cement treated base for the Department of highways of Thailand is 25 kg/cm^2, which corresponding to the cement about 3.45%,

Table 4.17 Comparison of the UCS in the test results and DOH for 7 days

Cement content (%)	Test results (kg/cm^2)	DOH (kg/cm^2)
2	21	16.20
3	28	24.00
4	37	31.80
5	48	39.50

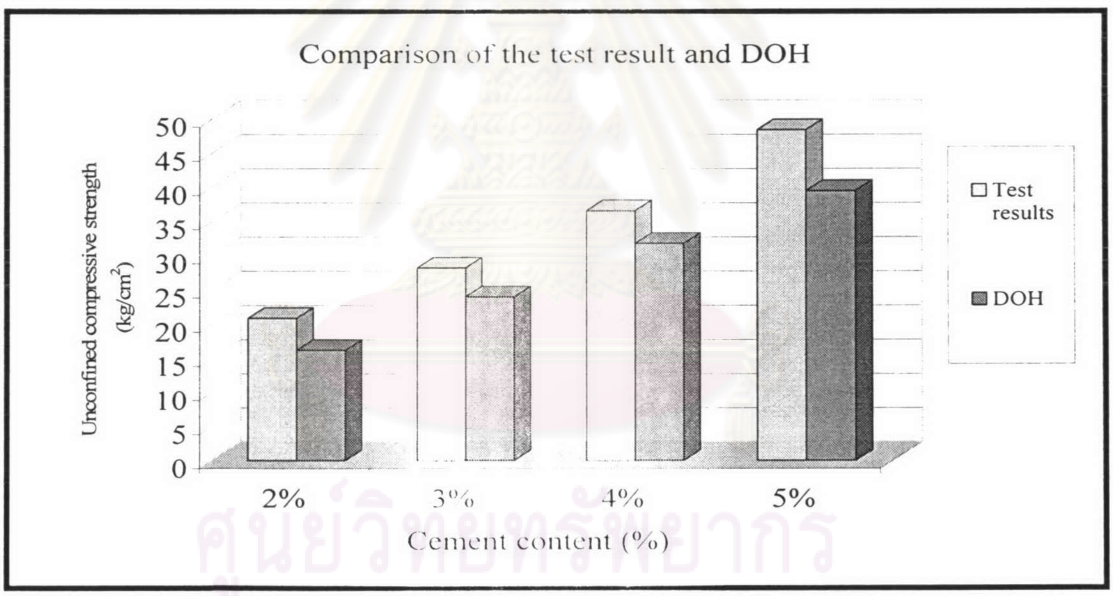

Figure 4.31 Comparison of the UCS test results and DOH

DOH: Department of highways

Table 4.17 and Figure 4.31 shown the UCS test results and DOH required of Portland cement stabilized mixtures, the UCS test results higher than the DOH required. Hence, the test results very closed in the DOH.