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Full Length Research Paper

A preliminary study on foamed bitumen stabilisation for Western Australian pavements

Yue Huan*, Komsun Siripun, Peerapong Jitsangiam and Hamid Nikraz

Department of Civil Engineering, Curtin University, P. O. Box U1987, PERTH WA 6845, Australia.

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Currently, the popularity of conventional cementitious stabilisation had been challenged by an innovative soil improvement technique, known as foamed bitumen stabilisation. Many Australian highway and road agencies have dedicated significant investigation and funds to investigate this technique in order to achieve a more flexible and fatigue resistant stabilised material suitable for a wide range of pavement conditions. This study aimed to report the preliminary study of the foamed bitumen properties and the mix procedures conducted at Curtin University which simulated the construction of the trial foamed bitumen stabilised project in Western Australia. Our findings show that 2.5% of cold water spraying into 180°C virgin Class 170 bitumen can produce foamed bitumen with a 15 to 20 times expansion rate and 20 s half-time suitable for foaming aggregates. Both resilient modulus and permanent deformation tests failed to predict an optimum foamed bitumen content when the aggregate was mixed with 1% hydrated lime, compacted at 100% optimum moisture content and plastic sealed curing for 7 days at room temperature. However, the ratio of crushed granite roadbase to limestone was found to be significant and a mixture consisting of 75% crushed rock base and 25% crushed limestone was determined as the optimum aggregate proportion, as it showed the best performance in unconfined compressive strength tests and obtained relatively higher values in indirect tensile strength tests. Based on our preliminary results, due to adding more foamed bitumen to *in-situ* recycled aggregate seems to reduce the performance of materials, a more comprehensive laboratory investigation of the foamed bitumen stabilisation process in Western Australia would be essential.

Key words: Foamed bitumen, crushed rock base, crushed limestone, indirect tensile strength, unconfined compressive strength, resilient modulus, permanent deformation.

INTRODUCTION

The foamed bitumen stabilisation, also called foamed asphalt stabilisation, is recently gaining acceptance of application in full depth reclamation (FDR) where deteriorated pavement materials can be *in situ* recycled with either foamed bitumen or cement to produce a new stabilised base course for road rehabilitation. Prior to the application of foamed bitumen, cement treatment was the major stabilisation method in road rehabilitation in Western Australia (WA) (Jitsangiam and Nikraz, 2009). However, due to the cement stabilised material tendency to deteriorate from shrinkage cracking in mid-term service and generate weak areas which is unlikely to occur when using foamed bitumen stabilisation, the popularity of the conventional cementitious method is being challenged (Ramanujam et al., 2009; Saleh, 2007). Although the foamed bitumen, introduced into Australia in the late 1960s, was not a new concept, it was not well recognising until the late 1990s that this stabilisation technique became widespread with the introduction of better reclaimers, the use of more experienced contractors as well as the expiry of the patent rights to the process which allowed competition in the market place (AustStab, 2002). In WA, four pavement sections located in the City of Canning were successfully rehabilitated with this method in 1999. Many other pavement sections around the City of Canning and in a few other local government areas were rehabilitated using this method afterwards (Leek, 2009). Despite the great successes that had been achieved in construction,

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*Corresponding author. E-mail: yue.huan@student.curtin.edu.au. Tel: +61-413470746.

Table 1. The Relationship between foamed bitumen content and fine content of mixture (Muthen, 1998).

Percent passing 4.75 mm sieve	Percent passing 0.075 mm sieve	Percent foamed bitumen
<50 (gravels)	3 - 5	3
	5 - 7.5	3.5
	7.5 - 10	4
	>10	4.5
>50 (sands)	3 - 5	3.5
	5 - 7.5	4
	7.5 - 10	4.5
	>10	5

the long term performance of foamed bitumen stabilised pavements is still questionable. A comprehensive laboratory mix design procedure in terms of optimum foamed bitumen content, treated materials, active filler content and type, moisture sensitivity and curing conditions needs to be investigated to gain more fundamental knowledge in general and WA particular.

In a common Western Australian pavement structure, crushed rock base (CRB) and crushed limestone (CLS) are normally used as the base and sub-base course materials, which are naturally becoming the target reclaimed aggregate materials in the FDR process in WA. As a preliminary part of an ongoing project conducted by Curtin University, not only does this study aim to familiarise pavement engineers with foamed bitumen properties and establish a mix procedure for Western Australian laboratory, but to determine the optimum foamed bitumen content and the reasonable proportion of CRB and CLS based on laboratory testing methods.

The foamed bitumen mix design process had been conducted in many *in-situ* and laboratory projects over the past few years. The common procedure assisting the completion of this research framework will now be briefly reviewed. Initially, the gradation of the aggregate to be treated was determined, followed by the relationships of the optimum moisture content (OMC) and the maximum dry density (MDD). Secondly, testing for the optimum foaming properties of the bitumen was undertaken where the optimum foaming temperature, water content and bitumen types were determined. Finally, after laboratory mixes of the constituent materials were prepared, compacted and cured for a certain time, laboratory mechanical testing methods were adopted to determine the optimum foamed bitumen content (Mallick and Hendrix, 2004; Kim and Lee, 2006; Fu et al., 2010; He and Wong, 2007; Long and Theyse, 2002; Muthen, 1998).

Many researchers have demonstrated in previous studies that the strength of foamed bitumen treated material can be significantly affected by several factors, such as foamed bitumen contents, moisture contents, active filler types and contents, aggregate properties and various curing methods, etc (Jenkins et al., 2007). Specifically, the optimum foamed bitumen content is the core property to be determined. In 1993, a technical note in Geopave indicated that 4% bitumen was the usual optimum bitumen content for maximising modulus (Geopave, 1993). Moreover, Muthen (1998) suggested that there might be a relationship between the foamed bitumen content and the fines content of a mixture, as can be seen in Table 1. Nataatmadja (2001) also presented that the optimum foamed bitumen content should range from 3.0 to 4.0%. Apart from these methods, most mix design processes started from 2 or 3% of the foamed bitumen contents with 1% increment to compare mechanical testing results, thereby determining the optimum bitumen content. Furthermore, in terms of aggregate gradation, the fines content, which is defined as the percentage of the granular material by mass passing the 0.075 mm (#200) sieve, had been realized as an essential factor that can affect the properties of the foamed bitumen stabilised material (Fu et al., 2010). Normally, more than 5% and less than 25% of fines content is preferably acceptable in the foaming process (Ruckel et al., 1983; George and Nigel, 2004). With regard to active fillers, both cement and lime are the two major supplementaries used in foamed bitumen stabilisation in many countries. However, lime is widely incorporated with foamed bitumen in Australia because Australian rehabilitation work is mostly base course work where lime shows good performance (George and Nigel, 2004).

MATERIALS AND METHODS

Aggregate mixture

Crushed rock base and crushed limestone that comply with MAIN ROADS Western Australia (MRWA) Specification 501 pavements were used in this study (MAIN ROADS Western Australia, 2010). After randomly collecting the materials from a local Gosnells quarry, they were directly transported to the laboratory of the Department of Civil Engineering, Curtin University. In accordance with MRWA Test Method WA 115.1, the particle size distributions (PSD) of CRB and CLS were obtained and listed as in Table 2, along with the specifications. Figure 1 shows the PSD of CRB and a comparison

Table 2. PSD of CRB and CLS compared with specification 501 (Main Roads Western Australia, 2010).

Sieve analysis (mm)	Passing by mass (%)			
	CRB	Specification 501-base course	CLS	Specification 501-bitumen stabilised limestone
19	100.0	95 – 100	100.0	90 - 100
13.2	85.8	70 – 90	98.4	-
9.5	71.4	60 – 80	96.4	-
4.75	55.5	40 – 60	89.2	60 - 90
2.36	45.2	30 – 45	83.7	-
1.18	32.3	20 – 35	74.6	35 - 75
0.6	22.7	13 – 27	65.0	-
0.425	19.4	11 – 23	56.7	-
0.3	16.5	8 – 20	45.1	-
0.15	12.1	5 – 14	21.4	-
0.075	9.2	5 – 11	11.1	-

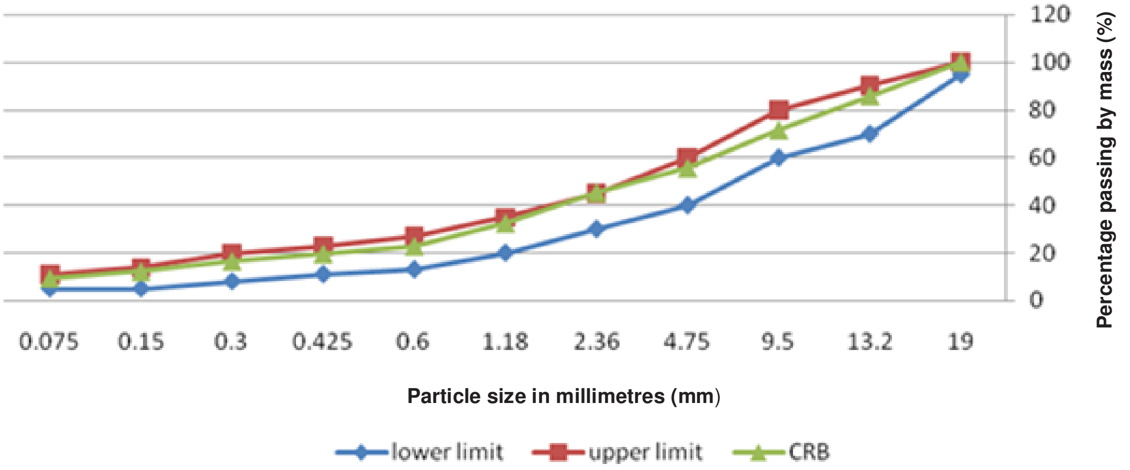

Figure 1. Particle size distributions of CRB compared with MRWA specification 501.

with MRWA base course specifications.

Bitumen selection

The virgin bitumen used was Class 170 from BP Company, the typical characteristics of which are shown in Table 3.

Active filler

Hydrated lime, stored under sealed conditions, was chosen as the active filler in this study. Table 4 lists some of its general properties.

Experimental methods

This study was a preliminary part of a larger ongoing research project conducted by the Department of Civil Engineering, Curtin University. The “parent” project had been designed to observe and establish relationships between strength and various factors, including moisture sensitivity, curing conditions, active filler contents, proportions of CRB and CLS mixes and foamed bitumen contents, as well as *in-situ* construction guidelines for the FDR process of the foamed bitumen stabilisation. However, a specific objective of this study was to determine an optimum foamed bitumen content and a reasonable mixing proportion of aggregates, whereas other factors are constrained and constant. As shown in Figure 2, a comprehensive flowchart of the mix design process was plotted to assist in understanding the project.

With respect to the constrained factors including moisture sensitivity, active filler contents and curing methods, in this study, specific conditions were applied to simulate the worst situations occurring in field sites. Firstly, although Lee (1981) and Bissada (1987) believed that 60 to 85% of the modified AASHTO OMC value was the optimum mixing moisture content for compaction and testing; 100% of OMC was used to be the reference for further compaction and testing. Moreover, 1% hydrated lime was used as the active filler in this study, because it is well-known that lime can effectively improve early stage strength of foamed bitumen and help bitumen adhere to fine particles (George and Nigel, 2004). Furthermore, a curing method was modified for this work. According

Table 3. Typical characteristics of BP class 170 bitumen (BP Bitumen, 2008).

Viscosity at 60℃ (Pa.s)	Viscosity at 135℃ (Pa.s)	Viscosity at 60℃ after RTFO (Pa.s)	Penetration at 25℃ (dmm)	Flashpoint (℃)	Viscosity of residue at 60℃ of original (Pa.s)	Density at 15℃(kg/m^3)
170	0.40	300	70	360	180	1.04

Table 4. General properties of hydrated lime in WA (Swan Cement, 2005).

Properties	Description	Range
Appearance	White amorphous powder	
Specific gravity (kg/m^3)	2300	
pH	12	
Chemical compositions (%):		
Calcium hydroxide ($Ca[OH]^2$)		80 - 90
Magnesium hydroxide ($Mg[OH]^2$)		0 – 6
Silicon dioxide (SiO^2)		2 - 6
Aluminium oxide (Al^2O^3)		0.2 – 0.6
Iron Oxide (Fe^2O^3)		0.1 – 0.3

to previous experience, 72 h in an oven at 40℃ is a commonly recognized curing time for a foamed bitumen mix design (Halles and Thenoux, 2009). However, as this period is not representative to WA field conditions, a modified method, sealed at an ambient temperature for 7 days, was suggested in this study.

Laboratory experiment programme

Overall, four major phases were undertaken.

Phase 1. Sample preparation and pre-mix

In this study, four representative of different proportions of aggregate mixtures were adopted on the basis of different reclaimed depths in the real trial project, that is, 100%CRB, 75%CRB and 25%CLS, 50%CRB and 50%CLS and 25%CRB and 75%CLS. After being dried in an oven at 105℃ to achieve a constant weight, the mixture was initially tested to establish compaction curves to determine OMC and MDD of mixes in accordance with MRWA Test Method WA 133.1. Once the values of OMC and MDD were obtained, the dried mixture was placed into a mixer (Wirtgen WLM30), with 1% hydrated lime for pre-mixing until the hydrated lime was mixed well with the aggregate as shown in Figure 3. The final step in this phase was to add certain amount water into the dried mixture to reach the moisture condition of mixing as equation suggested by the instruction book of Wirtgen WLB10S (Wirtgen, 2008). They are:

$$Wocc = Womc - Wreduc \qquad (1)$$

$$Wreduc = 0.3 * Womc - 0.6 \qquad (2)$$

$$Mwater = \frac{(Wocc - Wmosit)}{100} * (Maggregate + Mlime) \qquad (3)$$

Where: $Wocc$, the water content for optimum workability and compaction, %; $Womc$, the optimum moisture content obtained by modified proctor, %; $Wreduc$, the water reduction value, %; $Wmosit$, the own moisture content of aggregates, usually 0% in this study, %; $Mwater$, the mass of water to be added into the dry mixture, g; $Maggregate$, the mass of dry aggregate materials, g, and $Mlime$, the mass of hydrate lime to be added, g.

Phase 2. Foaming

Wirtgen WLB 10S and a Mixer WLM 30, were utilised in the foaming process, as can be seen in Figure 4. Basically, foamed bitumen is produced by spraying hot bitumen (usually 160 to 200℃) and a small amount of cold water (usually 15 to 20℃), together with compressed air, into a mixing chamber where virgin bitumen can instantaneously expand to greater than 10 times its original volume, forming a fine mist or foam (Ramanujam et al., 2009; AustStab, 2002). Prior to foaming, some essential parameters of WLB 10S, such as bitumen temperatures, moisture contents, expansion rates and half-life, that would affect foaming results were repeatedly observed and recorded. Table 5 illustrates final values used throughout the whole mixing design process in this study. During the foaming process, 3, 4 and 5% bitumen were injected into four different aggregate mixtures, respectively producing 12 samples. Figure 5 gives a mixing example of 5% foamed bitumen treated with materials consisted of 75% CRB and 25% CLS, along with 1% hydrated lime.

Phase 3. Compaction and curing

Once a mixed sample was obtained, another compaction test in accordance with MRWA Test Method WA 133.1 to determine a new OMC and MDD was undertaken again because it was believed that once the condition of the composition changed, the OMC and MDD would change as well. Subsequently, two compaction processes

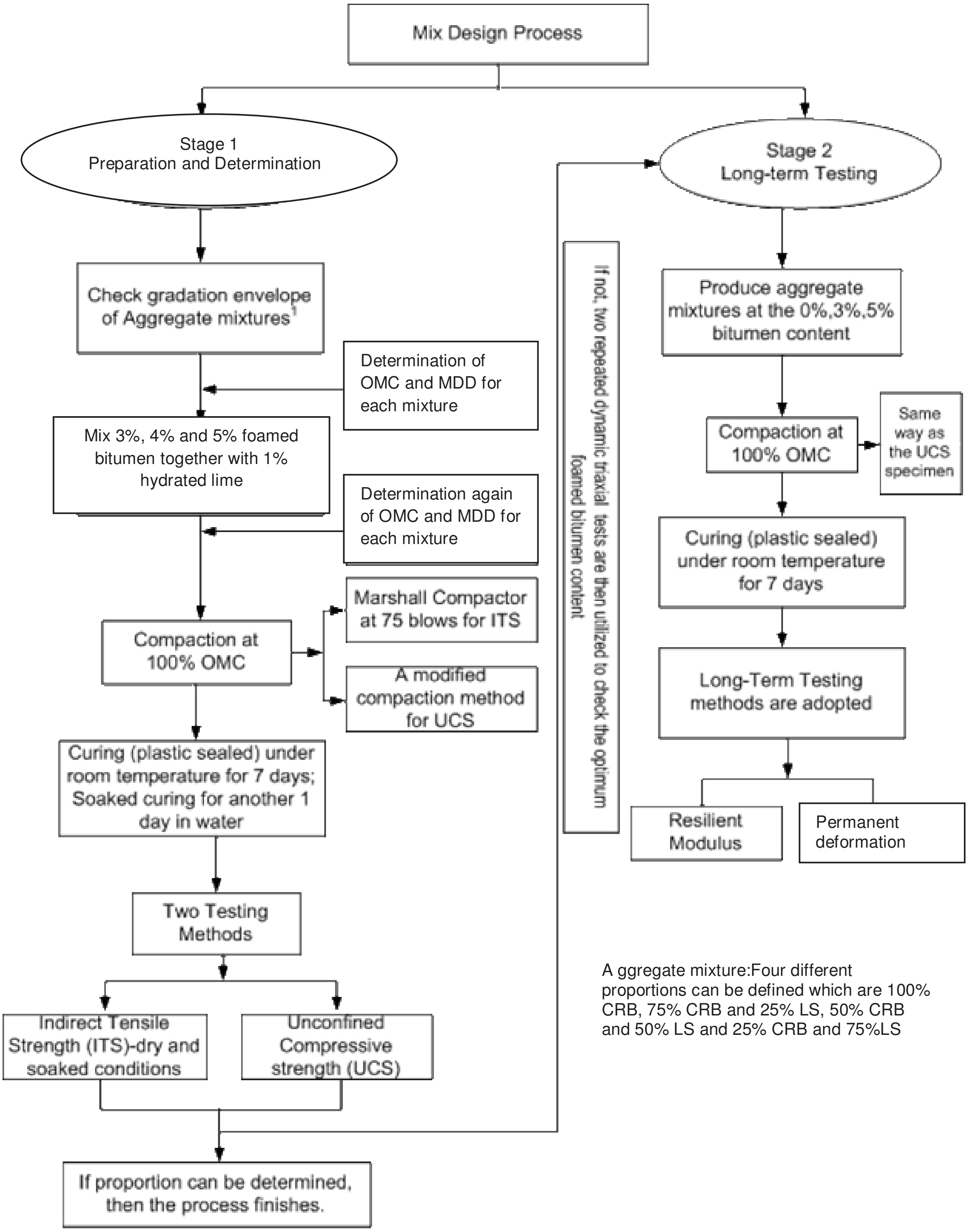

Figure 2. The mix design process flowchart.

were carried out at 100% of new OMC, as shown in Figure 6. The first compaction process where an automatic Marshall Compactor was employed produced six specimens for both unsoaked and soaked indirect tensile strength (ITS) tests. With the compaction condition of the Marshall Compactor, the material was compacted with 75 blows at one side in a mould 101 mm in diameter and 76 mm in height. A modified compaction method was then utilised to prepare the test samples for the tests of unconfined compressive

Figure 3. The dried mixture before foaming.

Figure 4. Wirtgen WLB 10S (right side), with a mixer WLM 30 (left side).

strength (UCS), resilient modulus (Mr) and permanent deformation (PD) with nine samples (three samples for each test). In this process, a mould 100 mm in diameter and 200 mm in height was used in which material was compacted 25 blows each for eight layers with a 4.9 kg rammer at a 450 mm drop height. After compaction, all specimens were sealed immediately in a plastic wrap and cured for 7 days at an ambient temperature. In addition, three samples were selected to continue soaking procedures and were immersed in a water bath at room temperature for another 24 h.

Phase 4. Testing

Four testing programmes were conducted. Firstly, due to the minimum requirements of the amount of materials and effort, the ITS test was normally performed as basic criteria to determine the optimum foamed bitumen content (Fu et al., 2010). Moreover, in order to check the compressive performance of the mixture and comply with the specifications, the UCS testing method in accordance with MRWA Test Method WA 143.1 was used. Apart from these two basic test methods, resilient modulus and permanent deformation tests in accordance with the standard method of Austroads – APRG 00/33 were followed to monitor the long-term behaviours of foamed bitumen stabilised materials (Jitsangiam and Nikraz, 2009). Each test utilised triplicate cylindrical shaped specimens to control the quality. The highest ITS and UCS values were selected as the criteria to determine the optimum foamed bitumen content and aggregate mixtures. Figure 7 illustrates the three apparatuses used in the laboratory at Curtin University.

Table 5. Foaming parameters used in the mixing design process.

Parameter	Values
Bitumen temperature (℃)	180
Foaming agent (%)	0
Added water content (%)	2.5
Bitumen flow quantity (g/s)	100
Water flow quantity (g/s)	9.0
Air pressure (bars)	4
Water pressure (bars)	5
Expansion rate	12 - 15
Half-time (s)	20

Figure 5. A mixing example of 5% foamed bitumen with 75% CRB and 25% CLS.

RESULTS

Gradation

Sieve analyses of the four different mixtures were performed to check the content of fine grains. As the particle size distribution listed in Table 6, all the fines contents (passing 0.075 mm sieve) were acceptable for the foamed bitumen stabilisation.

Figure 6. Automatic marshall compactor and modified compaction tools.

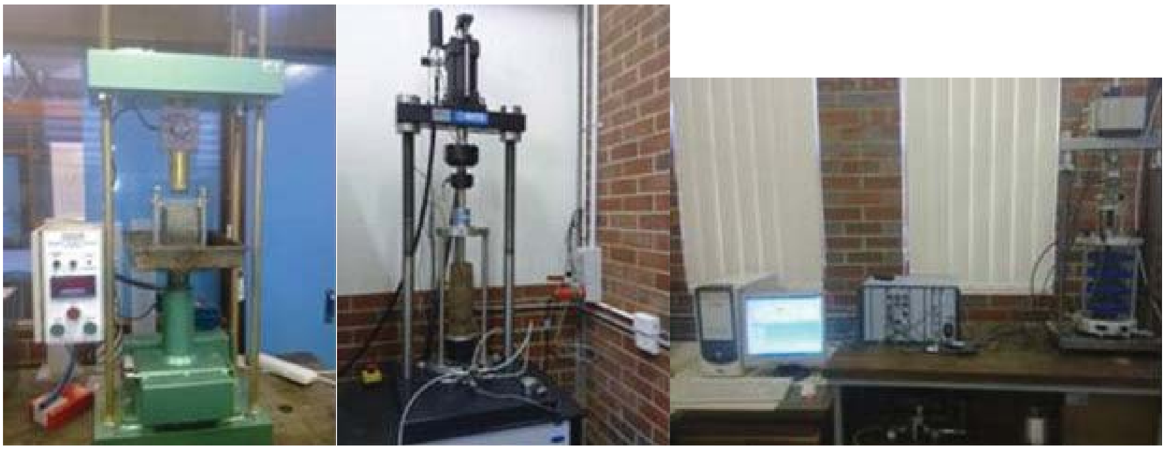

Figure 7. Test Apparatuses for ITS, UCS and resilient Modulus and permanent deformation (from left to right).

Table 6. Particle size distribution of aggregate mixtures.

Sieve analysis (mm)	100% CRB	75% CRB and 25% CLS	50% CRB and 50% CLS	25% CRB and 75% CLS
26.5	100.0	100.0	100.0	100.0
19	100.0	99.3	99.7	100.0
13.2	85.8	91.7	94.2	94.1
9.5	71.4	81.1	85.3	88.9
4.75	55.5	65.4	73.7	80.5
2.36	45.2	54.5	65.3	73.8
1.18	32.3	43.3	54.8	65.1
0.6	22.7	34.1	45.0	54.8
0.425	19.4	29.7	39.4	48.2
0.3	16.5	24.5	32.4	39.2
0.15	12.1	14.3	17.0	19.5
0.075	9.2	9.0	9.7	10.5

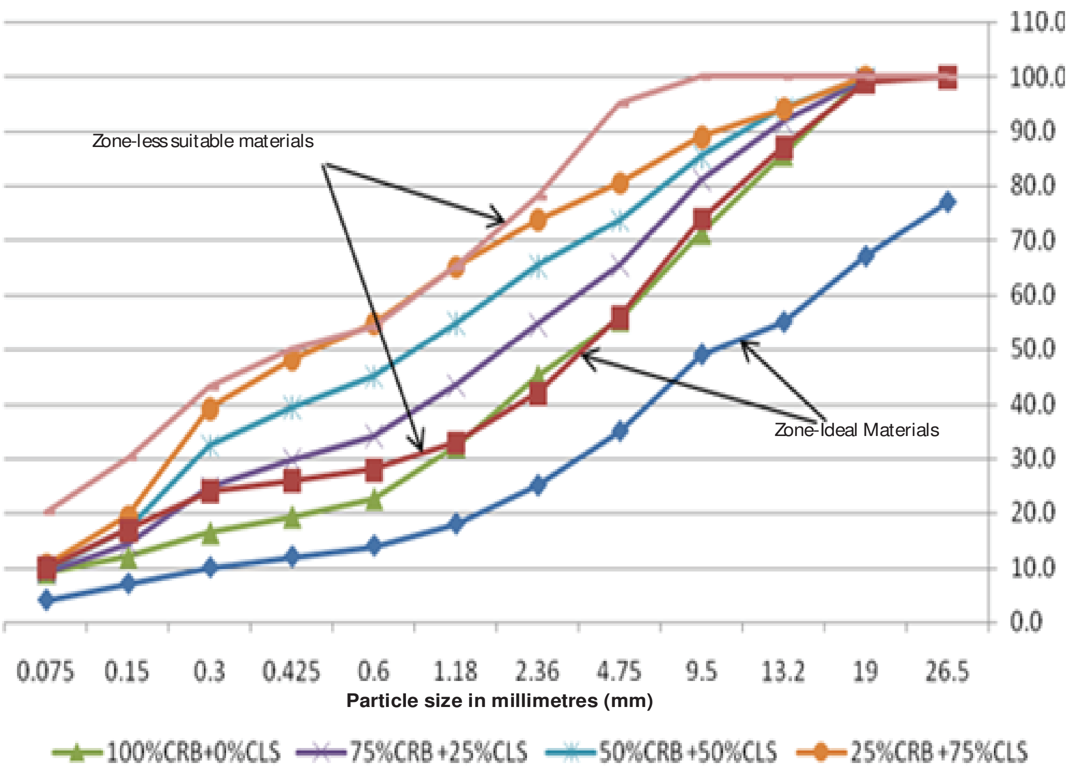

Figure 8. Particle size distribution of different mixtures compared with the grading zones for foamed bitumen introduced by Asphalt Academy.

Table 7. Maximum dry density with each different proportion aggregate and foamed bitumen content.

Maximum dry density (g/cm^3)		**Foamed bitumen content (%)**			
		0	**3**	**4**	**5**
Aggregate mixtures	100%CRB+0%CLS	2.310	2.221	2.168	2.163
	75%CRB+25%CLS	2.248	2.178	2.062	2.034
	50%CRB+50%CLS	2.081	2.092	2.021	1.984
	25%CRB+75%CLS	1.989	1.902	1.922	1.899

Figure 8 illustrates the PSD of different mixtures complying with the grading zones for foamed bitumen introduced by Asphalt Academy (2009). It is manifest that, apart from the grading of 100% CRB located in the ideal grading zone, the other three grading shift away to the less suitable grading zone even if the fine contents satisfy the minimum requirement of 5%. It can also be seen in the figure that with an increasing content of limestone, the mixture becomes finer, indicating that dry density decreases when more limestone was added.

Maximum dry density

As demonstrated in Table 7, it is apparent that with increased content of foamed bitumen, maximum dry density gradually decreases, which is confirmed by some *in-situ* projects. Adding more fine crushed limestone also decreases the dry density following which in gradation analysis.

ITS results

Indirect tensile strength (ITS) tests were performed on three different foamed bitumen contents and four different aggregate mixtures with 1% hydrated lime curing for 7 days at room temperature. The results from the tests are given in Table 8 and Figure 9.

Overall, the unsoaked ITS values were higher than the

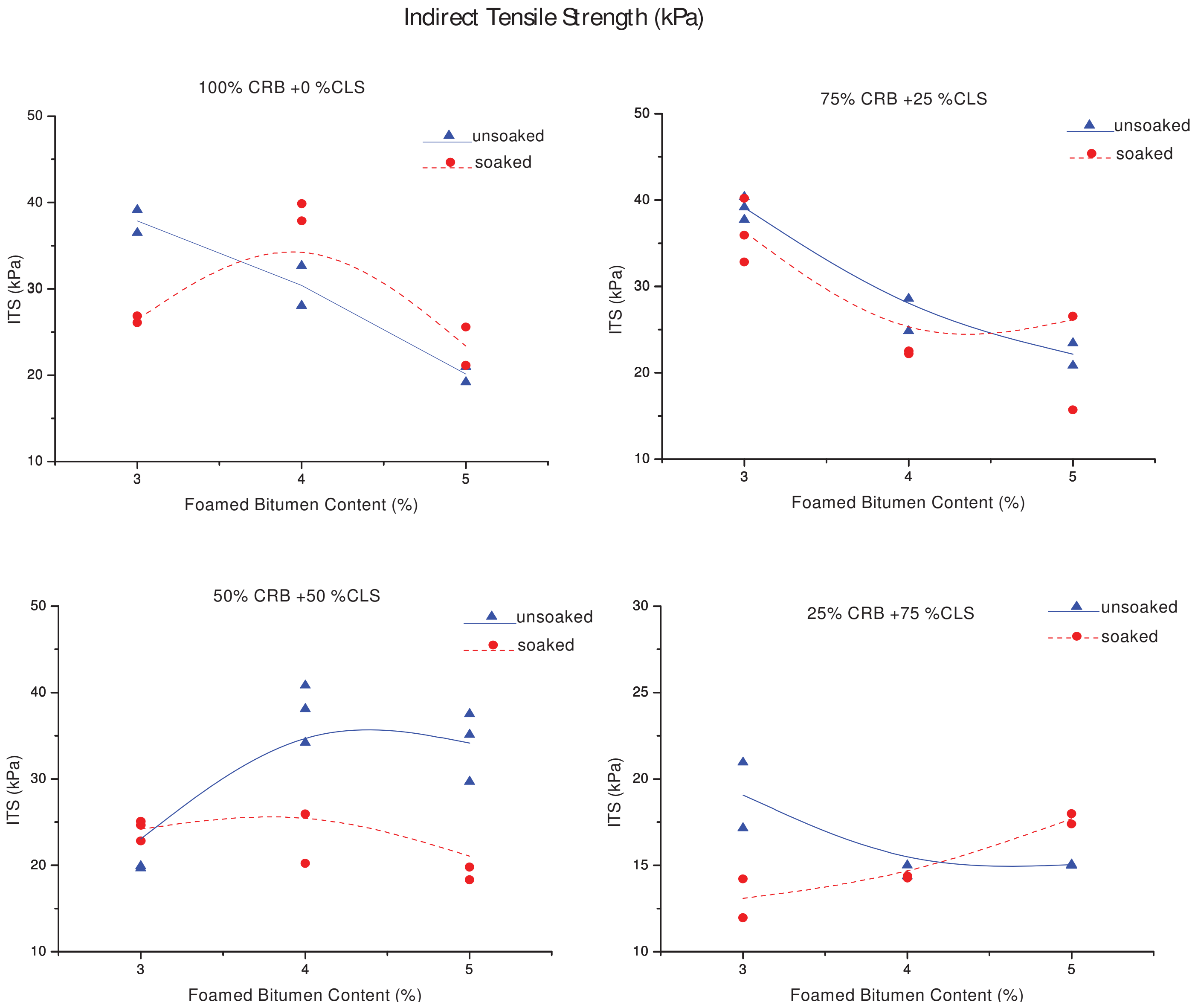

Figure 9. Plots of ITS *versus* Foamed bitumen content for four different mixtures.

soaked ITS. The highest unsoaked and soaked ITS values were both obtained at 3% foamed bitumen content with 100%CRB. In most cases, 3% foamed bitumen exhibited the highest ITS values for unsoaked samples apart from the sample of 50% CRB and 50% CLS in which 4% foamed bitumen showed the highest value. However in the case of soaked samples, there was not such a clear trend. Moreover, it was found that only in a soaked sample of 25% CRB and 75% CLS, was the ITS value slightly increased with increased foamed bitumen content, compared with most cases where ITS values were reduced with increased foamed bitumen content.

In order to control the samples' qualities, slight deviations of target dry densities were adopted ranging from 92.5 to 100% of the maximum dry density, acceptable for testing, otherwise, samples would need to be checked and probably be re-produced.

UCS results

The UCS samples consisted of four different proportions of aggregate mixtures treated with 3, 4, 5% foamed bitumen, with 1% hydrated lime, cured at room temperature for 7 days. The results of the unconfined compressive strength (UCS) tests are shown in Table 9 and Figure 10.

Generally, the highest UCS values were obtained at

Table 8. Indirect tensile strength test results.

Mixture	Foamed Bitumen content (%)	OMC (%)	MDD (g/cm^3)	Unsoaked sample					Soaked Sample		
				Dry Density (g/cm^3)	Deviation[1] (%)	ITS[3] (kPa)	Mean (kPa)	CV[2] (%)	ITS[3] (kPa)	Mean (kPa)	CV[2] (%)
100% CRB + 0% CLS	3	6.79	2.221	2.140	96.32	36.51		4	26.07		1
				2.135	96.11	39.16		3	37.91		
				2.164	97.39	45.90	37.84		26.83	26.45	1
	4	6.82	2.168	2.094	96.61	28.06		8	39.86		3
				2.036	93.89	32.66		8	37.87		3
				2.050	94.57	43.20	30.36		27.32	38.87	
	5	6.81	2.163	2.080	96.16	19.21		4	25.57		9
				2.112	97.66	32.07			21.13		9
				2.084	96.37	20.99	20.1	4	16.83	23.35	
75% CRB + 25% CLS	3	6.41	2.178	2.122	97.42	40.38		3	40.20		10
				2.090	95.94	39.18		0	32.81		10
				2.101	96.46	37.75	39.1	3	35.93	36.32	1
	4	7.17	2.062	2.021	98.02	24.87		7	22.19		1
				2.025	98.20	28.60		7	17.06		
				2.058	99.82	37.32	26.74		22.50	22.35	1
	5	5.92	2.034	1.978	97.26	20.85		6	26.53		2
				1.992	97.95	23.45		6	25.68		2
				1.975	97.09	31.96	22.15		--	26.11	--
50% CRB + 50% CLS	3	7.8	1.998	1.969	94.10	29.47			25.07		4
				1.968	94.07	19.93		1	24.64		2
				1.974	94.37	19.68	19.81	1	22.81	24.18	6
	4	8.54	2.021	1.900	94.03	40.85		8	34.33		
				1.930	95.50	38.13		1	20.22		10
				1.938	95.90	34.22	37.73	9	25.93	23.08	10
	5	7.91	1.984	1.943	97.96	29.72		7	25.09		
				1.968	99.18	37.55		7	18.29		4
				1.962	98.90	35.14	35.14	0	19.77	19.03	4
25% CRB + 75% CLS	3	9.1	1.902	1.815	95.43	20.96		9	--		--
				1.816	95.47	21.07			14.21		9
				1.781	93.62	17.16	19.06	9	11.95	13.08	9
	4	9.41	1.922	1.824	94.91	15.01		2	14.37		0
				1.857	96.61	16.22			18.08		
				1.839	95.67	14.38	14.7	2	14.27	14.32	0
	5	8.21	1.899	1.798	94.68	23.36			17.98		2
				1.816	95.65	15.06		0	12.86		
				1.812	95.42	15.00	15.03	0	17.39	17.69	2

1: Deviation equals dry density divided by maximum dry density, which is used as a quality control. 2: CV is also used to control sample quality and should be less than 10%. 3: Those specimens with large variation to mean value are marked and ignored in further analysis.

Table 9. Unconfined compressive strength test results.

Aggregate Mixture	Foamed Bitumen content (%)	OMC (%)	MDD (g/cm^3)	Sample				
				Dry Density (g/cm^3)	Deviation[1] (%)	UCS (kPa)	Mean (kPa)	CV[2] (%)
100%CRB+ 0% CLS	3	6.79	2.221	2.186	98.42	204	201.5	1
				2.172	97.81	199		1
	4	6.82	2.168	2.065	95.27	122	139	10
				2.124	97.97	156		10
	5	6.81	2.163	2.106	97.38	135	140.5	4
				2.122	98.12	146		4
75% CRB + 25% CLS	3	6.41	2.178	2.086	95.78	267	254.5	5
				2.082	95.61	242		5
	4	7.17	2.062	2.060	99.90	136	139.5	3
				2.061	99.95	143		3
	5	5.92	2.034	2.019	99.28	169	158	7
				2.033	99.95	147		7
50% CRB + 50% CLS	3	7.8	1.998	2.028	96.93	124	121.5	2
				2.051	98.03	119		2
	4	8.54	2.021	1.982	98.06	--	113	--
				1.979	97.97	113		0
	5	7.91	1.984	1.983	99.94	108	105.5	2
				1.981	99.85	103		2
25% CRB + 75% CLS	3	9.1	1.902	--	--	147	140	5
				--	--	133		5
	4	9.41	1.922	1.891	98.38	99	98.5	1
				1.903	99.02	98		1
	5	8.21	1.899	1.881	99.03	116	119.5	3
				1.898	99.95	123		3

1: Deviation equals dry density divided by maximum dry density, which is used as a quality control.
2: CV is also used to control sample quality and should be less than 10%.

3% foamed bitumen, the sample of 75%CRB and 25%CLS with 3% foamed bitumen showed the highest UCS value at 254.5 kPa. However, it is questionable that why all the 4% foamed bitumen treated materials demonstrated unreasonable lower UCS values. One possible explanation for this phenomenon is that, during mixing, the larger size particles would be better coated by the additional foamed bitumen, rather than combining with fines following as the theory. The foamed bitumen coating on large particles would interfere with the interlocking of those in resisting compressive strength. It should be noted that this phenomenon needs to be assessed in further research.

Resilient modulus

A repeated load triaxial test in terms of the resilient modulus test in accordance with the Austroads – APRG 00/33 standard, was utilised to characterise the vertical resilient strain under a combination of applied dynamic vertical and static confining stresses (Jitsangiam and Nikraz, 2009). The aggregate mixture consisted of 75% CRB, 25% CLS and 1% hydrated lime treated with 0, 3 and 5% foamed bitumen. Figure 11 illustrates a comparison towards the different foamed bitumen contents.

Figure 11 also depicts the results of the resilient modulus against with sequence numbers. It is clear that with an increasing content of foamed bitumen, the resilient modulus value decreases. The mixture without foamed bitumen exhibits the highest resilient modulus value between 235 and 570 MPa, whilst the 5% foamed bitumen (max. foamed bitumen content) shows the lowest resilient value between 165 and 360 MPa.

Permanent deformation

The permanent deformation test, also in accordance with the Austroads – APRG 00/33 standard, was performed to assess the permanent deformation behaviour of the

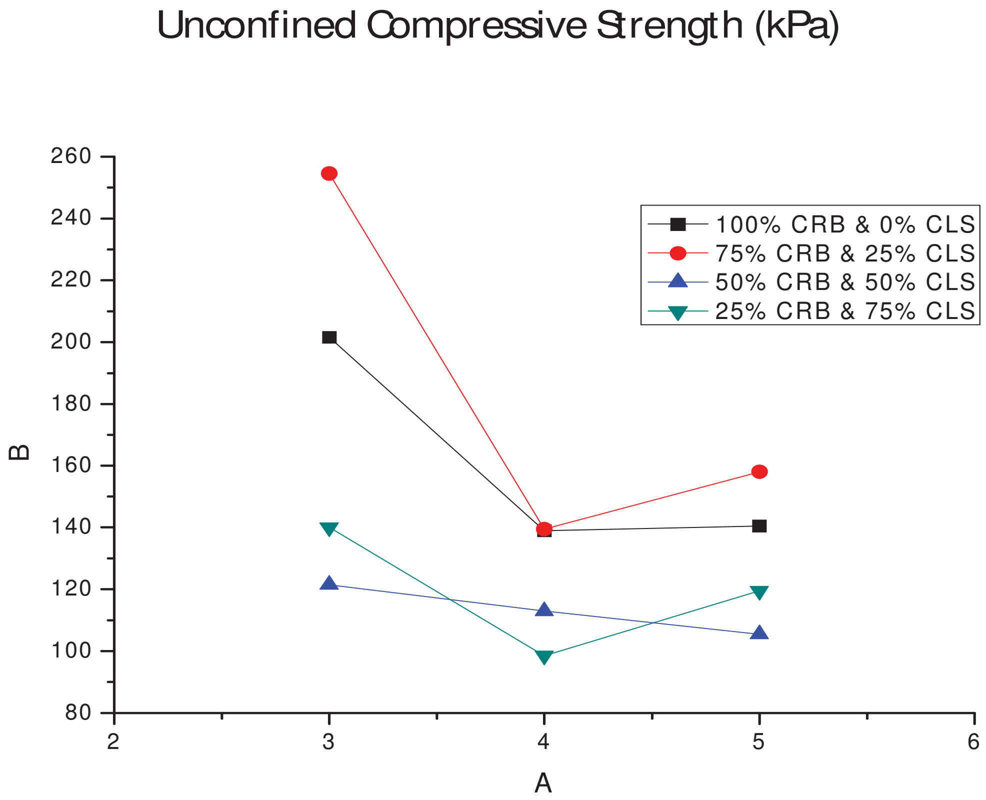

Figure 10. Plot of UCS versus foamed bitumen content for four different mixtures.

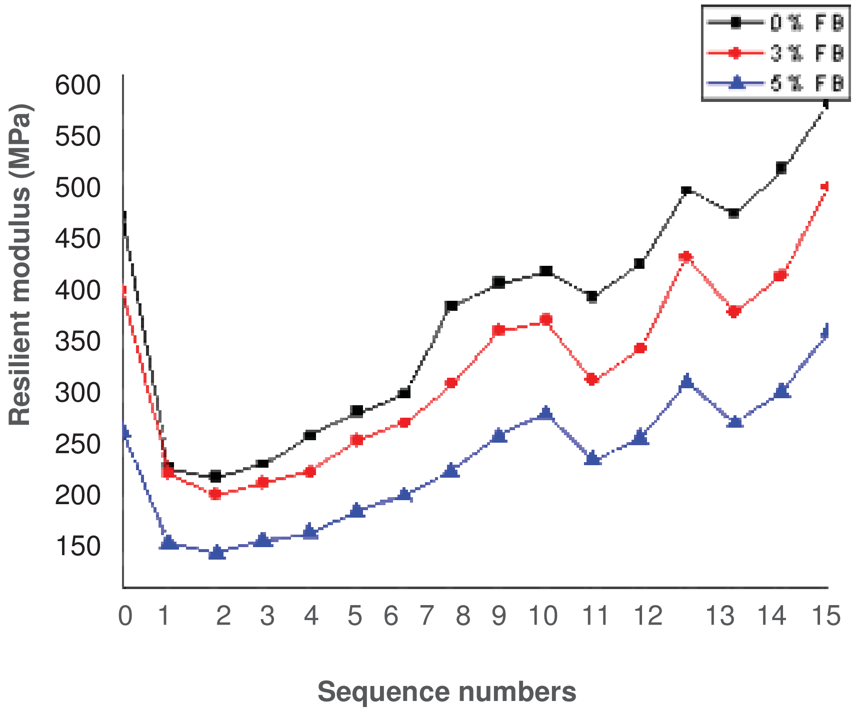

Figure 11. The resilient modulus test results.

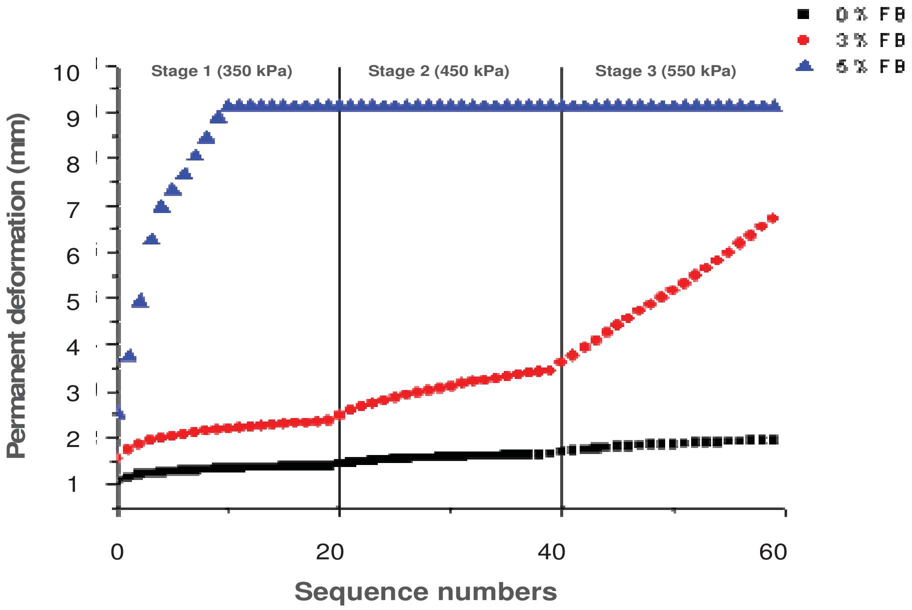

Figure 12. The permanent deformation test results.

75%CRB and 25%CLS mixtures treated with 0, 3 and 5% foamed bitumen. The test results are given in Figure 12.

As shown in Figure 12, it is manifest that 5% foamed bitumen was too weak to be acceptable for consideration because in sequence 10, the displacement exceeded the maximum value, reaching 9.123 mm and failure occurred afterwards in stage 2. Although, the failure was not exhibited in the 3% foamed bitumen mixture, a rapidly increasing displacement was obtained in stage 3 under a 550 kPa stress level in which the displacement increased from 3.605 to 6.706 mm eventually. Nonetheless, the mixture without foamed bitumen showed the best performance compared with the other two mixtures final 1.946 mm displacement was obtained at the end of the third stage, without dramatically increasing displacement in all the loading sequences.

DISCUSSION

In this preliminary study, a mix design in which four different aggregate mixtures treated with three different foamed bitumen contents compacted with 1% hydrated Lime at 100% of optimum moisture content and cured for 7 days at room temperature, was observed under laboratory conditions. The mechanical behaviours of these mixtures were then investigated by means of indirect tensile strength tests, unconfined compressive strength tests, resilient modulus tests and permanent deformation tests in order to determine both optimum foamed bitumen content and optimum aggregate proportion.

The main conclusions of this study are as follows:

1. Based upon the laboratory foaming experiment, 2.5% water content was selected as the optimum foaming water content, along with 180°C virgin Class 170 bitumen, to produce the foamed bitumen whose expansion rate was 15 to I20 times that of the original and the half-life was around 20 s under air pressure of 4 bars and water pressure of 5 bars.
2. The test specimens were prepared with four different aggregate mixtures and three different foamed bitumen contents. They were then compacted by 75 blows of a Marshall compactor, 25 blows each layer (eight layers in total) in a modified compaction method, followed by curing at room temperature for 7 days. The soaked specimens, however, were under water for another 24 h.
3. Basically, there was a gradual decrease in density when more foamed bitumen content was used or fine crushed limestone contained in the mixture. This, therefore, indicates that foamed bitumen can provide flexibility to the mixture, rather than strength.
4. According to particle size distribution, only the PSD of 100% CRB fall into the ideal grading zone, according to the specification introduced by Asphalt Academy. On the other hand, other mixtures' PSDs deviated to the less suitable zone with an increased content of crushed limestone.
5. For indirect tensile strength tests and unconfined compressive strength tests, it was apparent that 75%CRB and 25%CLS can obtain the highest values when treated with 3% foamed bitumen. Nonetheless, both resilient modulus tests and permanent deformation tests indicated that with an increased content of foamed bitumen, stiffness decreased and failure became serious. Therefore, it can be concluded that, in terms of the

resilient modulus and permanent deformation, no optimum foamed bitumen can be determined in this preliminary study, whereas the aggregate proportion of 75% CRB and 25% CLS could be selected as the optimum one for further tests, because it showed the best performance in the UCS test and obtained relatively higher values in the ITS test. Due to the inability to reproduce trends of foamed bitumen content as determined in previous research, it is essential that the laboratory characterisation of foamed bitumen materials be thoroughly investigated. However, it is not feasible to repeat the study at a reasonable cost. Lacking of standard laboratory method was suggested to explain the unusual results. Due to different mixing, compaction and curing conditions varying from previous research, it is pressing to develop a guideline to standardise laboratory experiments.

However, as this research is just the beginning of a comprehensive project, many other factors, such as moisture contents, gradations, curing methods and active filler content, were constrained. Hence, further research is necessary to find out, to what extent, these factors can affect the strength of foamed bitumen treated material.

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