

Evaluation of Factors Influencing strength of Foamed Bitumen Stabilised Mix

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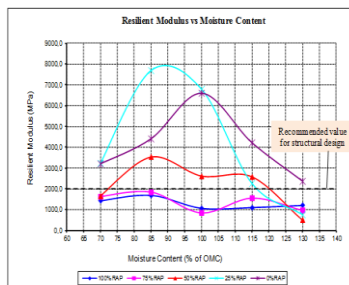
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Graphical abstract



Abstract

Over recycling of asphalt pavements involves mixing of existing pavement material with stabilizing agent such as foamed bitumen, bitumen emulsion, cement or lime and placed on the milled pavement and compacted. The strength of foamed bitumen stabilized mix is influenced by factors such as cement content, moisture level and curing time. It was found that the strength in terms of resilient modulus, Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) values, increased with curing time and percentage of active filler. It was also found that the maximum strength in terms of resilient modulus, Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) was not at Optimum Moisture Content (OMC) and the strength decreased as the RAP proportion increased

Keywords: Recycling; pavements; foamed bitumen; strength; optimum moisture content; RAP proportion

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1.0 INTRODUCTION

1.1 Background

Recycling of asphalt pavements has increased significantly since 1970. In Malaysia the cold recycling technique which involved in-plant recycling or in-situ recycling with foamed bitumen was first introduced in 2001. Since then the technique has become popular as a viable alternative pavement rehabilitation measure. The technique involves milling of existing pavement, mixed with the stabilizing agent and placed on the milled pavement and compacted [1-3]. The most common stabilizing agents used for cold recycling in Malaysia are foamed bitumen, bitumen emulsion, cement and lime. The cold recycling process is carried out either in plant or in situ using purposed built recycling machine and recycled layer will form a new road base stabilized layer. It is a normal practice in Malaysia to overlay the newly stabilized road base layer with 60mm thick of binder course and 50 mm thick of wearing course layers.

Cold recycling technology with foamed bitumen is economical, sustainable and environmentally friendly [4,5]. Foamed bitumen can be used to stabilize a variety of materials, including the RAP materials. From both economic and ecological points of view, cold recycling technology as much more beneficial than hot mix asphalt [6].

A number of cold recycling projects with foamed bitumen stabilised mix have been completed in Malaysia for the past 12 years and on-going performance monitoring are in progress [7,8]. However, despite such progress, option on foamed bitumen has been limited because of the lack of a standardized mix design, construction procedure and gaps that exist between the current knowledge and the knowledge that is needed to increase the probability of success when using this technology, particularly in the Malaysian hot and wet environment.

1.2 Objective

The objectives of this study are:

- (i) To investigate the effect of cement, moisture content and curing time at varying RAP proportions to the strength of foamed bitumen stabilised mix.
- (ii) To analyse and compare the results obtained with the requirement of the National Specification for Road works.
- (iii) To provide recommendations on the required cement content, moisture content and curing time for foamed bitumen stabilised mix based on the findings of the research.

2.0 METHODOLOGY

2.1 Experimental Matrix and Sample Preparation

In this study, foamed bitumen stabilised mix with different proportions of Reclaimed Asphalt Pavement (RAP) and Crushed aggregates (CA) were tested for their strength properties at various cement contents, curing time and moisture contents. Table

1 summarizes the experimental matrix used in the study involving five different RAP proportions which represent the possible combinations that may be encountered during construction. The experimental test matrix is therefore designed to investigate the strength characteristic in the laboratory and also the expected field performance for these different mixture compositions.

Table 1 Experimental matrix and specimen quantities

Aggregate Proportion	Strength Test	Curing Time (Day)					Moisture Content (% of OMC)					% Cement				
		1	2	3	7	28	130	115	0	85	70	0	1	2	3	
100% RAP	UCS	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSdry	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSsoaked	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Resilient Modulus	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
75% RAP + 25% Crusher Run	UCS	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSdry	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSsoaked	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Resilient Modulus	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
50% RAP + 50% Crusher Run	UCS	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSdry	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSsoaked	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Resilient Modulus	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
25% RAP + 75% Crusher Run	UCS	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSdry	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSsoaked	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Resilient Modulus	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
100%Crusher Run	ITSdry	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	ITSsoaked	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Resilient Modulus	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

* 6 denote number of specimen

2.2 Description of Materials

Samples for ITS and Resilient Modulus test (100 mm briquettes) were prepared and compacted at ambient temperature using Marshall compactor procedure of 75 blows per side. Table 2 clearly displays the material gradation and foamed bitumen content for the mixture. Samples for Unconfined Compressive Strength test (150 mm diameter) were prepared in accordance to BS 1377-Test 14 using the vibrating hammer. In order to analyse the effect of cement from 0-3% in the step of 1% on the strength properties, samples were mixed at optimum moisture content (OMC) as determined by the modified Proctor test method (BS 1377) and dry cured for 3 days. To determine the curative period, which is defined as the time taken for the samples to reach the required strength, the samples were dry cured for 1,2,3,7 and 28 days using 1% of cement being at OMC. The MDD and OMC for the mixture is shown in Table 3. Dry cured in this study means the samples are cured at ambient temperature without soaking in the water. To study the effect of varying moisture content from 30% above to 30% below OMC in the steps of 15% on the strength properties, the cement content was set constant at 1% and samples were dry cured for 3 days.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Variation of Curing Time on UCS

The relationship between UCS and curing time at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 1. From the result obtained, it can be seen that the UCS value increased with curing time and there was a rapid increase in UCS within the first 5 days of curing for all samples, after which the increase was gradual.

It was also observed that higher RAP content resulted in lower UCS values. In the local construction practice, the UCS requirement for recycling works is specified at 0.7MPa for a 7 days curing period. However, the protection and maintenance period before overlaying with the asphaltic layer is only 2 days. All samples achieved the required strength of 0.7MPa as early as 2 days of curing except for the 100% RAP. At 100% RAP, the UCS values meet the minimum requirement of 0.7MPa at seven days of curing time. In order for the treated road to be opened for traffic after 2 days it is recommended that the maximum RAP content be set at 75%. From Figure 1, foamed bitumen stabilised mix with 0% to 50% RAP achieved the 0.7MPa requirement as early as one day of curing time

Table 2 Material gradation and foamed bitumen content

Grading Sieve Size (mm)	Aggregate Proportion (% Passing)				100% CR
	100% RAP	75% RAP + 25% CR	50% RAP + 25% CR	25% RAP + 75% CR	
50	100		100		100
37.5	99		98		97
20	90		83		66
10	63		60		57
5	40		41		41
2.36	23		26		28
0.425	4		7		9
0.075	0.3		2		3
Foamed Bitumen content (%)	1.5		2.5		3

Table 3 Compaction parameters of the mixture

	100% RAP	75% RAP+ 25% CR	50% RAP+ 50% CR	25% RAP+ 75% CR	100% CR
MDD (Mg/m ³)	1.879	2.024	2.161	2.281	2.252
OMC (%)	4.481	5.140	5.820	6.080	6.130

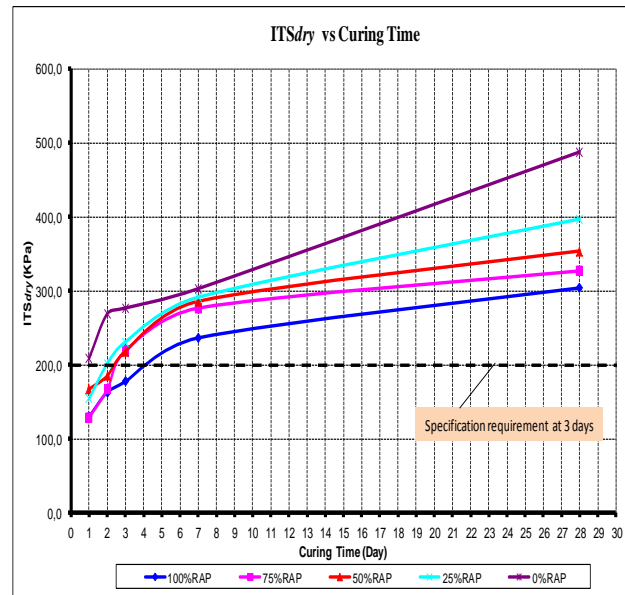


Figure 2 ITSdry vs curing time at various RAP contents

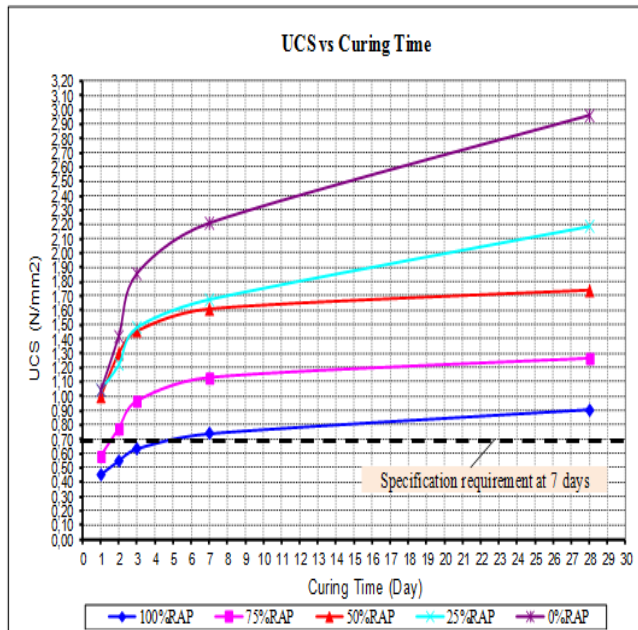


Figure 1 UCS vs curing time at various RAP contents

3.2 Effect of Curing Time on ITSdry

The relationship between *ITSdry* and curing time at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 2. The *ITSdry* values were observed to increase with curing time. There was a rapid increase in *ITSdry* within the first 5 days of curing for all samples, after which the increase was gradual. The 100% RAP did not achieve the required value of 200 kPa at 3 days as specified in national specification. The results did not seem to indicate positive correlation between RAP proportions and *ITSdry* values.

3.3 Effect of Variation of Curing Time on ITSsoaked

The relationship between *ITSsoaked* and curing time at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 3. Similar to the *ITSdry*, *ITSsoaked* values were observed to increase with curing time. There was a rapid increase in *ITSsoaked* within the first 7 days of curing for majority of the samples, after which the increase was gradual. Only the CIPR mix with 100% RAP did not achieve the required value of 150 KPa at 3 days as specified in national specification

3.4 Effect of Curing Time on Resilient Modulus

The relationship between resilient Modulus and curing time at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 4. There was a rapid increase in resilient modulus within the first 7 days of curing for all samples, after which the increase was gradual. It was also observed that the higher RAP proportion resulted in lower resilient modulus [9, 10]. Samples containing higher RAP proportion of 75% and 100% RAP, a longer curative period were required to achieve the required value of 2000 MPa. Samples with 100% RAP needed 10 days to achieve the minimum strength. This suggests that higher cement content shall be used to shorten the curative period in cases where it requires early opening to traffic

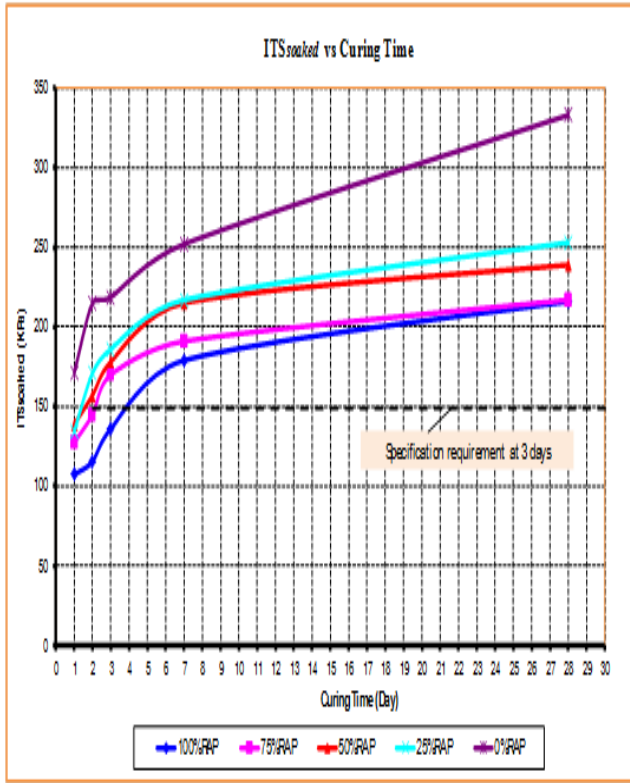


Figure 3 ITS_{soaked} vs curing time at various RAP contents

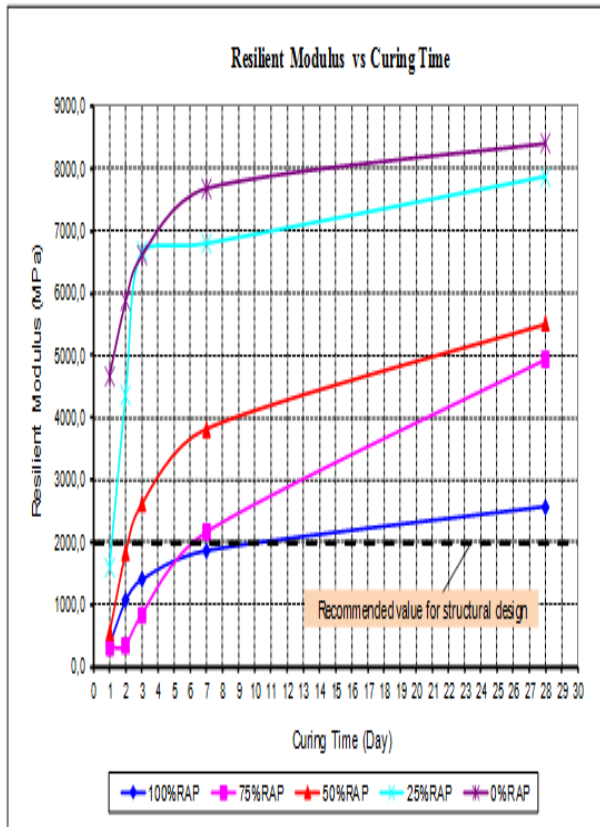


Figure 4 Resilient Modulus vs curing time at various RAP contents

3.5 Effect of Curing Time on Tensile Strength Ratio (TSR)

The relationship between Tensile Strength Ratio (TSR) and curing time at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 5. The TSR values were observed to decrease with curing time. Generally TSR value for all samples which are cured at 3 days is more than 75%. This value is within the requirement as stated in the national specification. Curing is the process where moisture content was reduced and air cavity increased with time. For ITS_{soaked} test, the specimen is immersed in water for 24 hours and in the process water will fill the air cavity and this will weaken the strength of the specimen. This factor led to the TSR will be lower when curing time increases

3.6 Effect of Moisture Content on UCS

The relationship between UCS and moisture content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 6. From the result obtained, it was observed all samples consistently showed the highest UCS values occurring at OMC. It was found for specimen with high RAP content, that variations in moisture content within $\pm 30\%$ of OMC did not affect the UCS values significantly. This confirms findings by other research work [1] that mixing can be done in the range of 65-85% of the OMC. It is a common practice in Malaysia to lay and compact the foamed bitumen treated layer at $\pm 20\%$ of OMC. The results also showed that UCS is a poor indicator of moisture sensitivity of treated samples. Similar conclusion has been suggested by other researchers [5, 11]. It was also observed that 0% RAP samples achieved higher UCS strength within the studied range of moisture content. This may be due to the presence of higher fines content in the crusher run which contributed to the strength.

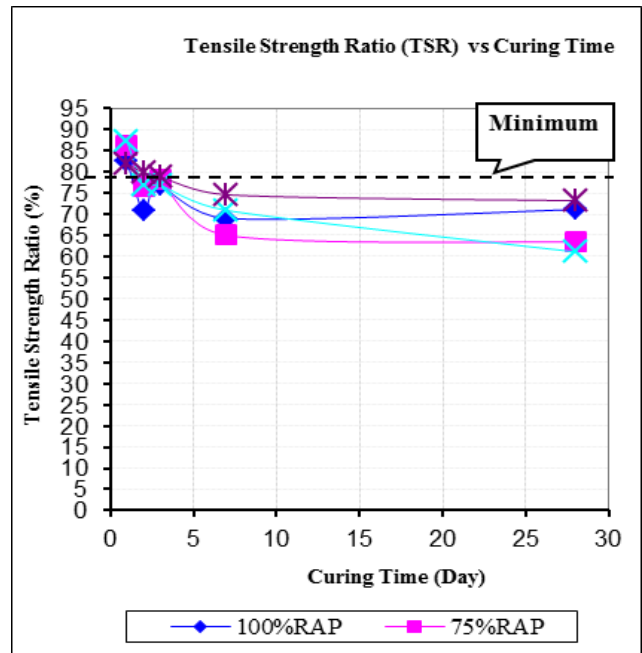


Figure 5 TSR vs curing time at various RAP contents

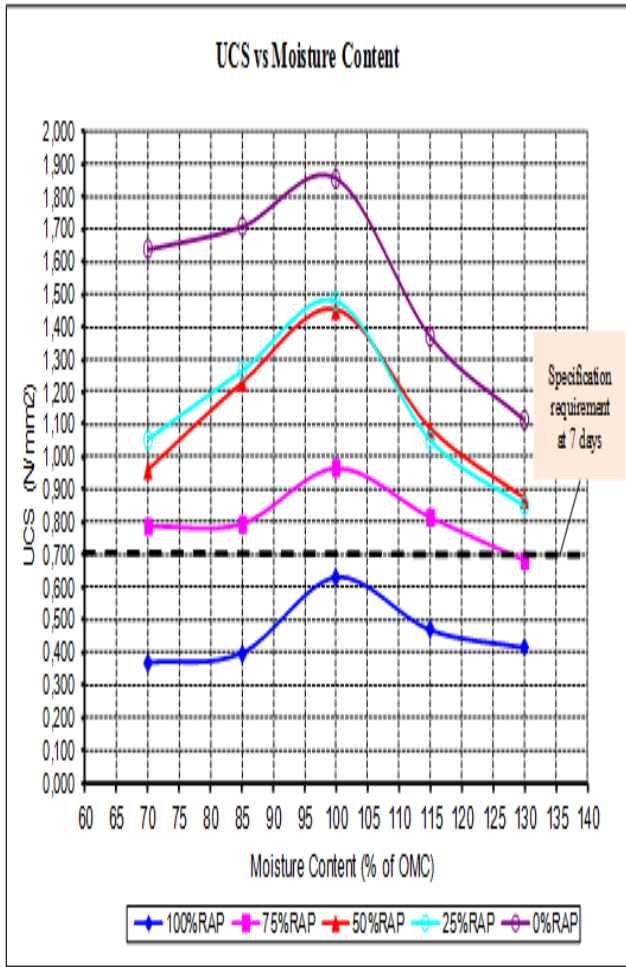


Figure 6 UCS vs moisture content at various RAP contents

3.7 Effect of Moisture Content on ITSdry

The relationship between ITSdry and moisture content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 7. The ITSdry values are also influenced by moisture content [10]. Similar to the UCS test, the maximum ITSdry value is expected to occur at the OMC since the sample achieved the highest density at this moisture level. However, this was not reflected in the results. Except for the 50% RAP samples which achieved the maximum ITS values at the OMC, most of the other samples achieved maximum ITSsoaked value at 85% of OMC. Samples with higher RAP content, variation in the moisture content did not affect ITSsoaked values significantly. However, for low RAP proportions of 25% RAP and below, the ITSsoaked values increased when the moisture content decreased.

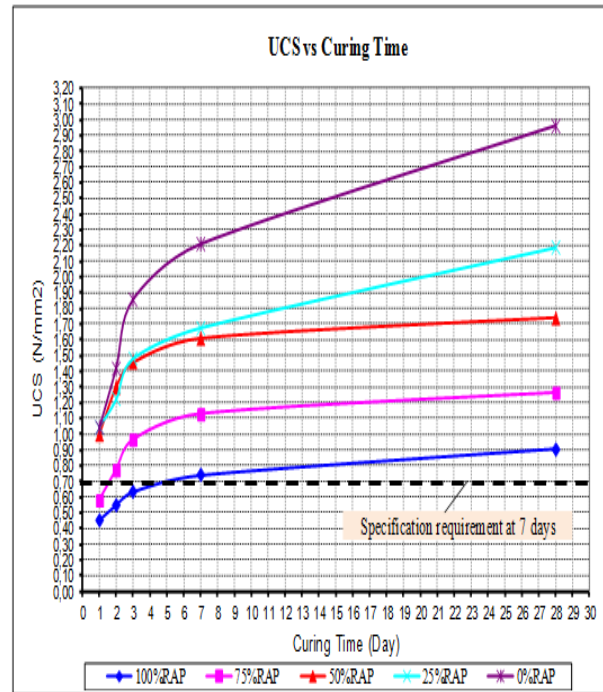


Figure 7 ITS dry vs moisture content at various RAP contents

3.8 Effect of Moisture Content on ITSsoaked

The relationship between ITSsoaked and moisture content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 8. Similar to the ITSdry test, the maximum ITSsoaked value is expected to occur at the OMC since the sample achieved the highest density at this moisture level. However, this was not reflected in the results. Except for the 50% RAP samples which achieved the maximum ITS values at the OMC, most of the other samples achieved maximum ITSsoaked value at 85% of OMC. Samples with higher RAP content, variation in the moisture content did not affect ITSsoaked values significantly. However, for low RAP proportions of 25% RAP and below, the ITSsoaked values increased when the moisture content decreased.

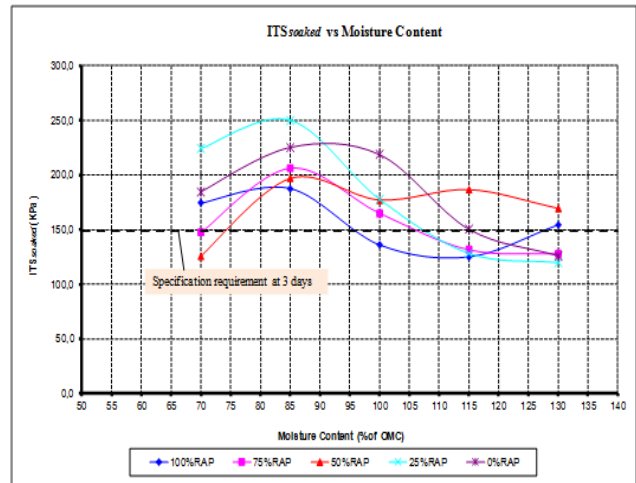


Figure 8 ITS soaked vs moisture content at various RAP contents

3.9 Effect of Moisture Content on Resilient Modulus

The relationship between Resilient Modulus and moisture content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 9. The variation 70% to 130% of optimum moisture content did not significantly affect the resilient modulus values of samples 100% and 75% RAP content. For samples with 25% and 50% RAP content, the resilient modulus peak at 85% of optimum moisture content and for 0% RAP content, the resilient modulus peak at optimum moisture content. For samples with low RAP contents, the resilient modulus at their respective OMC could be as high as 6000 MPa. Therefore it is suggested that the input values to be used in pavement design for RAP layer be based on the modulus of the corresponding RAP proportions.

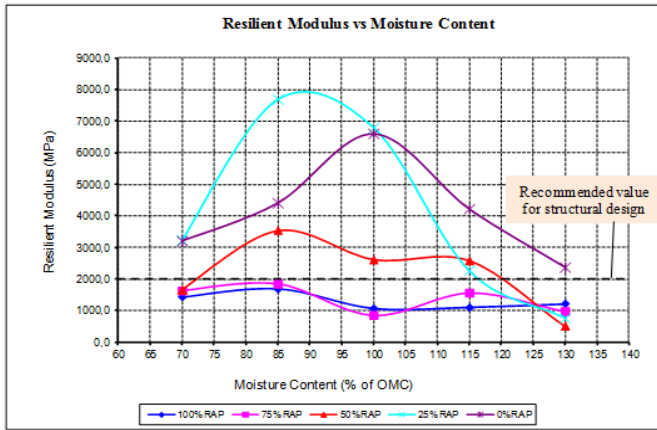


Figure 9 Resilient Modulus vs moisture content at various RAP contents

3.10 Effect of Moisture Content on Resilient Modulus

The relationship between Resilient Modulus and moisture content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 10. The variation 70% to 130% of optimum moisture content did not significantly affect the tensile strength ratio (TSR) values. It was observed, sample with 0% RAP and at 85% and 70% of OMC, TSR values are below the minimum requirement of 75%.

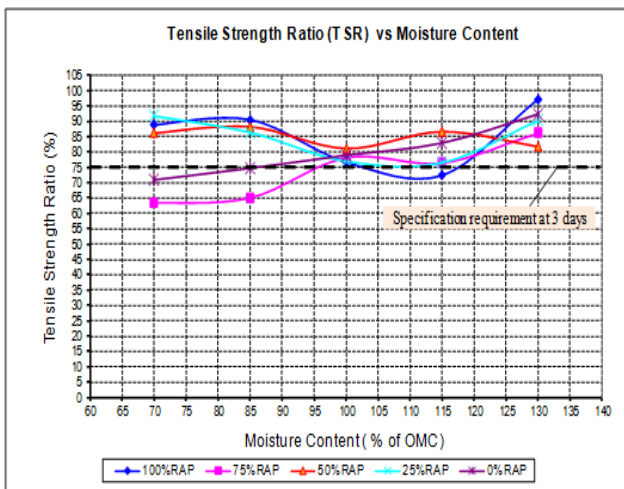


Figure 10 TSR vs moisture content at various RAP contents

3.11 Effect of Cement Content on UCS

The relationship between UCS and cement content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 11. For samples that contained 50% RAP and above, the required strength of 0.7MPa could not be achieved without the inclusion of cement as filler content. The results indicated that the active filler is vital in recycling works in Malaysia involving the use of RAP. It was also found that the UCS increases with the cement content. Except for 100% RAP, all other combinations of RAP satisfied the strength requirement when a minimum of 1% active filler was added. For the 100% RAP samples a minimum of 2% active filler was essential to attain the required strength. These observations suggest that 1% cement content was adequate to achieve the required minimum strength of 0.7 MPa except for mix containing 100% RAP. Higher cement content may be necessary to shorten the curing time in cases where it requires early opening to traffic.

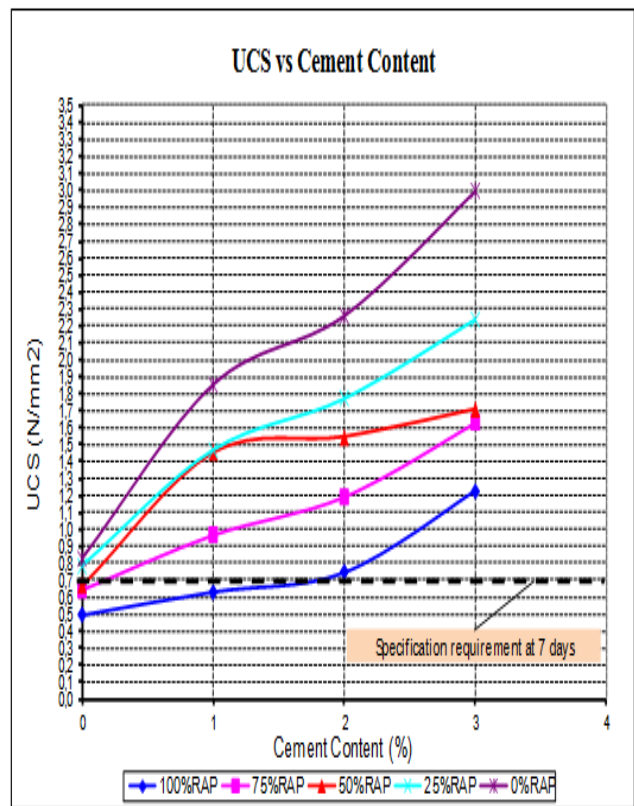


Figure 11 UCS vs cement content at various RAP contents

3.12 Effect of Cement Content on ITSdry

The relationship between ITSdry and cement content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 12. Generally, the ITSdry values increase with the amount of cement. The minimum cement content to achieve the required 200 KPa varied for different RAP proportions. From the graph, samples with 1.5% of cement content were sufficient for 100% RAP, whereas no filler was required for the 0% RAP.

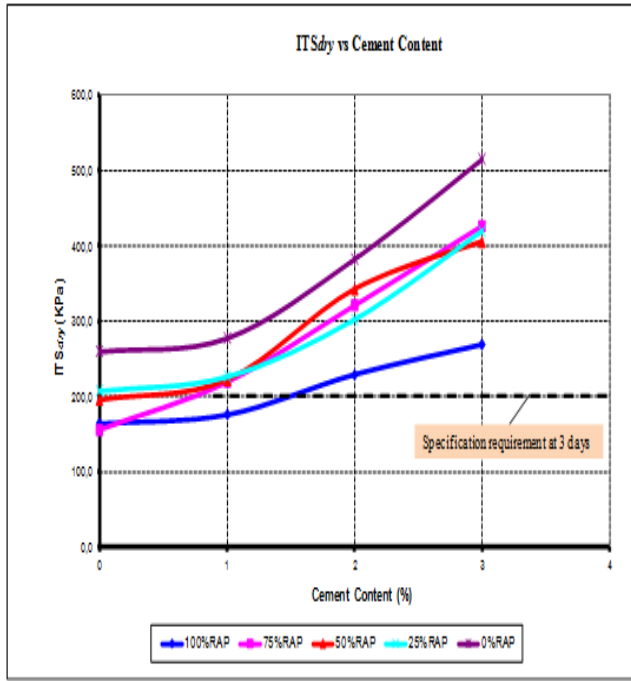


Figure 12 ITS_{dry} vs cement content at various RAP contents

3.13 Effect of Cement Content on ITSsoaked

The relationship between ITSsoaked and cement content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 13. The ITSsoaked values increase with the amount of cement. The minimum filler content to achieve the required 150 KPa varied for different RAP proportions. From the graph, at least with 1.2% cement content are required for 100% RAP and 1% cement content was required for other RAP content to achieve a minimum 150 KPa as stipulated in the national specification.

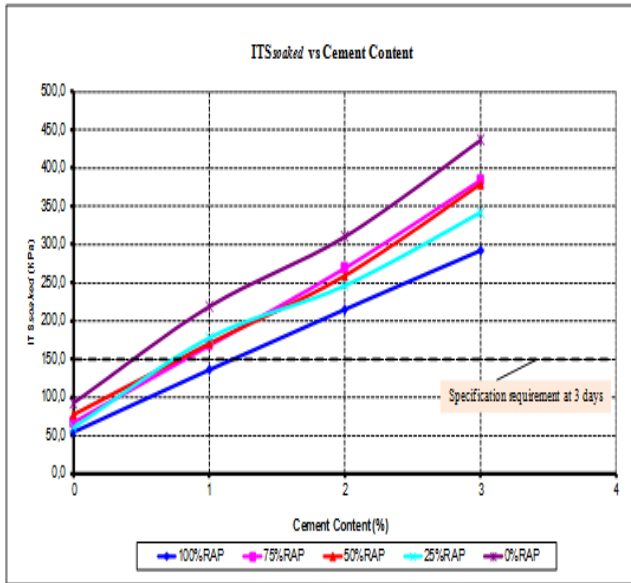


Figure 13 ITS_{soaked} vs cement content at various RAP contents

3.14 Effect of Cement Content on Resilient Modulus

The relationship between Resilient Modulus and cement content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 14. The resilient modulus increases with an increase of cement content. The results showed that at 1% cement content, samples with high RAP content of more than 50% did not meet the resilient modulus of 2000 MPa, a value normally assumed in pavement design. It was observed that samples with 75% and 100% RAP content, a minimum of 1.5% cement content was necessary to achieve the resilient modulus value of 2000 MPa cured at 3 days. This is in line with the construction practice in Malaysia of using 1.5% active filler for foamed bitumen recycled base.

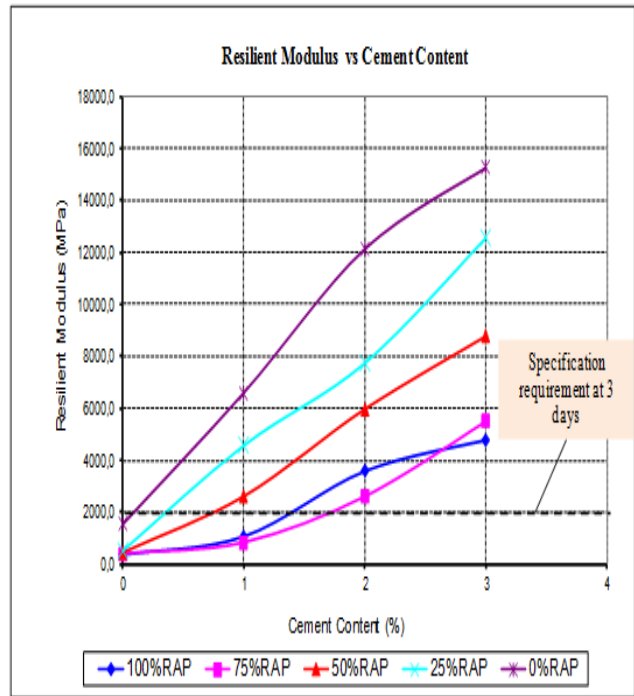


Figure 14 Resilient Modulus vs cement content at various RAP contents

3.15 Effect of Cement Content on Tensile Strength Ratio (TSR)

The relationship between Tensile Strength Ratio (TSR) and cement content at various RAP contents for the foamed bitumen stabilised mix is shown in Figure 15. Tensile Strength Ratio (TSR) results were evaluated to investigate moisture effect on property of indirect tensile strength of foamed bitumen stabilised mix. RAP and Cement content significantly affect ITS result of foamed bitumen stabilized mix, ITS will increase with an increase of cement content under both dry and soaked conditions. The tensile strength ratio increases with an increase of cement content. The results showed that at 0% cement content, all samples did not meet the wet and dry strength ratio of 75%, as required in the specification. It was observed a minimum of 1.0% cement content was necessary to achieve the wet/dry strength ratio of 75% cured at 3 days.

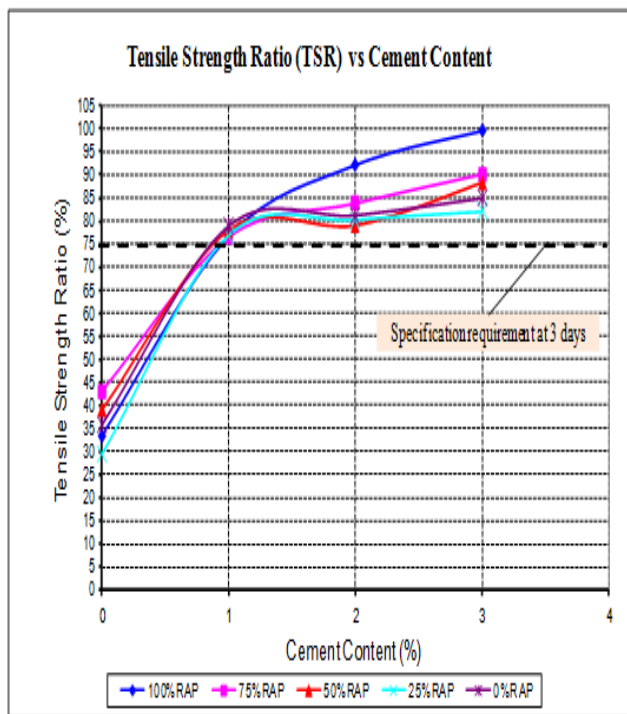


Figure 15 TSR vs cement content at various RAP contents

3.16 Discussions

From the research and analysis carried out, several findings can be made:

- Recycled Asphalt Pavement (RAP) has fewer fines than the normal crushed aggregate which is due to the conglomeration of fines in the RAP binder.
- For RAP content of 100%, 75% and 50%, percentage passing for aggregate size 0.425mm and 0.075mm are marginally outside of the grading envelope specified by the national specification.
- The Optimum Moisture Content (OMC) increases as the RAP content decreases since more fluid is required to pack the aggregate to its maximum density due to the presence of higher percentage of fines.
- Higher RAP content recorded lower optimum binder content (OBC) due to less surface area and higher percentage of existing bitumen content.
- The UCS value increased with curing time and there was a rapid increase in UCS within the first 5 days of curing for all samples.
- Higher RAP content resulted in lower UCS values.
- All samples achieved the required strength of 0.7 MPa as early as 2 days of curing except for the 100% RAP. National specification for recycling specified strength of 0.7 MPa cured for 7 days.
- Mix with 0% to 50% RAP achieved the 0.7MPa requirement as early as one day of curing time.
- The ITS_{dry} values were observed to increase with curing time. The 100% RAP did not achieve the required value of 200 KPa at 3 days as specified in the national specification.

- Mix with 100% RAP did not achieve the required ITS_{soaked} value of 150 KPa at 3 days as specified in the national specification.
- The higher RAP proportion resulted in lower resilient modulus.
- The TSR values decrease with curing time. All samples which are cured at 3 days recorded TSR value of more than 75% and the value satisfied the minimum requirement as stated in the national specification.
- All samples consistently showed the highest UCS values occurring at OMC.
- Except for the 50% RAP samples which achieved the maximum ITS values at the OMC, most of the other samples achieved maximum ITS_{dry} value at 85% of OMC.
- The variation 70% to 130% of optimum moisture content did not significantly affect the resilient modulus values of samples 100% and 75% RAP content.
- The variation 70% to 130% of optimum moisture content did not significantly affect the tensile strength ratio (TSR).
- For samples that contained 50% RAP and above, the required strength of 0.7MPa could not be achieved without the inclusion of cement as filler content.
- The 1% cement content was adequate to achieve the required minimum strength of 0.7 MPa except for mix containing 100% RAP.
- At least with 1.2% cement content are required for 100% RAP and 1% cement content was required for other RAP content to achieve a minimum 150 KPa as stipulated in the national specification.

4.0 CONCLUSION AND RECOMMENDATION

Based on the study, cement content, curing time, moisture content, and RAP content are contributing factors to the strength properties of foamed bitumen stabilized mix. The following conclusions can be made from the research:

Strength properties (ITS, UCS and Resilient Modulus) of foamed bitumen stabilized mix decreased with the increase of RAP content. This is because; RAP has fewer fines materials than the normal crushed aggregate which is due to the conglomeration of fines in the RAP binder. The percentage passing 75 micron is important and a minimum 4% of filler is required for optimal foamed bitumen mixes. For RAP content of 100%, 75% and 50%, percentage passing for aggregate size 0.425mm and 0.075mm are marginally outside of the grading envelope as specified in the national specification. Mix with higher RAP content recorded lower optimum binder content (OBC) due to less surface area and higher percentage of existing bitumen content.

The Optimum Moisture Content (OMC) increases as the RAP content decreases since more fluid is required to pack the aggregate to its maximum density due to the presence of higher percentage of fines. All samples consistently showed the highest UCS values occurring at OMC. It was found for specimen with high RAP content, that variations in moisture content within $\pm 30\%$ of OMC did not affect the UCS, ITS and Resilient Modulus values significantly. Except for the 50% RAP samples which achieved the maximum ITS values at the OMC, most of the other samples achieved maximum ITS value at 85% of OMC.

The strength properties (UCS, ITS and Resilient Modulus) values increased with curing time. Generally there was a rapid increase in strength within the first 7 days of curing for all samples, after which the increase was gradual.

The UCS, ITS, Resilient Modulus and TSR values increase with the increase of cement content. Cement as active filler is vital in cold recycling works in Malaysia involving the use of RAP. The results showed at 0% cement content, all samples did not meet the TSR of 75%, as required in the specification. Samples that contained 50% RAP and more, the required strength of 0.7MPa could not be achieved without the inclusion of cement as filler content. Samples with 75% and 100% RAP content, a minimum of 1.5% cement content was necessary to achieve the resilient modulus value of 2000 MPa cured at 3 days. This is in line with the construction practice in Malaysia of using 1.5% active filler for foamed bitumen recycled base.

To ensure a more comprehensive study on foamed bitumen stabilized mix, it is recommended that future research should be carried out as follow:

On site performance of foamed bitumen stabilized mix. The study shall include the variety of external factors that have an influence on performance, such as climate, loading speed and magnitude.

Study on the variety of mix properties and intrinsic material properties that can influence performance, such as gradation and hardness of aggregate, type of bitumen (60/70 and modified).

To develop the mix design procedure and provide a balanced material design that safeguards against shear, permanent deformation and fatigue failure.

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