Effect of Aggregate Fine Contents on Foamed Bitumen Stabilisation

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ABSTRACT

Increased popularity of foamed bitumen as a stabilising agent in recent years has resulted in a necessity for research into the material properties of foamed bitumen stabilised pavements, and the effects of varied design parameters on these properties. The objective of this project is to assess the effects of aggregate gradation in foamed bitumen mixes on material properties characteristics and mechanical performance. The focus was given into the fines particle percentage: that is, particles with a nominal diameter of 75μm or less, as it is recognised that this range of particle sizes has a significant effect on binding capabilities of foamed bitumen. The results were obtained by comparing a number of samples of ranging from 0% to 25% fines at 5% increments, and with 0%, 2% and 4% foamed bitumen contents. Comparisons were drawn by testing typical material prop erties of unconfined compressive strength, indirect tensile strength and indirect tensile resilient modulus. Test results indicated that deficient productions were yielded and nubby bitumen was easily to be observed with a lower amount of fines content. However, the higher fines content was detrimental to the mechanical strength which was mainly relied on the interlock between coarse particles.

Keywords: Foamed bitumen, Fine contents, Strength

1 INTRODUCTION

With over 140,000km of roads in Western Australia alone, at an estimated replacement value of $27 billion, the maintenance of these roads is a task which requires special attention [1]. As such, many methods of rehabilitation for road pavement layers have been developed and adopted. One of these is a process known as cold in-situ recycling (CISR), whereby the base course is milled on site without removal, and combined with a new adding stabilising agent at ambient temperature– typically bitumen, cement, or lime are chosen as additives.

Foamed bitumen, a product of CISR with more considerations on cost-effective, environmental and durable issues, is produced by injecting a small amount of cold water and compressed air into hot bitumen, typically about 180 degrees Celsius. The effect is that the water immediately turns to steam, resulting in an increase in volume of up to 15-20 times the original bitumen. This makes the bitumen much less viscous, making it easier to spray and mix hence eliminates the requirement of bitumen emulsifiers or cutbacks to achieve a reduced viscosity [2]. As the foam collapses most of the water is lost in the form of steam, the resulting bitumen has properties similar to the original bitumen and is well dispersed through the aggregate in very small droplets. The bitumen droplets are attracted to and coat the finer particles, forming a uniform matrix that effectively binds the mixture of particles together. Due to this apparent advantage, foamed bitumen has been trialled and well documented in numerous cases as a primary stabilisation method in Western Australian road construction activities [3].

Aggregate gradation is recognised as one of the most important factors when assessing the suitability of foamed bitumen as a stabilising agent for an aggregate mix. The suitability of specific gradations was highlighted by the recommendations of numerous papers, which provided representative grading curves intended to guide the evaluation of foamed bitumen use [2, 4-5]. Figure 1 presents these recommended typical grading envelopes. No apparent differences can be observed from the curves, especially in the finer fractions.

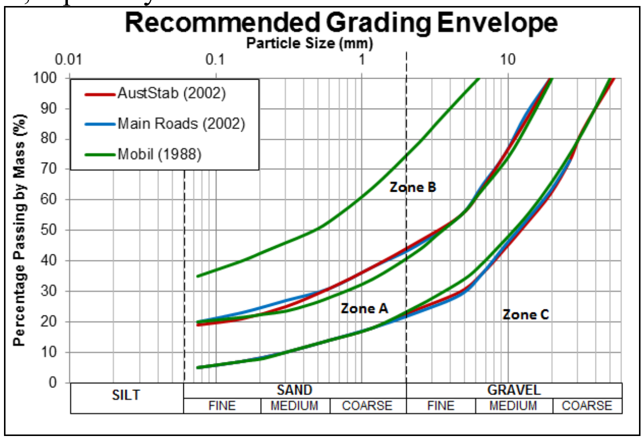

Figure 1. Recommended Grading Envelopes

Significant recognition was given to the importance of fines content (particles passing 75µm sieve size) in aggregate gradation within a foamed bitumen stabilised mix in many previous research topics. The reason for this lied in the method by which foamed bitumen imparts strength through stabilisation of aggregate particles with foamed bitumen matrixes. It has been proven that particle coating is especially important in foamed preparations, as the inherent strength is gained by "spot-welds" of bitumen droplets providing tensile strength in the mix [6]. This is an important consideration, as foamed bitumen will bind readily and coat fines particles, as dispersed throughout the mix – a careful assessment of the fines within a mix will allow for optimisation of the mechanical performances. Previous researchers have quantified the fine contents should be greater than 3%, 5% is much more preferable, with an upper limits at 20% [7-9]. Such conclusions are reinforced by the recommended grading curves presented in Figure 1. These curves all present a recommended limit of approximately 5% - 20% fines within an aggregate mix.

2 LABORATORY EXPERIMENTAL PROGRAM

The laboratory experimental program will consist of producing a number of sample aggregate batches with varied fines contents, and combining these with varying percentages of foamed bitumen. The proposed range of percentages for sample preparation is presented below in Table 1.

Table 1. Sample Schedule

Fines Content Variation	0%, 5%, 9% (nature mix), 15%, 20%, 25%
Bitumen Content Variation	0%, 2%, 4%

2.1 Materials

2.1.1 Foamed bitumen

Foamed bitumen has been produced in a Wirtgen WLB 10S, with guidance taken from the procedures outlined in the operating manual for this unit. The Wirtgen WLB 10S is capable of delivering the required mass of foamed bitumen to the nearest gram, into an operating twin-shaft pug-mill (WLM 30). For the purposes of laboratory preparations contributing to this report the foamed bitumen used has been prepared with Class 170 bitumen. This has been foamed using 2.5% cold water after heating to a temperature of 170°C-180°C, and delivered at a pressure of 2.5 bars.

This has resulted in an expansion ratio of 15-20 (likely to be dependent on ambient temperature and humidity) and a half-life of 20 seconds. No foamant additives have been used in any foaming process.

2.1.2 Host materials

Crushed rock-base (CRB) and crushed limestone (CLS), two locally sourced virgin materials, were chosen in this project. A nominal size of 19mm of both CRB and CLS was found to be conformed to Main Roads Western Australia (MRWA) specification 501[10]. Generally, CRB and CLS are commonly used as a base course and sub-base course in typical Western Australian road pavement structures. This is the main reason that they were selected as host parent materials.

2.1.3 Active filler

Hydrated lime (HL) was included within the mix as a secondary binder to provide additional required strength for specimen stability. However it should be noticed that the effect of hydrated lime content on strength was not a desired outcome to be measured, thus the content was kept to a minimum of 1% by mass in order to reduce the effects of hydrated lime binding and to provide a better insight to the effects of foamed bitumen on sample strength.

2.1.4 Mineral filler

In order to provide an increase in fine contents within the aggregate mix to be able to compare varied fines contents, an inert mineral filler, baghouse dust (BHD) was intentionally adopted to alert host aggregate fine contents. Figure 2 outlines the grading characteristics of baghouse dust.

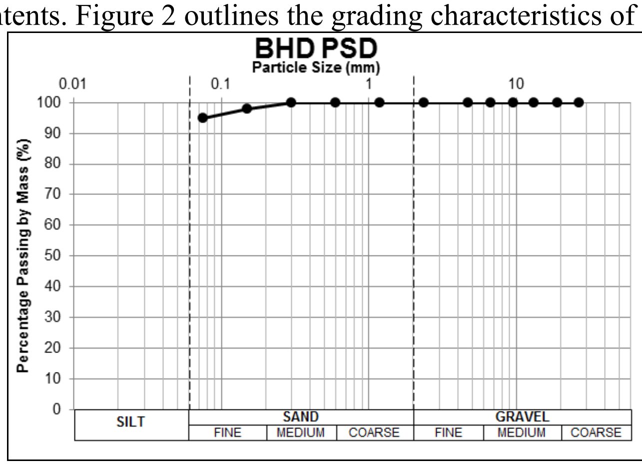

Figure 2. Gradation curve of Baghouse Dust

Whilst it is evident that this candidate material does not consist of entirely fines passing the 0.075mm sieve, it is accepted that the portion not meeting this criteria is small enough to be considered negligible. It should also be noted that there is a distinct possibility of variations within the chemical and/or physical properties of the inert filler used, and those of natural fines within the aggregate mix. This too shall be neglected, as the provision of fines in a practical application would be via the addition of some material similar to baghouse dust, rather than attempting to replicate a portion of the natural fines by complex and expensive grading procedures.

2.2 Sample Preparation

Host materials were firstly fabricated by blending 50% CRB with 50% CLS by mass into different batches followed by an important process which was addition or removal fines (passing 75 µm sieve size) to make up the target candidates. This step was successfully accomplished by washing (if less fines were required) and adding of BHD (if more fines were required). Preparation of foamed bitumen treated mixtures will be undertaken using the Wirtgen WLB 10S with external attachment WLM 30, a twin shaft pug-mill. A two-step mix process was recommend, first step only occurred by mixing the dry constituents (CRB, CLS, BHD and HL) for 60 seconds. This is to ensure that all dry constituents have been homogenously mixed, especially for the BHD and HL. Subsequently, suitable water (which is equal to optimum moisture content of host material), together with target mass of foamed bitumen were injected into the mixer drum for a further 60 seconds mix to ensure aggregates are moist and thoroughly combined with foamed bitumen.

On the completion of mixing, samples were ready to be compacted into cylindrical sizes for further tests. In this project, two different compaction methods were adopted. An automatic Gyrator Compactor was firstly employed to fabricate six small size specimens for indirect tensile strength (ITS) and indirect tensile resilient modulus (ITMR) tests. To be specified, Gyrator Compacter applied a constant vertical stress of 240kPa and gyrated at 60 rpm at an angle of 2° to compact samples into 100(±1) mm in diameter and 76(±1) mm in height. Besides, a modified compaction method was utilised to prepare three samples for the unconfined compressive strength (UCS) test. In this process, a mould 100mm in diameter and 200mm in height was used in which materials were compacted 25 blows each for eight layers with a 4.9kg rammer at a 450mm drop height.

The final process in sample preparation was to cure the specimens at required conditions. In this project, two separate methods of curing, namely soaked and unsoaked curing were adopted. Unsoaked curing process was used for the majority of samples prepared in this project, and will entail resting the sample in an oven at 40 degrees Celsius for 72 hours. The purpose of unsoaked curing is to obtain a similar maximum-dry moisture content to that obtained in optimum field conditions. Realistically this level of reduced moisture content would not be achieved in the field for many months under optimum conditions, so an accelerated drying method is adopted. The samples will remain wrapped, with only the top portion exposed, simulating the environment of typical stabilised materials. The choice of 40°C is based on findings which suggest that higher temperatures result in aging of the bitumen within samples, which will impact the accuracy of results obtained [9]. This method will be utilised for all specimens, including UCS test specimens and the tensile test specimens. Soaked curing was only applied to half of the tensile test samples, and required immersion of the sample under room-temperature water for 24 hours. The purpose of soaked curing is to assess the properties of the stabilised mix under worst-case conditions of moisture content.

2.3 Mechanical Test Programs

2.3.1 Indirect Tensile Resilient Modulus

Indirect tensile resilient modulus (ITM_R) testing has been undertaken in accordance with AS 2891.13.1-1995 (Standards Australia 1995b). The test involves diametrically loading samples under a pulsated load and taking measurements of the resulting recovered strain, as illustrated in Figure 3. This strain is then correlated to the applied loading and size of the sample to calculate the ITM_R. It should be noted that, in order to provide comparable results the pulse width will be adjusted to provide a rise time of approximately 40ms. The purpose of the ITM_R test is to obtain an estimated modulus value for the stabilised materials. This test has been chosen due to its popularity within asphalt and bitumen laboratory testing routines, and the general simplicity of results. These factors make results easily comparable and thus facilitate the contribution of this research to further investigation of foamed bitumen design methods.

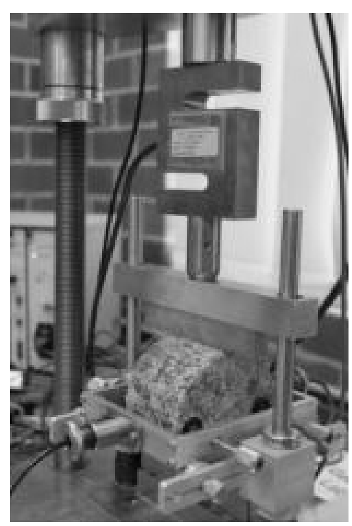

Figure 3. ITM_R Testing Apparatus

2.3.2 Indirect tensile strength

Indirect tensile strength (ITS) testing has been undertaken in accordance with AS 1012.10-2000 (Standards Australia 2000). The testing apparatus used for ITS testing is a Civilab Marshall Stability Machine (CL40580), which loads samples diametrically as shown in Figure 4. ITS testing has been chosen for its simplicity, and its widespread use in other literature and laboratory based studies. This makes for readily comparable and replicated test results, which is a key aim of this study. Furthermore it is important to understand the ability of foamed bitumen treated materials as base course or sub-base course materials to resist tensile loadings, as this is commonly a critical failure loading. Specimens were tested to failure, and the peak load on the actuator was recorded automatically by the apparatus. This peak load was used to back-calculate the ultimate tensile resistance of the specimen via the Equation 1.

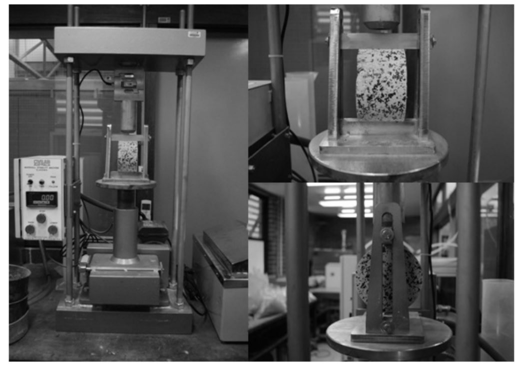

Figure 4. ITS Testing Apparatus

$$ITS = 2000 * P / \pi * L * D \qquad (1)$$

Whereby ITS= indirect tensile strength (kPa); P= Maximum applied force indicated by machine (kN); L= Height of specimen (mm); D= Diameter of specimen (mm).

2.3.3 Unconfined compressive strength

The testing of unconfined compressive strength (UCS) has been undertaken in accordance with MRWA Test Method WA 143.1, using the GCTS STX-300 testing apparatus located in the Geomechanics Laboratory, Department of Civil Engineering, Curtin University, pictured in Figure 5. During testing, a vertical force without confining pressure was applied to induce a strain rate of 1.0mm/min on top of the specimen. The results will not be obtained until the maximum axial stress had been reached. UCS testing provides information on the shearing resistance of a sample, and is useful to this research in providing an indication of the material properties when encountering similar loading patterns.

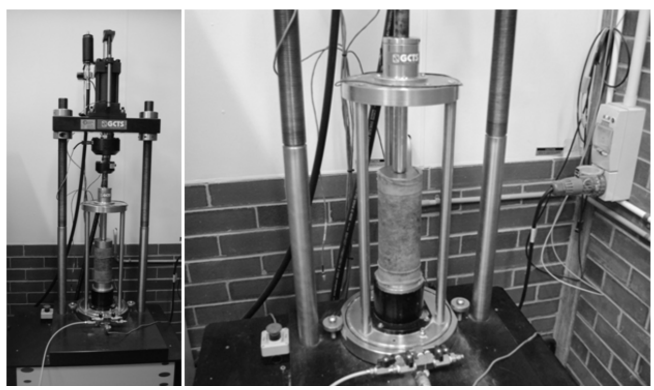

Figure 5. UCS Testing Apparatus

3. RESULTS AND DISCUSSION

3.1 Fine Contents Variation

A summary of the typical particle size distribution for each batch with different fine contents is presented in Table 2. Variations will occur over the entire grading due to the shift in percentage composition arising as a result of fines addition, yet these are minimal.

Table 2. Particle Size Distribution with Fines-Content Samples

Particle Size (% by mass passing sieve)	Fines Content of Test Batches (% by mass)					
	0	5	9.1 (Natural)	15	20	25
19.0 mm	100.0	100.0	100.0	100.0	100.0	100.0
13.2 mm	95.5	95.5	95.5	95.8	96.1	96.3
9.50 mm	83.9	83.9	83.9	85.0	85.9	86.8
4.75 mm	74.0	74.0	74.0	75.8	77.3	78.8
2.36 mm	65.8	65.8	65.8	68.1	70.2	72.1
1.18 mm	56.8	56.8	56.8	59.8	62.3	64.8
0.60 mm	48.2	48.2	48.2	51.7	54.8	57.8
0.425 mm	40.6	40.6	40.6	44.6	48.1	51.6
0.30 mm	28.5	28.5	28.5	33.4	37.6	41.7
0.150 mm	14.3	14.3	14.3	20.0	25.0	29.8
0.075 mm	0.0	5.0	9.1	15.0	20.0	25.0

Figure 6 presents the grading curves for all sample batches, identifying the gradation range in which aggregate testing will occur. As can be noted, the majority of the gradation curves for sample aggregate lie somewhat on the upper limit of recommended grading envelopes suggested by AustStab. Only the fine portion of gradation curves is shifted outside of this envelope, with batches consisting of 0% and 5% fines lying in the 'unsuitable' range. The natural aggregate (consisting of 9.1% fines) and altered batch with 15% fines both display gradation curves beginning in the 'ideal' range, whilst the 20% and 25% fines batches remain entirely within the 'suitable' envelope. It is anticipated to indicate these gradation curves should indicate that the 0% and 5% batches will perform significantly worse than other batches, and that the natural (9.1%) and 15% fines batches should display optimum performance.

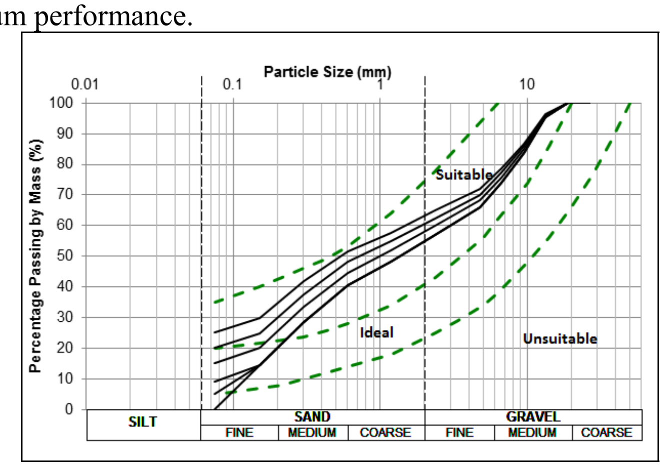

Figure 6. Particle Size Distribution of different batches

3.2 Bulk Density

On completion of compaction, all specimens were recorded in volume and mass to determine the bulk density. Figure 7 presents the average value of bulk density of each sample batch. Similarly, all samples reach a maximum density, after which further addition of fines has resulted in a reduction of compactability. Both bitumen stabilised mixes reach this maximum at 15% fines, whereas specimens prepared without foamed bitumen present a maximum density at 20% fines content. Another visible trend is the increase in density with increased bitumen content between samples of equal fines content. This trend is evident at all fines contents less than the maximum (i.e. less than 15% fines), after which the density of samples prepared from foamed bitumen treated mixes decreases almost equally, while that of the zero-bitumen samples remains relatively constant.

These trends would indicate that for mixes with lower fines content, an increase in voids present allows bitumen to fill these voids and thus result in a higher density after compaction. As both foamed bitumen stabilised sample groups reached a peak density at 15% fines content, it can be implied that this is the optimum level of fines content for compactability. This indicates that fewer voids are present within the soil structure and that as fines content increases beyond 15% the result is that both fines and bitumen are filling nearly all available voids, while also replacing larger particles within the mix. As the foamed bitumen will coat fines particles, effectively filling smaller voids between these, while also affording some reduction in granular resistance, it can be expected that samples produced without foamed bitumen will be less compactable. This is evident for the zero-bitumen samples of fines content greater than 15%, where the density remains relatively constant, yet significantly lower than the maximum obtained at 15% fines for both foamed mixes.

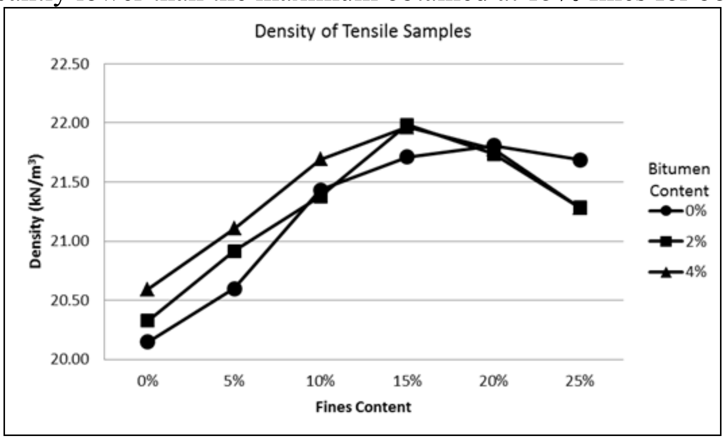

Figure 7. Specimen bulk density with different fine contents

3.3 Indirect Tensile Resilient Modulus

ITM_R testing was undertaken on six specimens from each batch, three of each undertaking unsoaked and soaked testing. Figure 8 presents the results for unsoaked and soaked indirect tensile modulus for all samples, taken as an average between specimens.

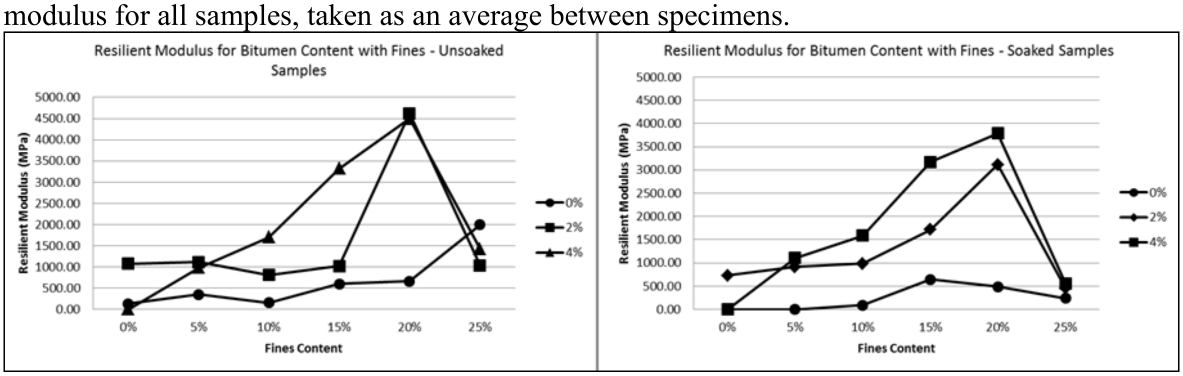

Figure 8. Resilient Modulus for unsoaked samples (left) and soaked samples (right)

The unsoaked plot presents a clear trend of an increased modulus with fines content for both 2% and 4% levels of bitumen content, reaching a maximum at 20% fines. Conversely, specimens prepared without foamed bitumen show no appreciable increase in modulus until fines content is increased to 25%. Specimens prepared with 4% foamed bitumen display a strong, near-linear trend of increasing modulus with fines content, however this reduces significantly after increasing fines content to 25%. This reduction in modulus is displayed almost identically in the 2% foamed bitumen specimens, which present very similar results for both 20% and 25% fines content. However specimens prepared with 2% foamed bitumen show only an appreciable increase in modulus over the 4% foamed bitumen mixes at extremely low fines contents (0% - 5%).

Soaked sample curves present a similar trend to that of unsoaked samples, indicating (for batches prepared with bitumen) a general increase in resilient modulus with fines content up to 20% fines, and a significant reduction in modulus at 25% fines. While the trend remains relatively constant for foamed bitumen treated specimens, it is evident that for those prepared without bitumen, moisture sensitivity increases significantly at fines contents above 15%.

3.4 Indirect Tensile Strength

Similar to ITS testing, ITS testing was undertaken on six specimens from each batch, three of each undertaking unsoaked and soaked testing. Figure 9 presents the results for unsoaked and soaked indirect tensile strength for all samples, taken as an average between specimens.

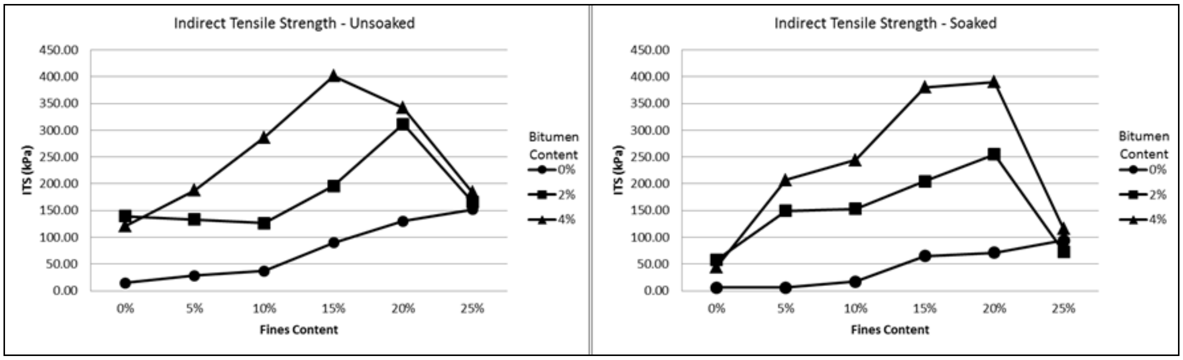

Figure 9. Tensile strength for unsoaked samples (left) and soaked samples (right)

Of the unsoaked samples tested for ITS, those prepared with 15% fines content and 4% foamed bitumen displayed the greatest performance, with an average strength exceeding 400kPa. For the majority of fines contents tested, the 4% foamed bitumen samples presented the greatest tensile strength, with the only exception being at 0% fines, where the 2% fines samples displayed a slight increase in tensile strength performance. Take 2% bitumen content as an example, unlike the 4% bitumen samples, those prepared with 2% foamed bitumen displayed a relatively unchanged tensile strength for samples of fines content ranging from 0% to 9.1%. An increase in strength is then notable at 15% and again at 20% fines, reducing once more at 25% in a similar fashion to the 4% foamed bitumen samples at these higher fines contents. This trends among the 2% foamed samples may be attributable to the existence of voids within the soil structure, which are replaced by the foamed bitumen coated fine particles – below 15% fines, no appreciable change is observed with the addition of fines. However, as the voids are filled, an increase either in granular friction or in bonds formed by the foamed bitumen mastic would result in an increase in sample strength. Similarly, as fines are increased above 20% and voids are no longer present, the bitumen and fines particles begin to replace larger particles within the mix, while an increase in fine particles may result in poorer coating of these particles, and thus diminished mastic strength. Samples of 0% foamed bitumen content presented a near-linear increase in tensile strength with increasing fines content ranging from 15kPa at 0% fines to 152kPa at 25% fines. This too may be attributable to the effect of filing voids and the resultant increase in granular stability due to particle friction. However it is notable that all samples presented tensile strength results of significantly lower values than the FBS mixes.

As in the soaked samples, the 0% bitumen mix gained strength with increasing fines content with a near-linear relationship. Similarly, the 2% foamed bitumen mix presented a peak value at 20% fines as with unsoaked samples, and the 4% bitumen mix displayed a similar trend which implies a peak value at approximately 17% fines.

3.5 Unconfined Compressive Strength

Results of UCS testing displayed a similar trend to previous tests of increasing strength with fines content. Figure 10 displays the results of UCS testing as an average of specimen performance for each sample group. Samples prepared without foamed bitumen are observed to receive a near-linear increase in compressive strength from 179kPa at zero-fines to 662kPa at 25% fines.

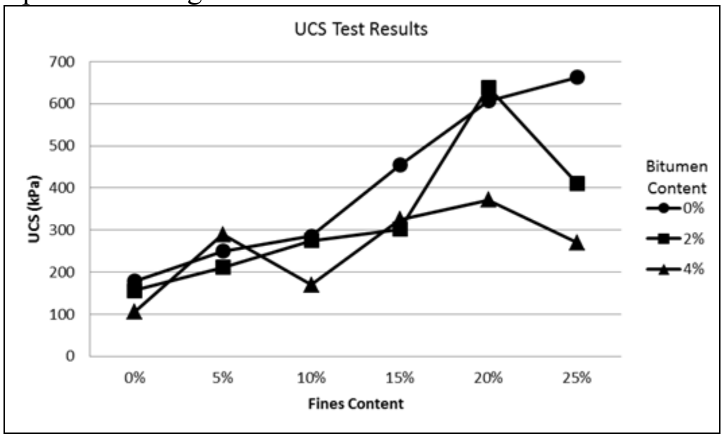

Figure 10. Compressive strength with different fine contents

This significant increase in compressive strength is considered to be attributed to the cementitious effect of hydrated lime within the mix. Further analysis of the 0% foamed bitumen curve indicates a sharp increase beyond the natural fines content, with 15%, 20% and 25% fines content samples appearing to display a more significant strength gain with fines addition. This may be due to the effect of increasing density within the soil structure resulting in fewer voids and an increased effect of granular friction, whilst also increasing the cemented structure of the specimen.

Samples prepared with 2% foamed bitumen present a trend similar to those of the 0% foamed mix at lower fines contents. While there is a strong linear correlation between compressive strength and increasing fines content for the 2% foamed mixes from 0% to 15% fines, no appreciable strength gain is recognised in comparison to the 0% foamed bitumen samples. However as fines content is increased to 20%, compressive strength is observed to increase significantly, yet reduces just as significantly with a further increase in fines to 25%. While the significant increase in compressive strength at 20% fines content indicates optimum fines content for 2% foamed mixes, there is no appreciable increase in compressive strength when compared to the 0% foamed mix at the same fines content. Similarly, samples prepared with 4% foamed bitumen displayed a weak trend of a comparatively minor increase in strength with increasing fines. However it should be noted that for 4% foamed bitumen, as with 2%, a fines content of 20% presents a peak compressive strength.

4. CONCLUSION

Analyses of the mechanical testing results confirm some general trends which are expected of varied fines content within foamed bitumen mixes. The effects of both increased fines content and foamed bitumen on density and mechanistic properties conform to expected trends, displaying an optimum density where voids are presumably filled and effectively removed, after which point further addition of fines results in a reduced density. While the optimum density is not directly related to the sample strength, a general trend of similarities between optimum compactability and optimum strength characteristics is evident. It is anticipated to conduct research into the effects of altering various coarse particle size ranges within the natural aggregate mix, as the strength is mainly coming from the interlock of coarse fractions.

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