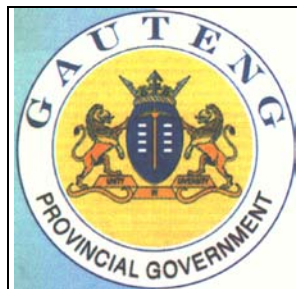

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Laboratory Testing on Foamed Bitumen and Cement Treated Material from the HVS Test Section on Road P243/1



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Abstract: <p>This report discusses results of laboratory tests performed on a treated ferricrete obtained from the HVS DISR test site on road P243/1. The tests include UCS, ITS, flexural beam fatigue and CBR tests. The materials were treated with 0 or 1 per cent cement and different percentages of foamed bitumen. Test results from previous work on the untreated material were combined with the results from this study to supplement the analysis.</p> <p>In general, the results show that the foamed bitumen adds flexibility to the material, whereas the cement adds strength. A minimum amount of foamed bitumen (more than 1.8 per cent) is needed to have an influence on the test results. Similarly, at least one per cent cement is necessary for strength gain.</p> <p>By using a microscope, the appearance and distribution of the foamed bitumen in the mix could be analysed. There is a significant difference between the laboratory samples and a HVS sample. The quality of mixing using DISR is better than the laboratory mixing procedure used in this work, and improvements to the laboratory procedure are necessary.</p>				
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1. INTRODUCTION

1.1. General Background

This report is in support of the objectives of a framework that has been created for the long-term assessment and implementation of Deep In Situ Recycling (DISR) technology using bituminous emulsion and foamed bitumen treatment processes. The objective of the long-term assessment and implementation programme is to produce guideline documents and design methods for use by the road-building industry on DISR using the bituminous emulsion and foamed bitumen treatment processes. These guideline documents and design methods will ensure better designs reducing the risk of premature failure and increasing the probability of optimal performance.

The assessment process used the following assessment techniques: laboratory testing, Heavy Vehicle Simulator (HVS) testing and field trials to assess the benefits of DISR combined with bituminous emulsion and foamed bitumen treatment and to create the knowledge base from which the guideline documents and design methods will be developed. The main aspects that were investigated include:

- The engineering properties (such as the bearing strength, permeability and erodibility);
- The mechanical properties (such as the stiffness, shear strength and strain-at-break);
- The material and pavement behaviour and performance of the products from these processes, and
- All aspects that impact on the above such as design, construction and maintenance.

1.2. Objectives and Project Deliverables

The laboratory work explained in this report supports Heavy Vehicle Simulator tests that were performed on road P243/1 near Vereeniging. More materials and combinations of materials can be tested in the laboratory than is possible with the HVS. The laboratory tests performed for this research are part of the larger framework of testing. Previous test results are also discussed in relation to the results from the latest tests.

The objective of this research is to gain an understanding of the engineering behaviour and performance properties of materials treated with foamed bitumen. This

understanding will aid in the development of comprehensive material and structural design procedures for this material type.

2. MATERIALS

One type of aggregate was used for testing. The aggregate is a mixture of previously cement treated ferricrete and old surfacing (multiple seal) milled from a DISR site on road P243/1. Some laboratory tests have already been completed on this aggregate. The bitumen and the cement used in the tests described in this report are the same as those used in previous testing, described by Long and Theyse¹.

2.1. Aggregate

The aggregate is the same as was used for the rehabilitation of road P243/1 on which HVS tests were performed. The aggregate, which consists of the old cemented ferricrete base, the multiple seal surfacing and some material of the subbase, was milled with a Wirtgen DISR machine. The material was mixed with 1 per cent cement and 1.8 per cent foamed bitumen. The reader is referred to Long and Theyse¹ for detailed material properties of the untreated, milled aggregate.

2.2. Binders

The binder is an 80/100 penetration grade bitumen from NATREF. Previous penetration tests on the bitumen showed that it is within the specification limits. The bitumen used in this study comes from the same batch as used for the previous tests and was procured at the same time.

The cement is an Alpha CEM I, 42.5 MPa. This is the same cement used in the previous tests, although procured at different times.

3. LABORATORY TESTS

The aggregate was mixed with two different binders, cement and foamed bitumen. The mixes were compacted and cured before the testing started. The mixing and compaction procedure is described in this chapter.

3.1. Testing Programme

The tests used in this study are the unconfined compressive strength (UCS), indirect tensile strength (ITS), flexural beam (FB), and California Bearing Ratio (CBR) tests. Microscopic photographs were taken for a closer examination of samples prepared at different binder contents. The test framework is listed in Table 1.

Table 1. Laboratory Tests for Bitumen- and Cement Content Combinations

Test	Number of tests per material	Time of testing (days)	Cement content (%)	Foamed bitumen content (%)
UCS	3	28	0	1.8
			1	0.0
				1.8
				3.0*
				5.0
			2*	0.0*
1.8*				
ITS (unsoaked)	3	28	0	1.8
			1	0.0
				1.8
				3.0*
				5.0
			2*	0.0*
1.8*				
Flexural beam test	4	28	0	1.8
			1	0.0
				1.8
				3.0*
				5.0
			2*	0.0*
1.8*				
CBR	3	28	0	0.0
			0	1.8
Electron microscope images	-	0, 1, 7, 28	0	1.8
			1	0.0
				1.8
				3.0
				5.0
			2	0.0
1.8				

* Combinations tested earlier¹

3.2. Mix Design and Compaction Process

The tests described in this report are additional to earlier tests¹. To allow comparison between the results, it is important that the aggregate be treated, and the tests performed under the same conditions as the previous tests.

The specimens were prepared in the soil laboratory at Transportek, CSIR. The foaming machine used in the process is a WIRTGEN laboratory foaming machine (Figure 1), which was obtained from SIMLAB in Bloemfontein.



Figure 1. Mixer and Wirtgen Foaming Machine

3.2.1 Foaming Machine Setup

The setup of the machinery is identical to that used for the earlier tests. The mixer used is a concrete mixer (Figure 1). Tape on the floor was used to mark the correct position for the foaming machine.

The amount of water added to the bitumen for the foaming process was 3 per cent of the mass of the bitumen. The correct application rate was determined by measuring the flow of water out of the nozzle. On average, the actual amount of water was 2.9 per cent. This setup was not changed during the foaming process. The temperature of the bitumen was fairly constant for the different batch preparations, ranging between 177 and 180°C, as shown in Table 2. Table 2 also shows that the temperature of the aggregate was low, between 15 and 18°C. Earlier tests were mixed at an average aggregate temperature of 20°C. The reason for the difference is the time of the year that the testing was carried out.

Material was stored and collected from outside and, because the specimen preparation described in this report was performed in winter, the ambient temperature was lower. Other properties of the foaming process are shown in Table 2.

Table 2. Foaming Process

Test	Binder content (%)	Cement content (%)	Pressure (bar)			Temperature (°C)		
			Water	Air	Nozzle	Binder	Aggregate	Mix
CBR/UCS	1.8	0	6	5	2.6	179	not measured	
ITS/FB	1.8	0	6	5	2.6	180		
UCS/ITS	1.8	1	6	5	2.7	179	15	19
FB	1.8	1	6	5	2.7	179	16	20
UCS/ITS	5.0	1	6	5	2.5	177	15	21
FB	5.0	1	6	5	2.5	177	18	24

3.2.2 Expansion Ratio and Half Life

The foamability of a bitumen is determined by the expansion ratio and half-life, defined below:

- The expansion ratio is a measure of the viscosity of the foam and determines how well the binder will disperse in the mix. It is calculated as the ratio of the maximum volume of foam relative to the original volume of bitumen.
- The half-life is a measure of the stability of the foam and provides an indication of the rate of collapse of the foam during mixing. It is calculated as the time taken in seconds for the foam to collapse to half of its maximum volume.

The expansion ratio and half-life were measured according to guidelines described by Jenkins². Three measurements were taken. The temperature of the bitumen was 180 °C. Table 3 gives the results of the three measurements taken.

Table 3. Expansion Ratio and Half Life

Measurement	Expansion Ratio	Half-life (seconds)
1	6	14
2	7	9.5
3	9	8

The earlier tests on the bitumen showed different results for the half-life values¹. The half-life was 6 seconds where it is now between 8 and 14 seconds. Different people measured the half-life in the two situations, which can give different results, as the test is subjective in interpretation. Another reason could be the longer storage of the bitumen. The expansion ratios were comparable.

3.2.3 Foaming of the Mix

The aggregate was air-dried as it went into the mixer. The cement (if used) was mixed with the air-dried aggregate for several minutes to get a good distribution of the cement. Thereafter, the amount of water required to obtain the optimum fluid content (OFC) was added and the material mixed again. The OFC is defined below. During continuous mixing, the desired amount of foamed bitumen was added.

Because the bitumen is sprayed into the material while it is being mixed, the mixing paddles are also sprayed with bitumen. This causes a reduction in the amount of bitumen in the specimens. The amount of bitumen loss is not known, however extractions of the mixes tested previously showed that the mixes contained less bitumen than intended. Figure 2 shows the mixing paddles covered with bitumen.



Figure 2. Mixer Arm with Bitumen

The mixing moisture content was calculated from the optimum moisture content of 12.5 per cent. During construction with foamed bitumen treated materials, the optimum fluid content is typically used for compaction. The fluid content consists of both the water and the bitumen. Research by Jenkins² shows that mixing should be performed at 'fluff point', i.e. 65 to 85 per cent of the optimum fluid content (OFC). For this reason, tests should be performed to determine the correct OFC. In this work, the OFC was not determined, because of time and economic constraints. It was assumed that the OFC is the sum of the water and foamed bitumen contents. This means that higher bitumen

contents require lower water contents during mixing. For the mix with 5 per cent bitumen, the water content was $12.5 - 5 = 7.5$ per cent, which is 60 per cent of OFC. This is lower than the recommended minimum moisture content of 65 per cent of OFC, but the material could not be mixed at a higher moisture content and left to dry as it contained cement. However, it is more important that the mix has the correct fluid content during compaction.

Problems were encountered with the first batch of mix with 5 per cent foamed bitumen and 1 per cent cement in that the mix appeared too dry. The bitumen was very poorly mixed in the material, and it was not possible to get the required compaction for the beam specimens. The material was mixed again at a higher moisture content (10 per cent) and an improved mix was obtained. However, it was 'wetter' than intended. This meant that, for compaction, the material was above the assumed OFC. For the UCS and ITS tests, this can influence the compaction as the compaction is force controlled rather than volume controlled. For the beam test, this should not make a difference, as the material is weighed, accounting for the extra water, and pressed in the mould. However, by pressing the material in the mould, maximum saturation was achieved and because water could not drain out the mould, the correct height (75 mm) and associated density could not be achieved. It was decided to remove some material to get the correct height for the beams. The change of dry density must be taken into consideration when the different tests are compared.

No problems were encountered with any of the other mixes.

After mixing with the foamed bitumen there were, for all the mixes, several concentrations of bitumen, looking like small balls, with diameters ranging from 1 mm to 30 to 40 mm. The concentrations did not bond with any of the aggregate particles and were formed before they could be mixed and bonded with the aggregate. The higher the bitumen content, the larger the number of balls found in the mix. This means that the bitumen was not mixed in properly and could not be considered as part of total OFC, as it acted more as a particle than a fluid.

Several reasons can be postulated for the formation of the bitumen concentrations. Firstly, the distance between the nozzle and the material is large (approximately 650 mm). The temperature of the bitumen can drop between leaving the nozzle and coming in to contact with the aggregate. Secondly, the temperature of the aggregate was low. Earlier work has shown that the minimum mixing temperature for foamed bitumen is around $12\text{ }^{\circ}\text{C}^2$. The aggregate had a temperature of around $16\text{ }^{\circ}\text{C}$, which is above the minimum, but still on the low side. A third reason is the large concrete mixer that uses a

blending action rather than creating airborne aggregate particles that meet a curtain of foamed bitumen, as happens in the field construction with the DISR equipment. The mixer is therefore not well suited for mixing foamed bitumen, because the mixing energy, that can be generated during the short period in which the foamed bitumen can be mixed, is too low. All these factors possibly result in a material that is different from the material mixed in the field.

Tests by Jenkins² have shown that the type of mixer is of great importance for the quality of the mix. Identical mixes were produced with both a Hobart mixer with an improved mixing arm and a Pugmill mixer. The UCS value for the Hobart mix was 1600 kPa and for the Pugmill mix 2100 kPa, a difference of 500 kPa, which is a reduction in strength of approximately 30 per cent. The Pugmill mixer is considered to have the closest resemblance to field mixing.

3.2.4 Compaction

The UCS, ITS and CBR are compacted at 100 per cent Mod. AASHTO, following standard TMH 1 procedures. The beams for the flexural beam test were compacted in the beam mould in three layers, with each layer having 56 blows with an AASHTO hammer. After this compaction, the material was compacted to a standard height of 75 mm using a compression apparatus with a maximum effort of 275 kN. As mentioned in Section 3.2.3 the beams with 5 per cent foamed bitumen and 1 per cent cement were compacted to a lower level, as the material would not fit in the mould. All the other specimens were compacted to a dry density of 2030 kg/m³.

3.2.5 Curing

Except for the untreated CBR specimens, all the specimens were cured for 28 days at ambient temperature. The beams were sealed in a chamber, and were dried out at a later stage to establish the correct moisture content. The ITS specimens were also dried out, if necessary, to obtain the target saturation level. The correct testing moisture content for the target saturation level was calculated from the initial moisture content and the weight of the sample.

4. MICROSCOPIC PHOTOGRAPHS

For a good understanding of the material it is important to know the microstructure of the material. For this purpose, the material specimens were examined under a microscope.

4.1. Microscope

The initial intention was to use an electron microscope. However this device can only handle specimens without water. This means that drying out of the material in an oven is necessary. This can change the properties and the distribution of the bitumen, which is not an ideal situation.

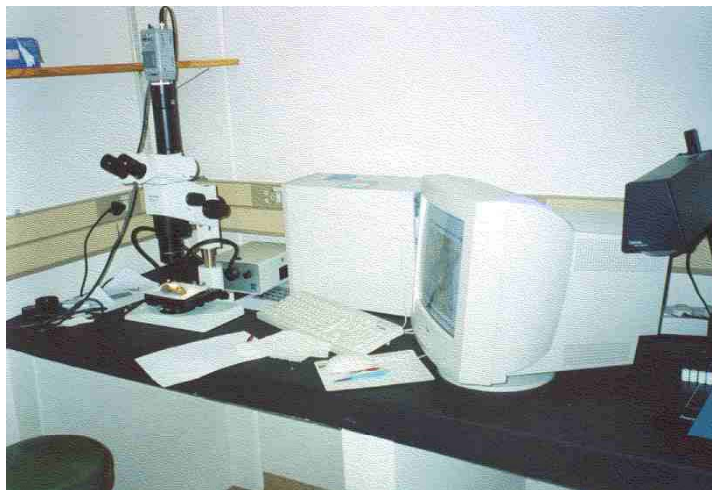


Figure 3. Optical Microscope

Therefore, for this project, a stereo-microscope was used. A video camera is mounted on top of the microscope for taking photographs (Figure 3). With this device it is possible to capture a three-dimensional photograph. The computer compiles separate photographs into one three-dimensional photograph.

Photographs were taken after different curing times to see if any changes in the material could be observed. The growing of the cementitious bonds in time was very difficult to identify. This could be because of the relatively small amount of cement (1 per cent). In some situations, the cement was visible by eye (through the microscope), but not on a photograph.

The distribution and appearance of the bitumen was very visible in the photographs. Consequently the scope of this microscope work moved from identifying the cement growth towards observing the appearance of bitumen. The specimens prepared in the laboratory were compared with treated material obtained from the HVS test section.

4.2. Photographs of Laboratory and HVS Site Specimens

The material on the HVS section of road P243/1 was milled and mixed by a Wirtgen DISR machine. This machine has 16 nozzles for spraying the bitumen and a drum for milling and mixing. As seen in Figure 4 it is clear that this method gives a fine distribution of the bitumen throughout the mix. What appear to be small drops of bitumen are actually thin layers bonding the material together and capturing the fines.

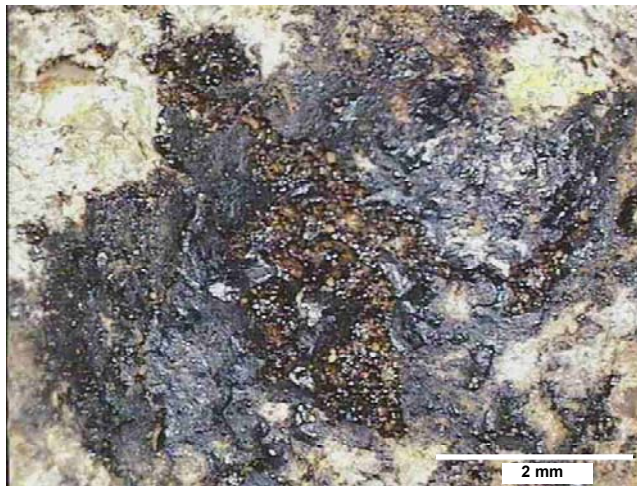


Figure 4. Sample from the HVS Site

The laboratory mixing process differs from the field process. Only one nozzle is used and the mixing process is completely different, as discussed in Section 3.2.3. One extra specimen per material was compacted at 100 per cent Mod. AASHTO, and pieces of the samples were used for photographing with the microscope.

The concentrations of bitumen witnessed after mixing are also visible under the microscope, only the concentrations are much smaller, as seen in Figure 5. Almost no thin layers, as witnessed on the core from the road, were seen. The concentrations of bitumen were mixed in as small particles. Some additional photographs are shown in Appendix A.



Figure 5. Sample from Laboratory (5 per cent bitumen)

The distribution is also different between the two mixing methods. The road samples showed certain areas with more bitumen than others. These areas could have had a higher concentration of fine material. But, the appearance showed thin layers of bitumen bonding with the aggregate itself. The laboratory samples also showed areas with more bitumen than other areas. However, the concentration of bitumen in certain parts was in some cases very high. The low temperature of the aggregate (approximately 16 °C) in combination with the concrete mixer used could be the cause of the differences observed. As it hits the relatively cold aggregate the bitumen reverts to its viscous state and a good distribution could not be attained.

It was often difficult to visually distinguish between the higher and lower binder content mixes. The variation was caused more by the different samples taken from the material rather than the different bitumen contents. Sometimes one sample of higher binder content material showed almost no bitumen and vice versa. Because a new sample was used every time, comparison between the different bitumen contents was difficult. It was also sometimes difficult to distinguish between the bitumen milled from the road surface layer and the new bitumen in the mix.

An important conclusion that can be drawn from the microscopic photographs is that the appearance of the bitumen in the mix is very different for the two different mixing techniques. In this research the aim was to obtain a material using laboratory mixing that is similar to what is obtained in the field with the DISR equipment. It seems that this is not the case with the mixer used in the laboratory. To what extent the material responds differently is not known, and should be further investigated.

It is necessary to do more work to identify the differences in the microstructure of the mix in terms of the bitumen appearance and distribution in the aggregate. Preferably this has to be done on material that contains no old bitumen in the aggregate, so that the identification of bitumen is easier.

5. LABORATORY TESTING

Four different laboratory tests were performed on the materials, being the UCS, ITS, flexural beam fatigue and CBR tests. For a list of the tests performed on each material combination, see Table 1¹.

5.1. CBR

The CBR test is described in TMH 1. The CBR test was only performed on the material combinations without cement, i.e. untreated aggregate and aggregate with 1.8 per cent foamed bitumen.

Three tests per material combination were performed at a density level of 100 per cent Modified AASHTO. The intention of the test is not to determine the relationship with density, but to assess the quality of the material. The relationship between density and CBR was already established in earlier testing, and is shown in Table 4 for the different compaction levels¹. These results are for the untreated material.

Table 4. Previous CBR results¹

Compaction (Mod AASHTO) (%)	Compaction Moisture Content (%)	CBR
90	12.1	5.8
93	12.1	17.5
95	12.1	23.0
98	12.1	56.0

Table 5 gives the results of the current CBR tests. The CBR value at 2.54 mm penetration is generally used for assessing the quality of the materials. There is some variation in the results, but it is clear that the CBR for the material treated with the foamed bitumen is higher than the untreated material. This means that the strength of the treated material is higher than the untreated material.

The CBR values in Table 4 are higher than those in Table 5. The large difference in the results cannot be explained. The testing equipment will be calibrated to ensure the values reported in future testing are correct.

Table 5. Current CBR Results at 100% Mod. AASHTO

Sample	Bitumen Content (%)	Cement Content (%)	Compaction Moisture Content (%)	Density (kg/m ³)		Swell	CBR	% of Mod. AASHTO Compaction*
				Including Bitumen	Excluding Bitumen			
1	1.8	0	10.6	2020	1983	0.02	26.6	97.6
2	1.8	0	10.6	2034	1997	0.06	27.0	98.4
3	1.8	0	10.6	2020	1983	0.00	36.0	97.7
4	0	0	12.8		1976	0.02	6.7	97.3
5	0	0	12.8		1974	0.00	10.9	97.2
6	0	0	12.8		1986	0.00	11.3	97.8

* 100% Mod. AASHTO compaction = 2030kg/m³

5.2. Unconfined Compressive Strength (UCS)

Tests were performed on the material treated with 0 and 1 per cent cement and different percentages of foamed bitumen, as shown in Table 1. For completeness and to be able to make a comparison, the results reported by Long and Theyse¹ from the tests on the materials with 1 and 2 per cent cement are shown with the latest results. The results are shown in Figure 6 and Table 6. All the specimens were cured in a sealed container for 28 days. Test preparation and testing was done according to TMH 1.

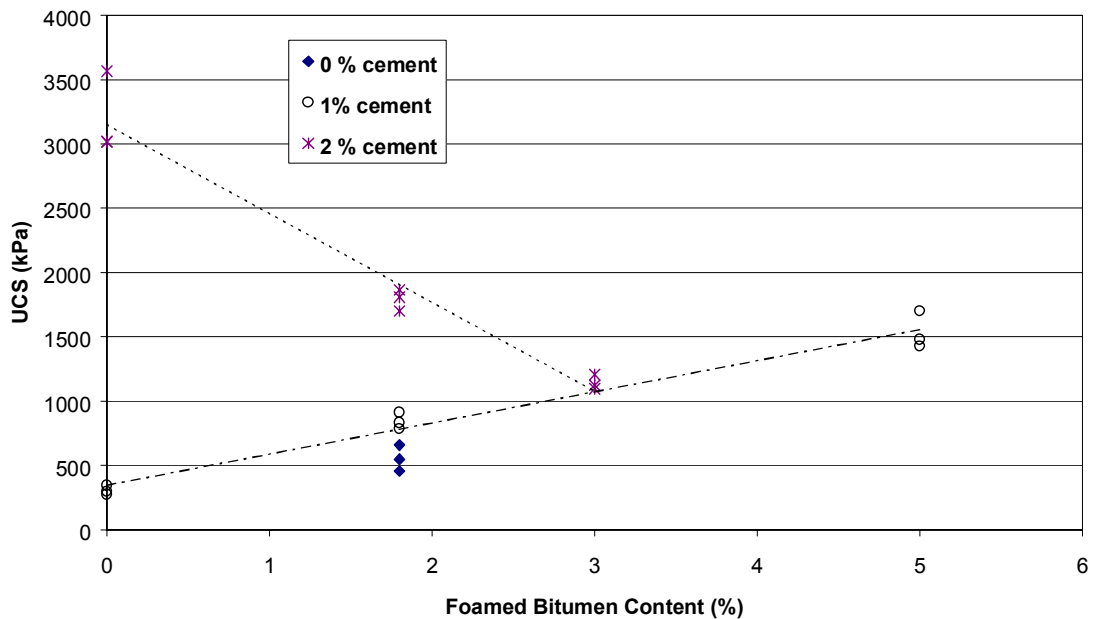


Figure 6. Unconfined Compressive Strength Versus Foamed Bitumen Content

Table 6. UCS Results for Foamed Bitumen Material

Status	Sample	Bitumen Content (%)	Cement Content (%)	Density (kg/m ³)	Moisture Content (%)	UCS kPa
Previous tests	CTB1	0	2	2039	9.5	3564
	CTB2	0	2	1986	10.5	3015
	CTB3	0	2	1990	9.9	3015
	FTB1	1.8	2	1978	11.4	1809
	FTB2	1.8	2	1985	10.4	1864
	FTB3	1.8	2	1961	10.9	1699
	FTB7	3	2	1878	10.9	1124
	FTB8	3	2	1886	10.3	1206
	FTB9	3	2	1869	10.6	1096
Current Tests	BFTF1	3	1	1953	10.6	877
	BFTF2	3	1	1952	10.6	822
	BFTF3	3	1	1957	10.6	905
	CFTB1	1.8	0	2002	10.6	548
	CFTB2	1.8	0	1993	10.6	455
	CFTB3	1.8	0	2002	10.6	658
	CFTB4	1.8	1	1992	9.9	910
	CFTB5	1.8	1	2009	9.9	784
	CFTB6	1.8	1	2004	9.9	833
	CFTB7	5	1	1916	10.7	1700
	CFTB8	5	1	1933	10.7	1480
	CFTB9	5	1	1925	10.7	1425
CFTB10	0	1	1942	12.8	296	
CFTB11	0	1	1950	12.8	345	
CFTB12	0	1	1942	12.8	274	

The mix with 2 per cent cement shows that an increase in the foamed bitumen content results in a lower UCS value. A possible explanation is that during mixing and compaction the foamed bitumen encapsulates the cement so that the cement cannot bond with the material resulting in a lower stiffness.

On the contrary, the mix with 1 per cent cement shows that increasing the percentage of bitumen results in a higher UCS value. Considering the result of the test without cement, it would appear that the cement does not add much strength to the material. The higher UCS value with higher bitumen contents and 1 per cent cement is influenced more by the foamed bitumen than by the cement.

The reason for the cement adding only little strength to the material is not completely clear. It is possible that the foamed bitumen encapsulates the cement, and the cement cannot gain strength. It is also possible that the 1 per cent cement has not satisfied the initial consumption of cement (ICC) of the material, and only above the ICC will the cement strengthen the material. This may explain the higher strength, and the contradictory results of the mixes with 2 per cent cement. This needs further investigation. It was not necessary to increase the amount of fines by adding cement as the material already has 12.6 per cent of fine material (smaller than 0.075 mm).

It is shown in Figure 6 that the slope of the mix with 2 per cent cement is rather steep. By adding bitumen there is a large reduction in the UCS value. However the slope of the trend line in the situation with 1 per cent cement is flatter. The bitumen adds strength to the material, but it is not as much as the strength reduction in the 2 per cent cement situation.

It is possible that the UCS value would increase for materials with 2 per cent cement and foamed bitumen contents greater than 3 per cent bitumen. In this case the foamed bitumen would have encapsulated much of the cement so there is no longer good bonding of the cement in the mix. If so, the strength of the mix should show similar behaviour as is the case with 1 per cent cement. Further research is necessary to confirm this hypothesis.

With the large percentage of fines in the material, one would not expect such a dramatic reduction of strength (2 per cent cement), because there are enough fines for the bitumen to encapsulate. It is possible that the bitumen is prone to bonding with the cement, thus interfering with the cement and interfering with the formation of cementitious bonds.

5.3. Indirect Tensile Strength Test (ITS)

The indirect tensile strength (ITS) test was performed on the same mixes as the unconfined compressive strength tests. The results are given in Table 7 and Figure 7. For these mixes, the curing time was 28 days of normal curing. Some of the previous test results had 28 days curing, whereas others had rapid curing. The specimens with rapid curing were used for a mix optimisation study. For the data and a discussion on these samples refer to Long and Theyse¹.

Table 7. ITS Test Results

Status	Sample	Bitumen Content (%)	Cement Content (%)	Density (kg/m ³)	MC at Compaction (%)	ITS kPa	Curing
Previous tests	CTB4	0	2	2017	10.0	339.0	28 days
	CTB5	0	2	2002	10.9	493.0	28 days
	CTB6	0	2	2005	8.5	395.0	28 days
	FTB4	1.8	2	1981	10.9	230.0	28 days
	FTB5	1.8	2	1970	10.9	230.0	28 days
	FTB6	1.8	2	1976	10.9	230.0	28 days
	FTB10	3	2	1888	10.6	329.0	28 days
	FTB11	3	2	1871	10.6	329.0	28 days
	FTB12	3	2	1876	10.6	329.0	28 days
Current Tests	CFTB1	1.8	0	2009	10.0	69.1	28 days
	CFTB2	1.8	0	1977	10.0	59.2	28 days
	CFTB3	1.8	0	2020	10.0	51.7	28 days
	CFTB4	1.8	1	2018	10.0	75.6	28 days
	CFTB5	1.8	1	2010	10.0	75.6	28 days
	CFTB6	1.8	1	2010	10.0	98.7	28 days
	CFTB7	5	1	1913	6.8	213.8	28 days
	CFTB8	5	1	1908	6.8	226.9	28 days
	CFTB9	5	1	1905	6.8	200.6	28 days
	CFTB10	0	1	1945	11.8	32.9	28 days
	CFTB11	0	1	1937	11.8	32.9	28 days
	CFTB12	0	1	1945	11.8	32.9	28 days

As shown in Figure 7, the previous tests with 2 per cent cement and no foamed bitumen have the highest ITS value. When adding bitumen to the mix, the ITS value initially decreases and afterwards it increases. As in the case of the UCS results, possible explanation for this phenomenon can be that the foamed bitumen encapsulates some of the cement, which results in less cementitious bonding and a lower ITS. By adding more bitumen, the material becomes more flexible, but also seems to add increased tensile strength, would could explain the higher ITS. However, this trend is not very distinct and is possibly caused by variance in test results.

The trend for the situation with the 1 per cent and 0 per cent cement is similar to that of the UCS results. The material gives higher ITS values with increasing foamed bitumen content. And the difference between the tests on the mixes with the 1 per cent cement and without the cement is small. Again, for this material it looks as if the addition of cement does not influence the ITS tensile strength much, at these lower cement contents.

The bitumen may encapsulate the majority of the cement, and the cement added may not be satisfying the ICC and therefore not contributing to the strength of the material.

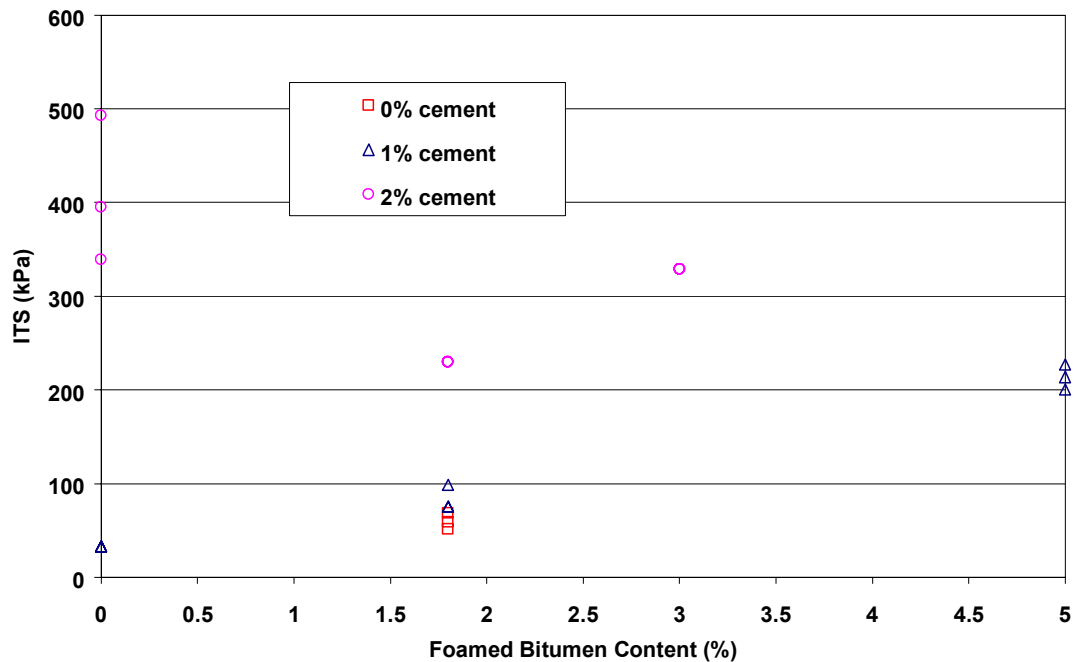


Figure 7. ITS Results with 28 Days of Curing

The ITS test results from the mix optimisation study are shown in Figure 8 with the latest data. The samples used in the test were cured at ambient temperature until an equilibrium moisture content had been reached. After that, the samples were sealed and cured in an oven at 40°C for 72 hours. The curing is according to guidelines published by Jenkins².

For the samples with 1 per cent cement, Figure 8 shows that the samples with rapid curing have higher ITS results than the samples cured at ambient temperature for 28 days. It is not known why there is such a large difference. A possible explanation is that the chemistry of the cementitious bonding is different between the two methods of curing, with rapid curing giving higher ITS results. The temperature during mixing and compaction may also have an influence on the results, especially for the bitumen distribution. The difference between the slopes of the two trend lines can be caused by variability in the test results.

The trend in the data from mixes with 2 per cent cement and 28 days curing is unusual. With the limited amount of data, it is not possible to identify the cause of this unusual trend.

At the lower cement content, the trend is that the bitumen is the dominant factor for the strength of the material and the cement has little influence.

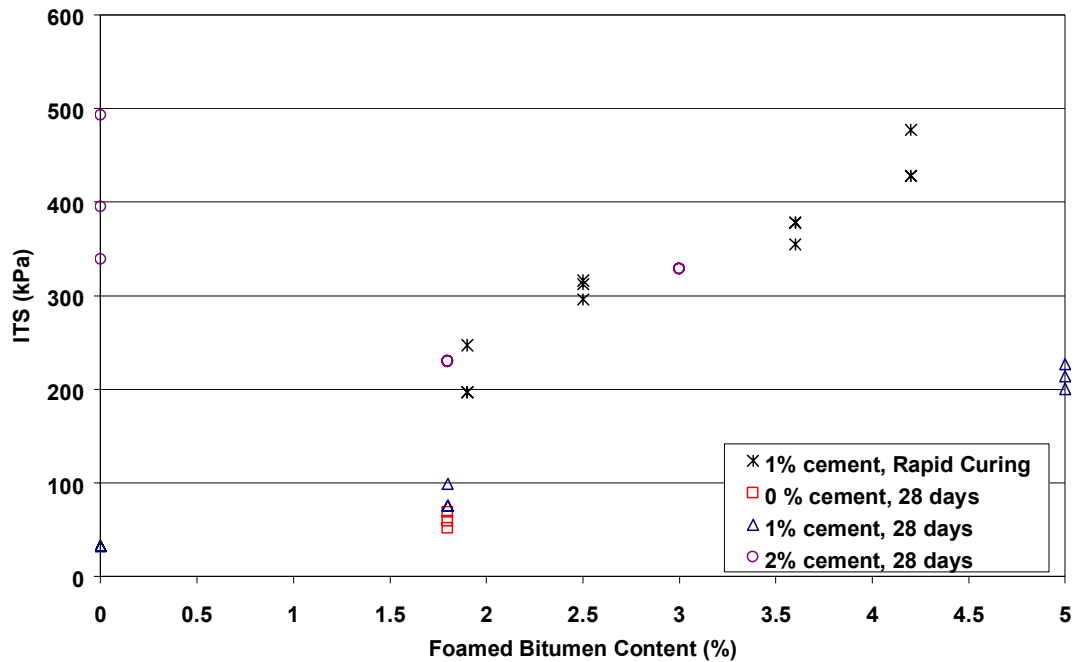


Figure 8. ITS Test Results, 28 Days of Curing and Rapid Curing

5.4. Flexural Beam Test

The flexural beam test was performed on the different mixes. The test is described in Theyse³. The test setup is shown in Figure 9 with the location of a linear variable displacement transducer (LVDT) indicated. The machine imposes a constant displacement of one mm per minute.

In this test, the stress-at-break, strain-at-break, dissipated energy and stiffness of the material can be determined. The strain-at-break is the strain corresponding to the maximum stress. The initial slope of the stress-strain curve is the initial stiffness of the beam. The stiffness-at-break is calculated by dividing the maximum stress by the strain at break.

For comparison reasons it is important that all the different specimens are tested under the same conditions. The density is constant for the beams (2030 kg/m³, except the beams with 5 per cent foamed bitumen), and a study on the previous tested beams showed that the saturation at the time of testing was very constant, more constant than the moisture content. It was decided to test the beams for this work at the average saturation level determined by the previous work.

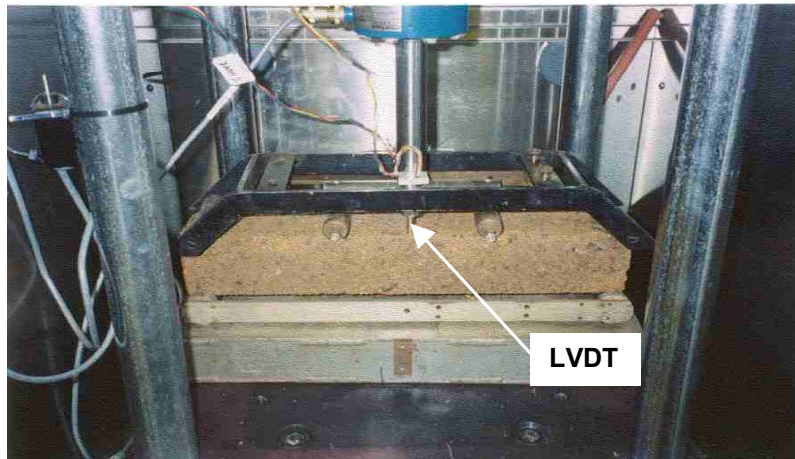


Figure 9. Test Setup, Flexural Beam Test

The average saturation including both water and bitumen was 89.8 per cent with a standard deviation of 1.1 per cent at the time of testing. The saturation including only water was 75.4 per cent. At this saturation level, the target moisture content for testing was calculated. The materials were all mixed and compacted at a higher moisture content than was necessary for the testing, and drying out of the specimens after curing was needed to achieve the target moisture content.

Appendix B gives the flexural beam test results, which are summarized in Table 8.

The flexural beam test is designed for cemented and asphaltic materials. However the work described in this report shows that some bitumen or cement is necessary in the mix to give it sufficient initial strength. The specimens with only 1.8 per cent foamed bitumen and those with only 1 per cent cement did not have sufficient initial strength. During the installation of the specimens in the test-setup some beams broke because of their dead weight or because of the weight of the bracket (2 kg) that holds the two LVDTs in place, see Figure 9. The front LVDT is shown, the second one is at the same point on the opposite side of the beam.

As already mentioned there were problems with the mixing procedure. One of the beams with 5 per cent foamed bitumen and 1 per cent cement broke while being installed in the test setup (by dead weight only). No bitumen was visible in the cross-section of the crack. This is indicative of poor distribution of the bitumen through the mix.

Table 8. Flexural Beam Test Results

	Sample	Foamed Bitumen Content (%)	Cement Content (%)	Moisture Content at testing (%)	Dry Density (kg/cub m)	Strain-at-break (microstrain)	Stress-at-break (kPa)	Initial Stiffness (MPa)	Stiffness-at-Break (MPa)			
Previous tests	Cement Treated Ferricrete	CTB 1		2	12.2	2030	165	419	7600	2539		
		CTB 2		2	11.9	2030	179	320	5500	1788		
		CTB 3		2	11.2	2030	223	231	3230	1036		
		CTB 4		2	12.4	2030	179	192	3300	1073		
		CTB 5		2	11.2	2030	152	356	7353	2342		
		CTB 6		2	11.3	2030	148	121	2540	818		
	Foam Treated Ferricrete	FTB 1	1.8	2	9.8	2030	111	230	5975	2085		
		FTB 2	1.8	2	10.1	2030	236	307	3843	1301		
		FTB 3	1.8	2	9.7	2030	162	20	352	123		
		FTB 4	1.8	2	9.0	2030	55	22	1638	398		
		FTB 5	1.8	2	9.7	2030	179	294	4950	1644		
		FTB 7	3.0	2	10.3	2030	335	382	3420	1139		
		FTB 8	3.0	2	10.2	2030	344	270	2483	784		
		FTB 9	3.0	2	9.9	2030	426	192	1350	451		
		FTB 10	3.0	2	9.3	2030	299	310	3019	1037		
		FTB 11	3.0	2	9.3	2030	307	342	3229	1115		
		FTB 12	3.0	2	9.1	2030	404	325	2288	804		
		BFTFB1	3.0	1	8.7	2030	600	140	650	233		
		BFTFB2	3.0	1	7.8	2030	557	133	660	239		
		BFTFB4	3.0	1	8.1	2030	527	116	605	220		
		BFTFB5	3.0	1	9.7	2030	396	111	765	280		
		BFTFB6	3.0	1	8.9	2030	369	126	946	341		
		Current tests	Foam Treated Ferricrete	BM1-4	1.8	0	9.6	2012	broke before testing			
				BM1-7	1.8	0	9.7	2012	broke before testing			
BM1-15	1.8			0	10.0	2005	broke before testing					
BM1-16	1.8			0	9.2	2006	broke before testing					
BM2-5	1.8			1	9.6	2046	251	76	820	303		
BM2-8	1.8			1	8.3	2049	238	74	825	303		
BM2-12	1.8			1	9.6	2042	230	62	815	289		
BM2-17	1.8			1	9.2	2047	unreliable results					
BM3-6	5.0			1	6.6	1851	broke before testing					
BM3-10	5.0			1	6.6	1864	848	177	407	143		
BM3-13	5.0			1	6.0	1889	764	107	396	140		
BM3-14	5.0			1	6.6	1891	898	193	595	215		
BM6-6				1	11.5	2015	broke before testing					
BM6-13				1	12.3	2028	broke before testing					
BM6-16		1	12.5	2019	broke before testing							
BM6-26		1	12.2	2019	broke before testing							

5.4.1 Flexibility (Strain-at-Break)

The strain and stress-at-break of the specimens are shown in Figure 10 and Figure 11. Higher foamed bitumen contents (greater than 1.8 per cent) show higher strain-at-break values. The material therefore becomes more flexible as the foamed bitumen content increases. For the material with no bitumen and the material with 1.8 per cent bitumen there is not much of a difference between the strain-at-break results. This indicates that a foamed bitumen content greater than 1.8 per cent is necessary to increase the flexibility of this material.

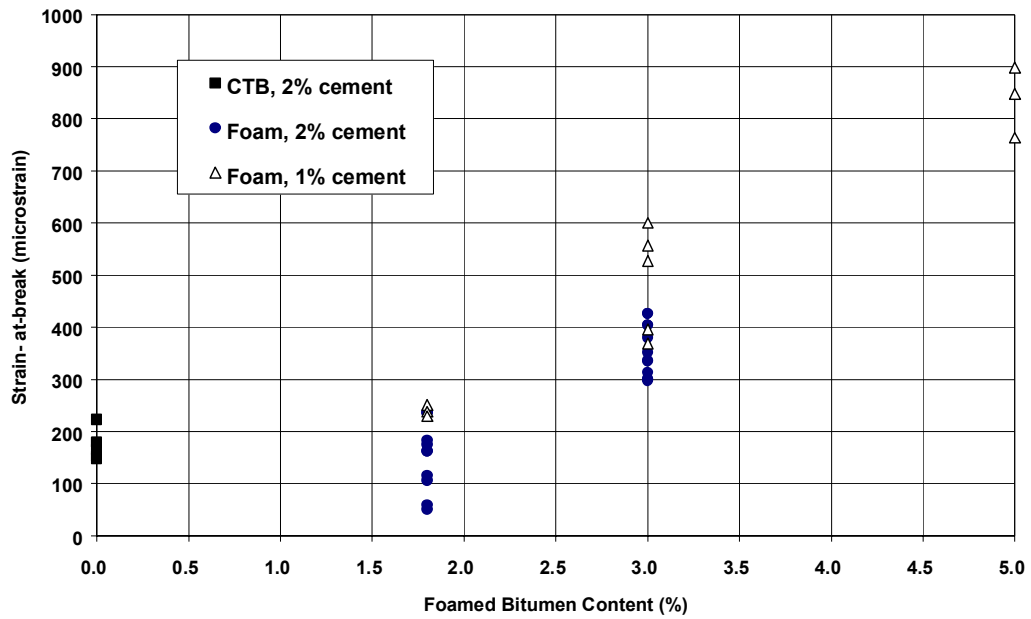


Figure 10. Strain-at-break from Flexural Beam Test

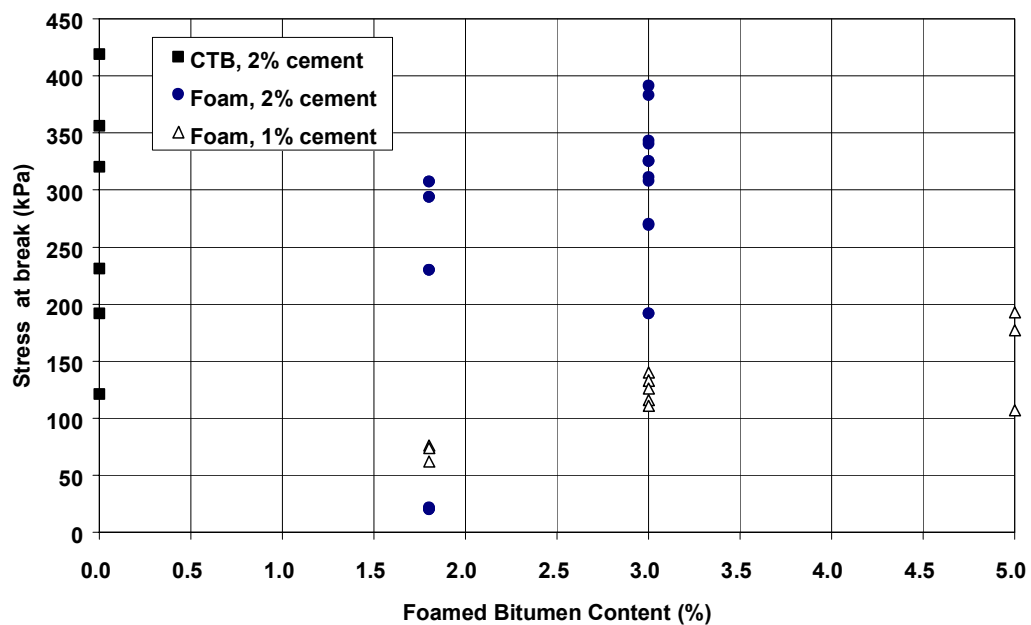


Figure 11. Stress-at-break from Flexural Beam Test

The lower cement contents show slightly higher strain-at-break results, although these may not be significantly higher. A reason may be that the material with the higher cement content is more brittle. The stiffness is higher, but the flexibility is lower.

In Table 9 the effective fatigue life is calculated from the average strain-at-break results. The effective fatigue life was calculated using the expression developed by Long⁴ assuming a tensile strain of 100 microns. An increase in the strain-at-break increases the effective fatigue life, as expected.

Table 9. Effective Fatigue Life from Strain-at-break

Binder Content	Cement Content	Average Stress-at-break	Average Strain-at-break	Effective Fatigue Life
1.8	1	71	240	2.11×10^6
	2	174	172*	1.61×10^6
3.0	1	125	490	2.98×10^6
	2	303	352	2.62×10^6
5.0	1	159	837	3.42×10^6

* Specimen FTB4 excluded from average calculation, data unreasonably low.

5.4.2 Tensile Strength (Stress-at-Break)

The stress-at-break shows more variability in the results at the different cement contents. The cement plays an important role. Although there is scatter in the results the specimens with 2 per cent cement show a higher stress-at-break than the specimens with 1 per cent cement. Increasing the bitumen content results in an increase in the stress-at-break. In agreement with the strain-at-break, the addition of 1.8 per cent bitumen does not increase the stress-at-break. It seems as if a minimum amount of bitumen is necessary in the mix before an improvement in the flexibility is noticeable.

When considering both the stress-at-break and the strain-at-break, it appears as if the cement makes the material more brittle. It slightly reduces the strain-at-break but increases the stress-at-break. The results in Appendix B show that the initial slope of the stress-strain curve at the higher cement content is steeper and reaches a higher stress-at-break value than the specimens with the lower cement content.

In Table 10, the tensile strength of the materials determined from the flexural beam test are compared with those determined from the ITS test for the mixes for which data are available for both tests. The data follow the same trends.

Table 10. Comparison of Tensile Strengths from ITS and Flexural Beam Tests

Bitumen Content	Cement Content	Tensile Strength (kPa)	
		ITS	Beam
0	2	395 - 493	121 - 419
1.8	1	76 - 99	62 - 76
	2	230	20 - 307
3.0	2	329	192 - 382
5.0	1	200 - 227	107 - 193

5.4.3 Dissipated Energy

The areas under the stress-strain curves are shown in Figure 12 plotted against the foam bitumen content. This area gives an indication of the dissipated energy during testing. The higher the dissipated energy, the better a material can accommodate loading. The dissipated energy results are shown in Figure 12. Again, some scatter in the results is visible. However, in general, the specimens with the higher cement content (2 per cent) show higher results for the dissipated energy. There is also a trend that with increasing foamed bitumen content the dissipated energy increases. However, relatively high binder contents are necessary to see the benefit of adding foamed bitumen.

In accordance with the strain-at-break results, there does not seem to be much of a difference in results of dissipated energy by adding 1.8 per cent foamed bitumen to the material containing 2 per cent cement. Adding 1 per cent cement gives a lower result. And, as mentioned before, the specimens containing only cement or only bitumen broke before testing.

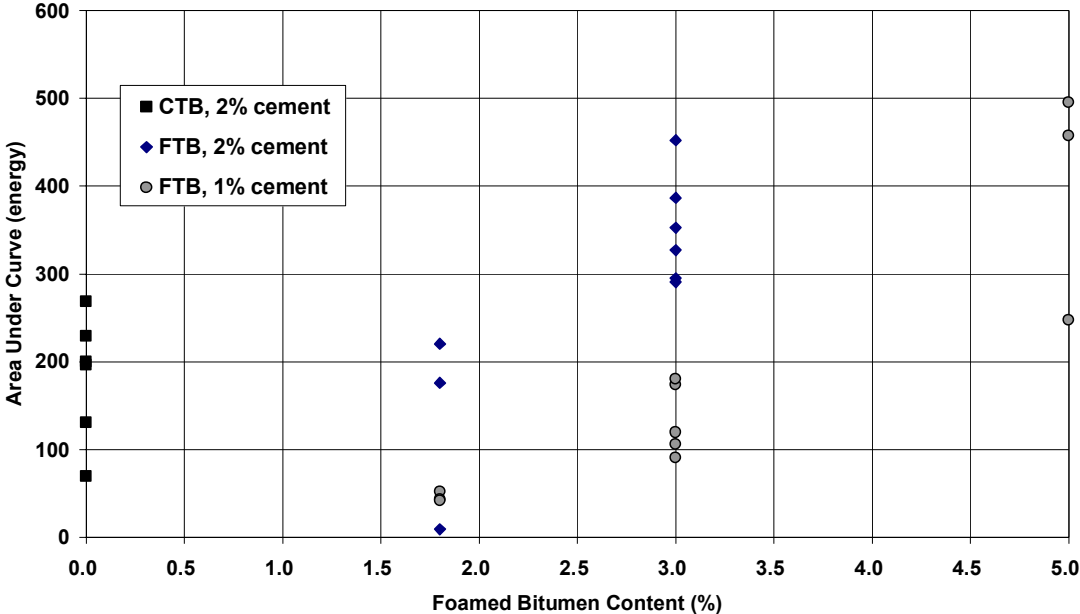


Figure 12. Dissipated Energy at Different Foamed Bitumen Contents

6. CONCLUSIONS AND RECOMMENDATIONS

In South Africa the use of cold treatment of materials in combination with Deep In Situ Recycling is becoming more popular. The three binders used for the cold treatment are cement, foamed bitumen and bituminous emulsion. To understand the behaviour of the material it is beneficial to perform both HVS- and laboratory testing. HVS tests have been performed on road P243/1 and laboratory tests were performed in the laboratory at Transportek, CSIR.

In this report the results from several widely known laboratory test are discussed, namely the UCS, ITS, flexural beam fatigue and CBR test. These tests are complementary to earlier tests performed on the same aggregate¹.

A material that is representative of the material mixed in the field had to be tested in the laboratory, as the ultimate goal is to relate the results to the field performance and to implement the test results as a practical guideline.

During the mixing procedure and the microscopic work there was a distinct difference visible between the laboratory mixes and the field mix both in appearance of the bitumen in the material and the distribution of the bitumen in the mix. The quality of the material mixed in the field was better in both aspects. It is possible that the laboratory mixes can be considered as a material different from the DISR material, with different behaviour and properties. For this reason, it is necessary to improve the laboratory mixing methods to better represent the field mixing. The mixing procedure in the laboratory can be optimised by:

- Mixing at a higher aggregate temperature (20 to 25 °C) than the approximately 16 °C used in this work;
- Using a different mixer, which uses a different mixing technique and can give more energy to the mix in a shorter time, e.g. a Hobart mixer or Pugmill mixer, and
- Minimising the distance between the nozzle of the laboratory foaming machine and the aggregate.

For both the UCS and the ITS test results, there is a difference in the trends in the strength data for the material with 2 per cent cement and the material with 1 per cent cement. The material with 2 per cent cement shows decreasing strength with increasing foamed bitumen contents. The bitumen encapsulates the fine material, which results in lower values for the UCS and ITS. The material with 1 per cent cement shows increasing strength with increasing foamed bitumen contents, and the difference in strength of the

material without cement is small. This suggests that 1 per cent cement does not add much strength to the material and the increase is mainly caused by the foamed bitumen, or that the bitumen encapsulates the cement preventing it from forming a bond. It is also possible that, at the lower cement contents, the initial consumption of cement (ICC) of the aggregate has not been satisfied, and, only at higher cement contents will the additional cement contribute to the strength of the material.

For the flexural beam test, the bitumen content has the largest influence on the strain-at-break. Higher cement contents give slightly lower strain-at-break results, but this is not significant. The stress-at-break is mainly influenced by the cement content. Higher cement contents result in a higher stress-at-break values. The foamed bitumen content does not significantly affect the results. The area under the stress-strain graph is the energy dissipated during the test. It is concluded that the cement has a larger influence on the results than the foamed bitumen, and the material with the highest percentage of cement dissipates the highest energy. There is not a significant difference in energy dissipation between the beams with 5 per cent and 3 per cent foamed bitumen and 1 per cent cement.

The CBR increases when foamed bitumen is added to the untreated material.

All the testing has been done on only one material type with one gradation. For improved knowledge of the advantages and disadvantages of treating material with foamed bitumen and cement, different types of aggregate should be tested. Although the results are only valid for one material type, the combinations of bituminous binder and cement that were tested, indicated a complex interaction between these two stabilizing agents that influences the properties of the resulting mix. This has implications for the mix design procedure of these materials. A combination of 3 per cent bituminous binder and 2 per cent cement gave good flexibility with a high strength for the material that was tested.

The tensile strength determined from the ITS and flexural beam tests showed a good correlation and the same trends were noticed in the data from the two devices. In terms of flexural strength, the ITS test presents a practical testing alternative to the more complicated flexural beam test, but unfortunately there is not yet a substitute for the flexural beam test as far as testing the flexibility of the material is concerned.

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2. JENKINS K.J., **Mix design considerations for cold and half-warm bituminous mixes with emphasis on foamed bitumen**, Ph.D. Thesis, Department of Civil Engineering, University of Stellenbosch, South Africa, 2000
3. THEYSE, H.L. **Laboratory design models for materials suited to labour-intensive construction**, Transportek, CSIR, Contract report CR-99/38, 1999.
4. LONG, F.M., **The development of structural design models for foamed bitumen treated layers**, Transportek,CSIR, Contract report CR-20017, 2001.

APPENDIX A: Microscopic Photos

This appendix contains a selection of the microscopic photos of the different material combinations.

As explained in the report, the visible difference in bitumen content was more dependent on the particular sample than on the actual bitumen content.



Laboratory mix: 1.8 % foamed bitumen, 2% cement. Possible forming of cement bonding (light colour)



Laboratory mix: 1.8% foamed bitumen, 2% cement. Small film of bitumen (thicker than on HVS material)



Laboratory mix: 1.8% foamed bitumen, 1% cement. Small 'balls' of bitumen.



Laboratory mix: 3% bitumen, 1% cement. Possibly an piece of the old surface seal.



Laboratory mix: 3% foamed bitumen, 1% cement. Bitumen mixed with aggregate



Laboratory mix: 3% foamed bitumen, 1% cement. Channel of bitumen in the mix



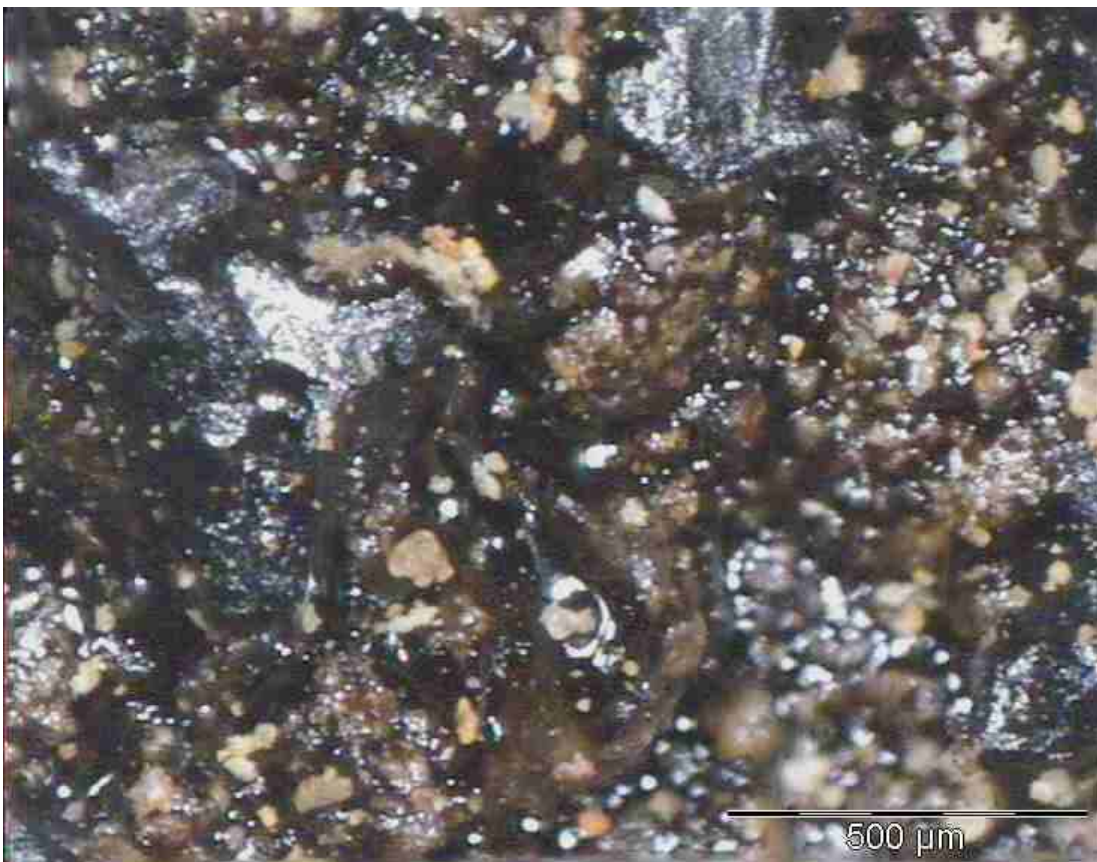
Laboratory mix: 5% foamed bitumen, 1% cement. Small 'balls' of bitumen.



HVS mix. 1.8% foamed bitumen, 2% cement. spray of bitumen on the aggregate

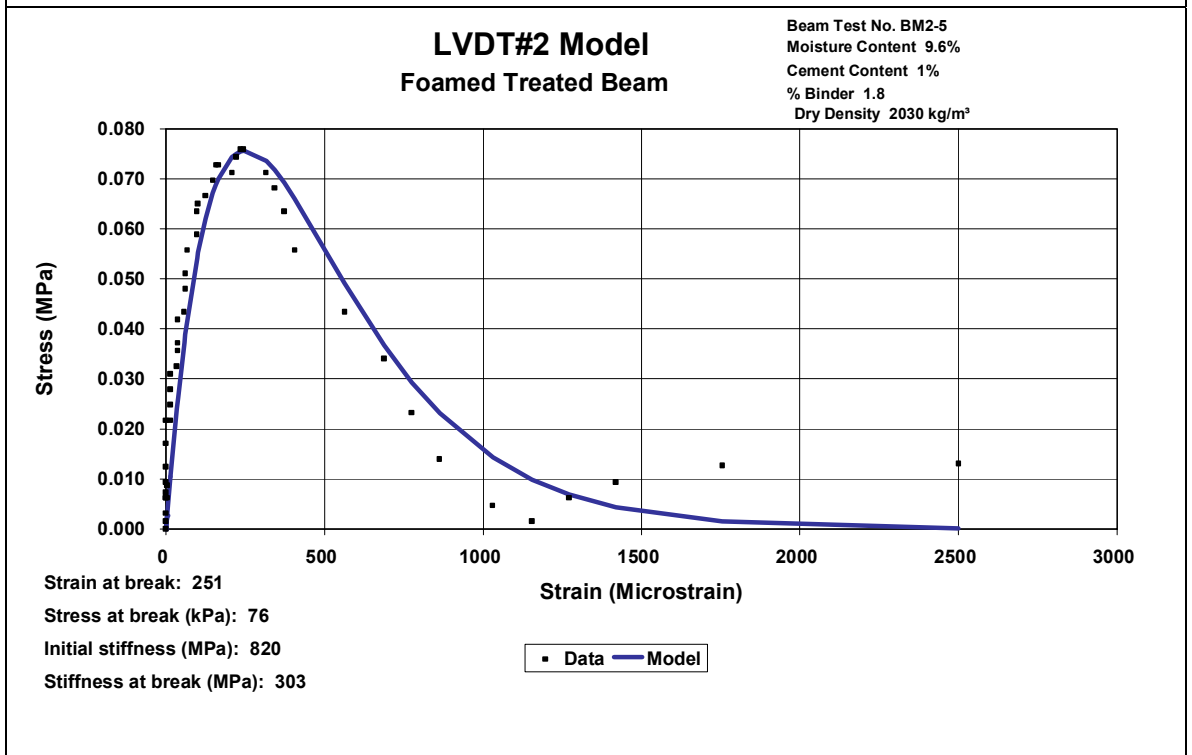
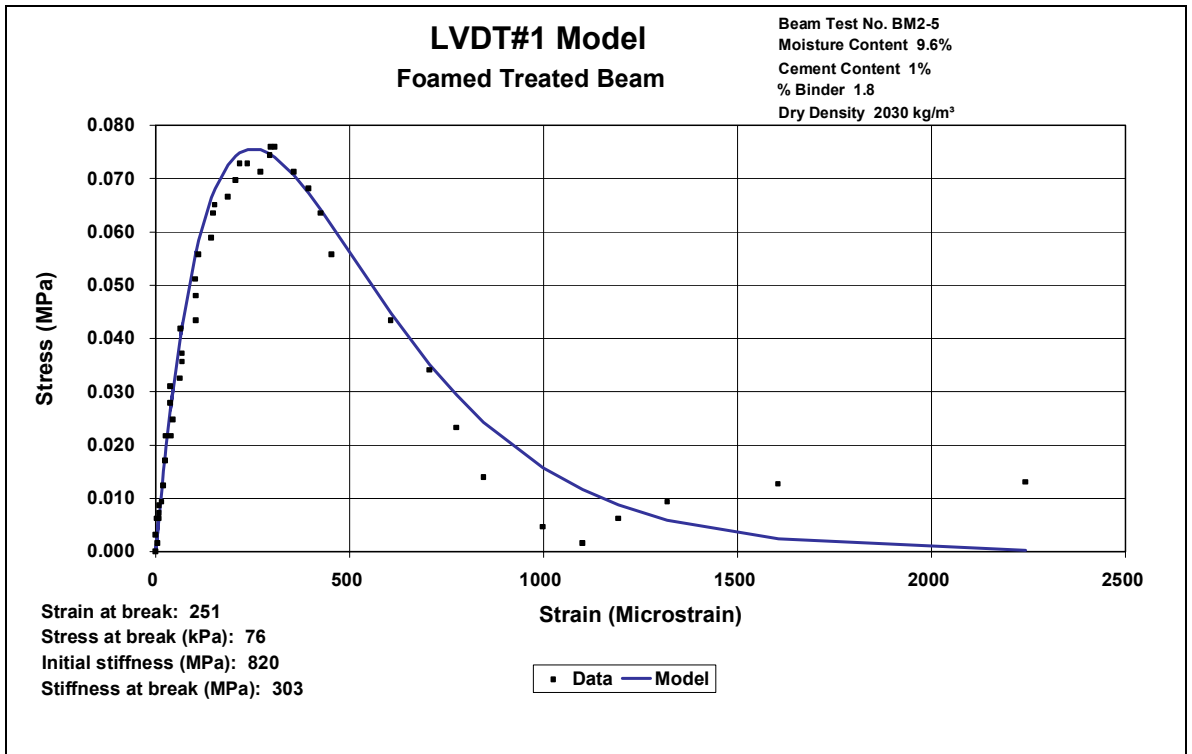


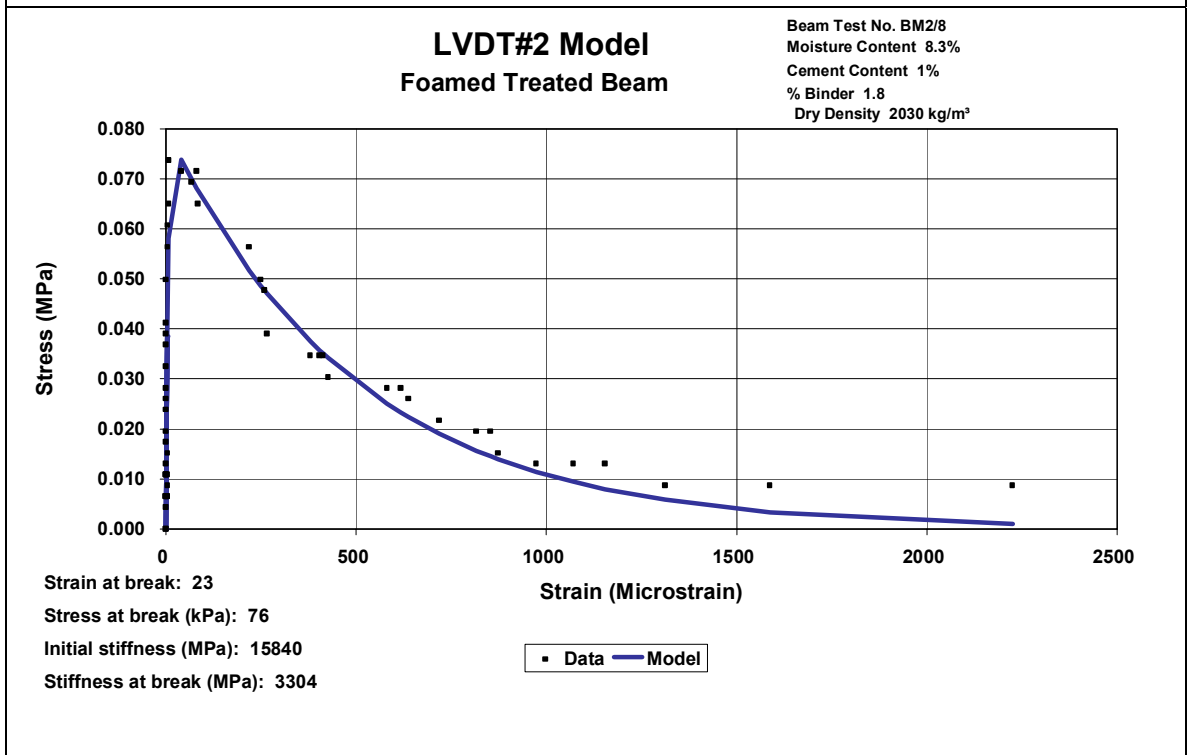
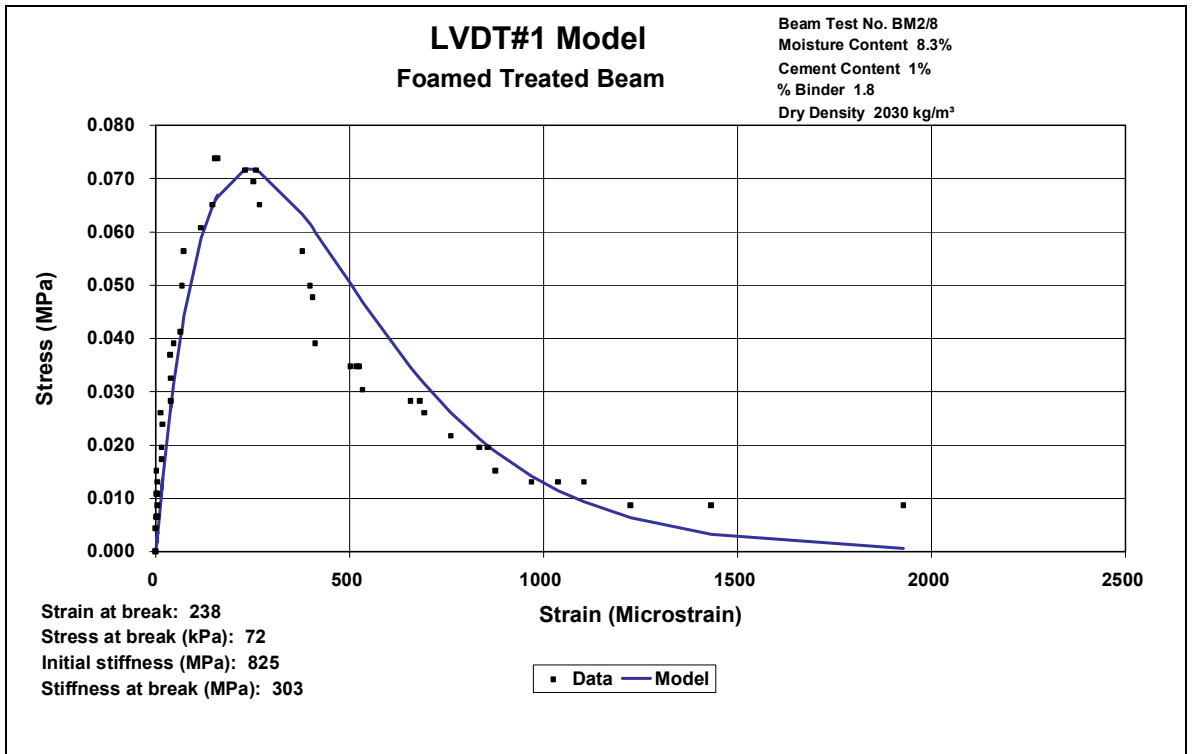
HVS mix. 1.8% foamed bitumen, 2% cement

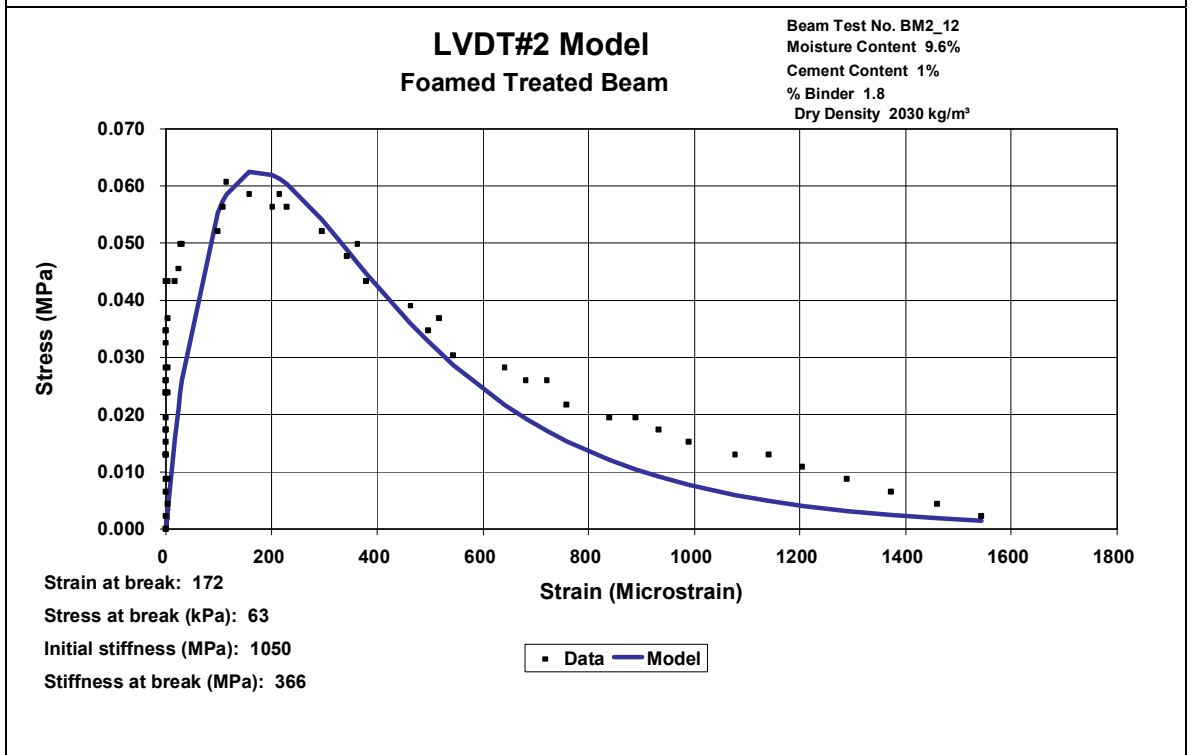
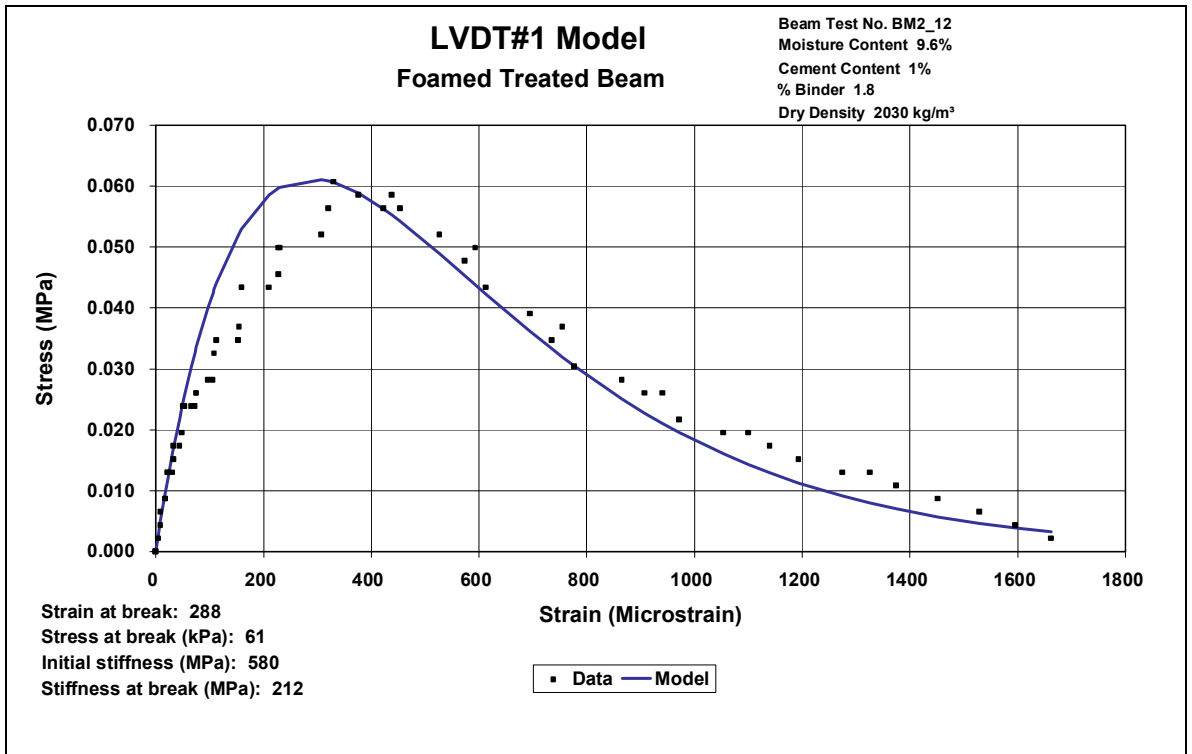


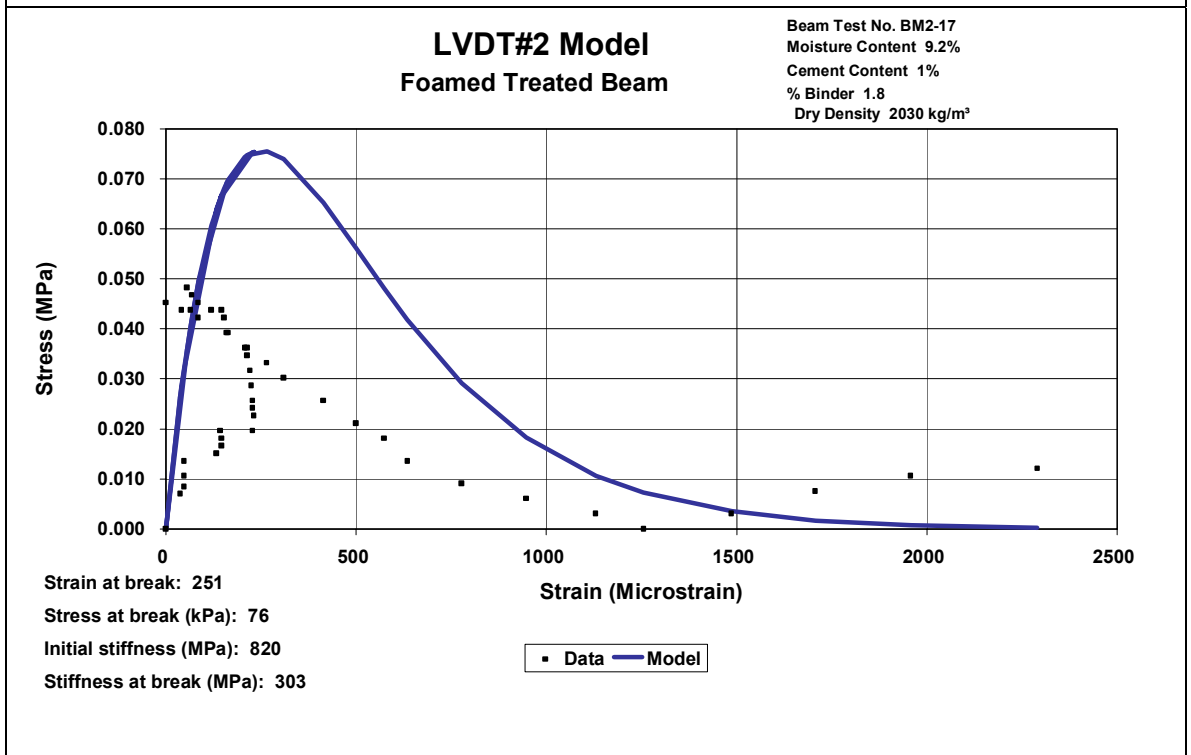
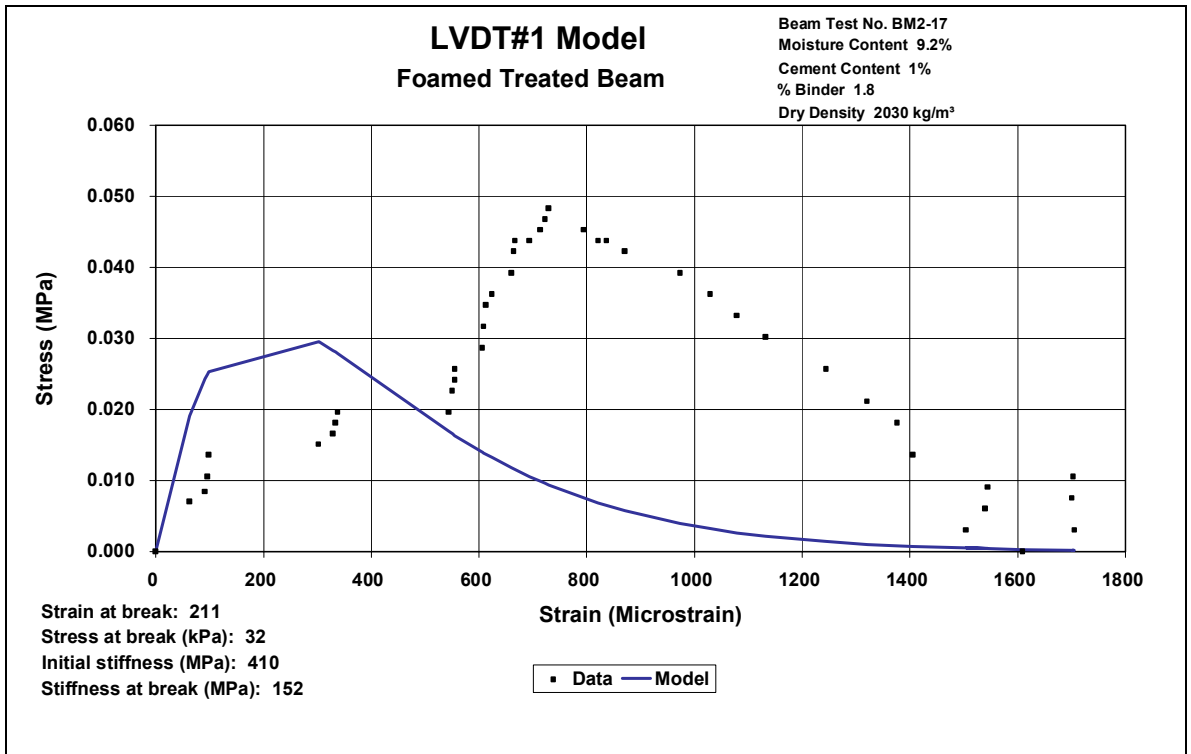
HVS mix. 1.8% foamed bitumen, 2% cement. Mix of bitumen and aggregate

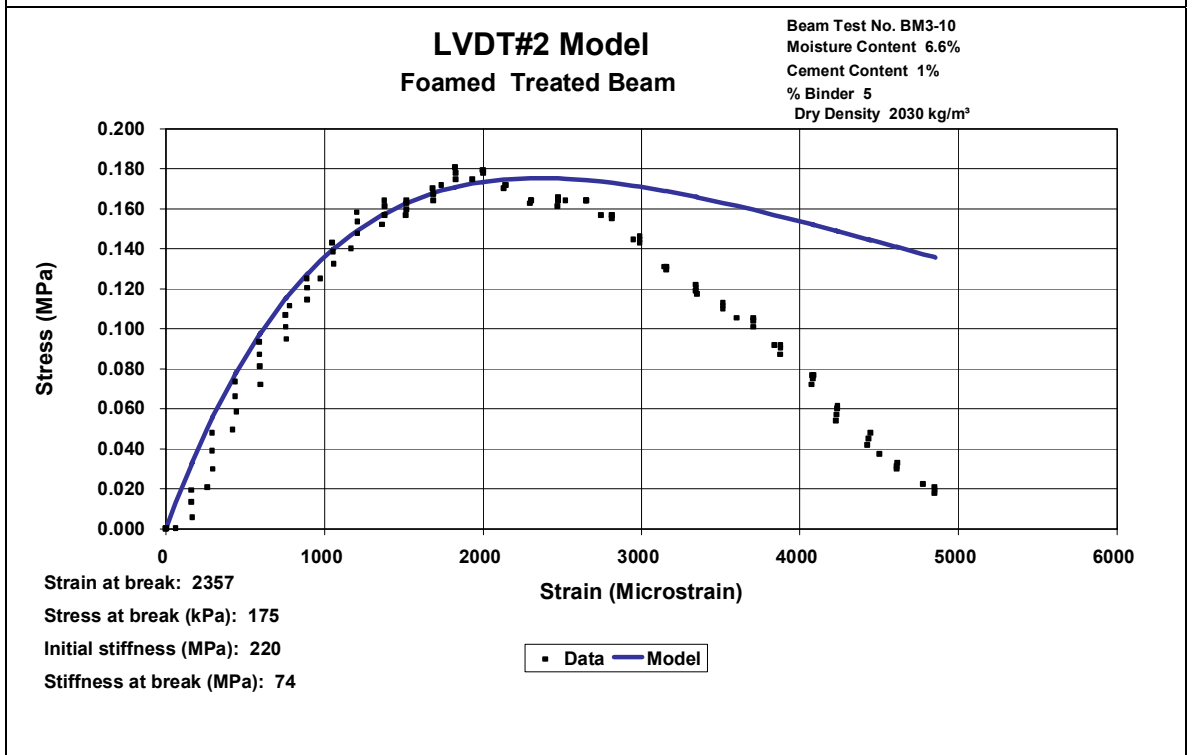
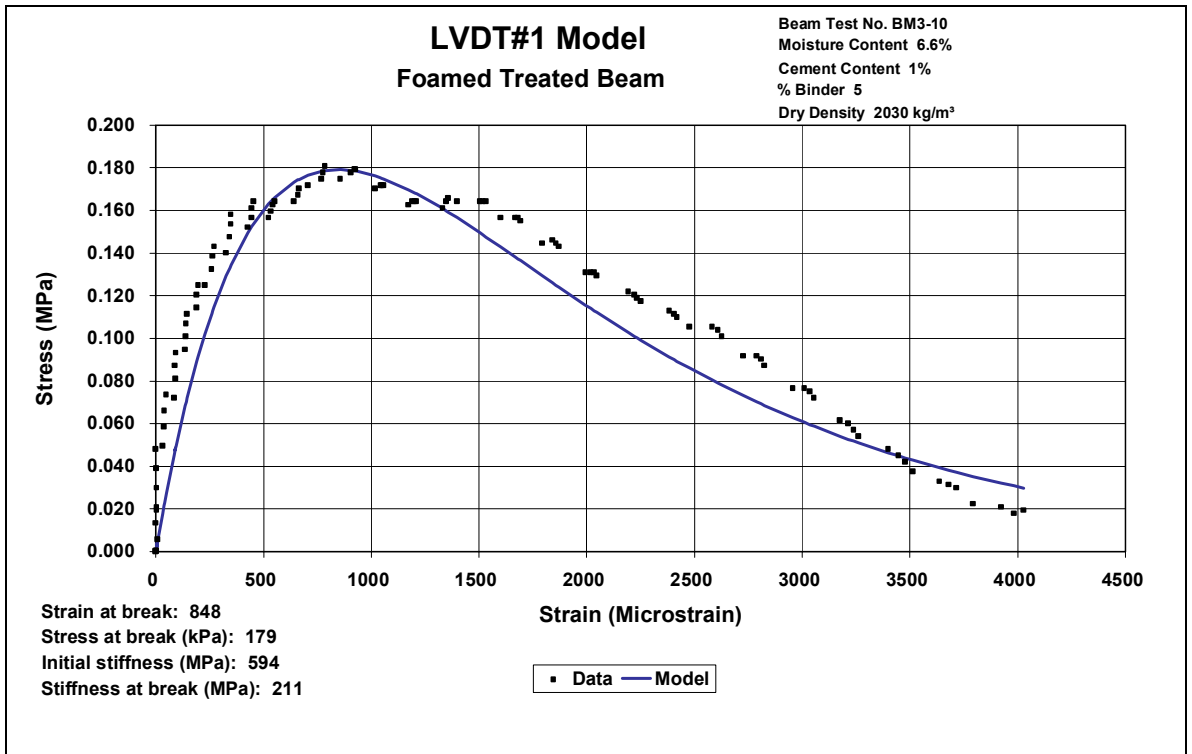
APPENDIX B: Flexural Beam Test Results

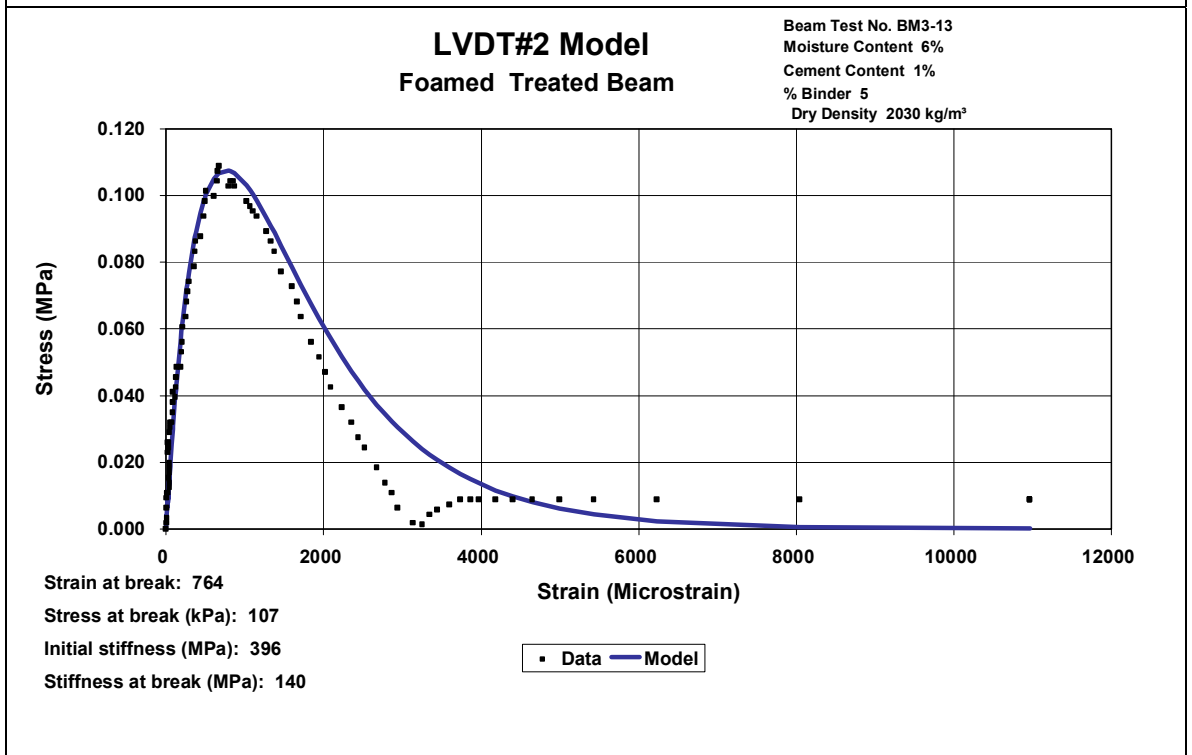
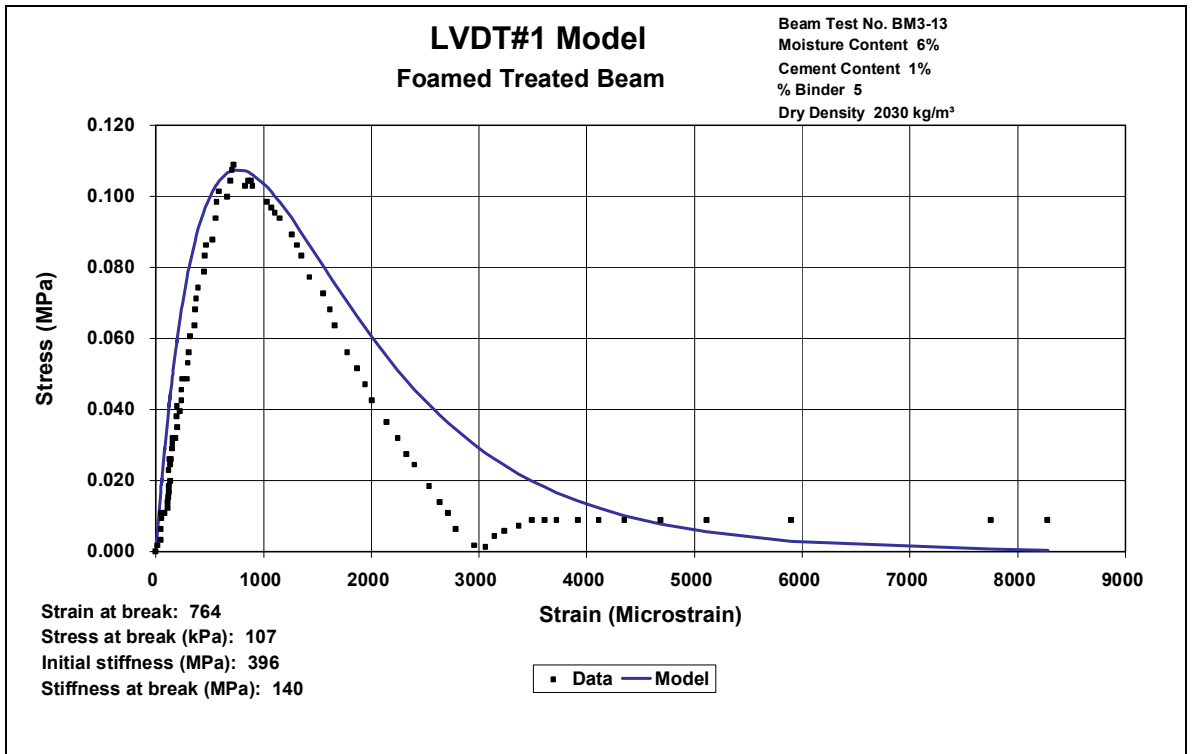


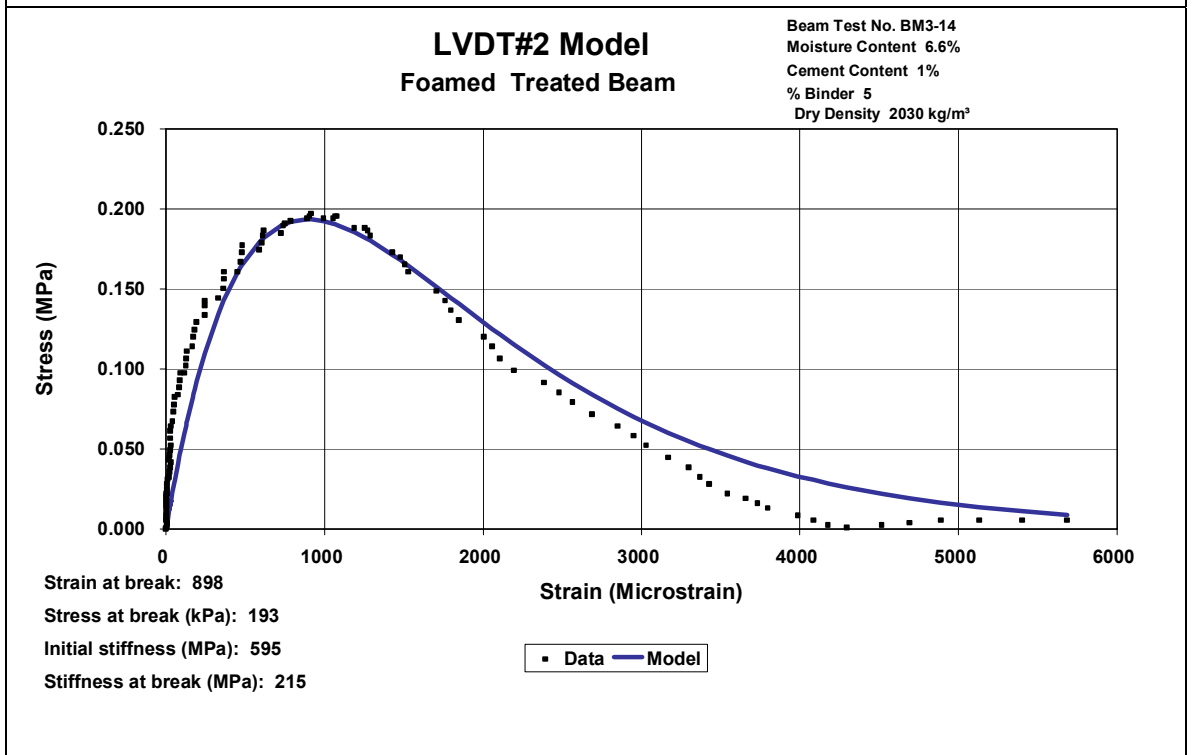
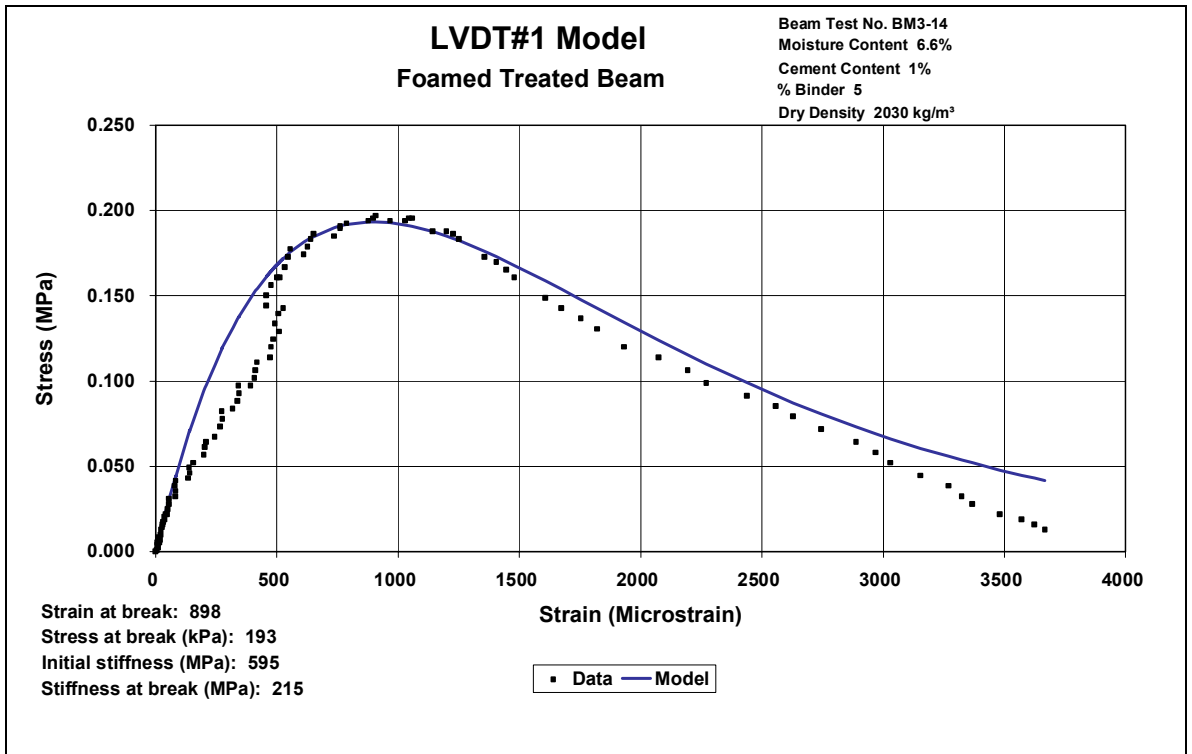












APPENDIX C: Work Proposal

Transportek, CSIR
PROJECT PROPOSAL
June 2001

The influence of different cement and foamed bitumen contents on the compressive, tensile and flexural strength of Foam Treated Materials

BACKGROUND

This project proposal is in support of the objectives of a framework that has been created for the long-term assessment and implementation of Deep In Situ Recycling (DISR) technology using bituminous emulsion and foamed bitumen treatment processes. The objective of the long-term assessment and implementation program is to produce guideline documents and design methods for DISR using the bituminous emulsion and foamed bitumen treatment processes for use by the road-building industry. These guideline documents and design methods will ensure more optimal designs reducing the risk of premature failure and increasing the probability of optimal performance.

The assessment process will mainly use the following assessment techniques

- laboratory testing,
- Heavy Vehicle Simulator (HVS) testing and
- field trials

to assess the benefits of DISR combined with bituminous emulsion and foamed bitumen treatment and to create the knowledge base from which the guideline documents and design methods will be developed. The main aspects that will be investigated include

- the engineering properties (such as the bearing strength, permeability and erodibility) of the products from these processes, and
- the mechanical properties (such as the stiffness, shear strength and strain at break) of the products from these processes,
- the material and pavement behaviour and performance of the products from these processes and
- all aspects that impact on the above such as design, construction and maintenance.

PROBLEM STATEMENT AND MOTIVATION

The use of foamed bitumen in road rehabilitation has recently been introduced in South Africa. Various studies in the past have indicated the advantages of treatment with foam, but limited long-term pavement performance analyses have been carried out. Guidelines for the design of roads treated with foamed bitumen have relied on observation, experience and engineering judgement. There is, therefore, a need for a comprehensive study to quantitatively analyse the performance of these types of deep in-situ recycling (DISR) using several combinations of material types and binders.

The objectives of this study are twofold, namely:

- Perform laboratory tests to gain an understanding of the engineering and performance properties of pavements treated with foamed bitumen, which ultimately can be used to develop a comprehensive structural design procedure for inclusion in the South African Mechanistic Empirical Design Method.
- To develop a classification system for foam treated materials based on the foam and cement content that will generically describe the structural design parameters of the material.

METHODOLOGY

This proposal describes compressive, tensile and flexural testing in the laboratory to enable development of a structural design guide. The study is part of an extensive project to develop a structural design procedure for bituminous emulsion and foam bitumen treated pavement layers.

The laboratory tests required to develop a classification system as well as to gain understanding of the engineering properties of foam treated materials under various foam and cement contents are outlined below.

Materials

For the purpose of this study, only one material with a constant grading will be used. The material is from the HVS test section on Road P243/1 and consists of ferricrete milled from the base layer and the milled asphalt concrete surfacing. The influence of different materials and gradings will therefore not be researched in this study.

Standard tests

By performing standard tests, general material properties will be determined. Variation or optimisation of these properties is not part of the study, and the standard test results will only be used for classifying and characterising the materials. The following general material properties will be determined:

- Grading
- Atterberg limits
- Density/moisture relationship (MDD/OMC)
- Strength/Density/Moisture relationships ($CBR=f(MC,d)$). The CBR will only be performed at 100% Mod. AASHTO
- Initial Lime Consumption
- pH of the material

Chemical agents

Two types of chemical agents will be used, namely foamed bitumen and cement. The type of bitumen and cement is not varied in the tests.

Mixing

The mixing process of the material with the chemical agents is not part of the study. One mixing process will be used throughout the tests.

Curing

In the laboratory, to represent field conditions, curing for 28 days at ambient temperature will be used.

Compaction

Compaction of the mixed material will only be done at one level, which is compacting to 100% mod. AASHTO.

Saturation

All the samples will be tested at the same saturation level. The level of saturation will be determined in a later stage.

Time of testing

All the specimens will be tested after a curing of 28 days.

Test methods

The types of tests that will be performed are outlined in Table 1. The material property that the test captures and the number of tests typically performed per set of variables are also shown in Table 1. The temperature during testing will be kept constant.

Table 1. Type of tests included in experimental programme

Property	Test	Number of tests	Cost of test
Compressive strength	UCS	3	R 250
Tensile strength	ITS	3	R 100
Flexibility	Flexural beam test	4	R 600
Bearing strength	CBR	3	R 100
Material structure	Electron microscope ⁽¹⁾	-	R 350

- (1) Electron microscope photos should be taken at various times to study the change of material structure during curing.
- (2) The UCS, ITS and CBR will be tested according to the specifications described in TMH 1
- (3) The specifications for the flexural beam test are described in 'Laboratory design models for materials suited to labour-intensive construction, H L Theyse, June 2000.

EXPERIMENTAL DESIGN

The combinations of tests proposed in the experimental design are presented in Tables 2 and 3.

Table 2. Foamed bitumen and cement content combinations

		Foamed bitumen content (% residual bitumen)			
		0 %	1.8 %	3.0 %	5.0 %
Cement content	0 %	A	B		
	1 %	C	C	C	C
	2 %	C	C		

Table 3. Test methods for different bitumen- and cement content combinations.

Test	Time of testing (days)	Bitumen and cement content		
		A	B	C
UCS	28		X	X
ITS unsoaked	28		X	X
Flexural beam test	28		X	X
CBR	28	X	X	
Electron microscope images	0, 1, 7, 28		X	X

BENEFIT TO THE ROAD AUTHORITY

The laboratory work, combined with HVS test results, will contribute towards the development of methods for the rational assessment of the bearing capacity of roads rehabilitated with the deep in-place recycling method using a cold treatment process. The understanding of the variables that influence the performance of these materials will be improved and these effects of the variables will be quantified. In terms of practical benefit to the road authority, a guideline for the structural design and performance of these materials will be available.

DELIVERABLES

The final deliverables will be a report that contains the processed test data that will be used in the second level report of Road 243/1 for developing design models and transfer functions for the mechanistic empirical design method for foamed bitumen.

This study will form part of the Masters degree of Sietse Robroch, which involves the development of a mechanistic-empirical design method for foam treated materials. He will have the responsibility to analyse the data and to interpret the results of the testing. The results will be presented as a part of his Masters degree dissertation, however a separate report for the test results only will be written. The

work forms part of an academic study and as a result human resource costs are lower than normally would be expected.

TIME SCHEDULE

	Week 1	Week 2	Week 3	Week 4	Week 5
August 2001		Sample preparation	28 days curing time		
September 2001	28 days curing time	Sample Testing	Report writing		

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