Confidential Contract Report CR-2001/77 October 2002

The Influence of Various Emulsion and Cement Contents on an Emulsion Treated Ferricrete from the HVS Test Sections on Road P243/1

DOCUMENT RETRIEVAL PAGE			**Report No: CR-2001/77**
Title: The Influence of various emulsion and cement contents on an emulsion treated ferricrete from the HVS Test Sections on Road P243/1			
Author: JJE Liebenberg			
Client: Gauteng Department of Public Transport, Roads and Works	**Client Reference No**:	**Date**: October 2002	**Distribution:** Restricted
Project No: TIJ56	**OE2:** 9431: Transport Infrastructure		**ISBN:**

Abstract: This report discusses the results of laboratory tests performed on a ferricrete material milled from the HVS site on Road P243/1. The tests include CBR, UCS, ITS and flexural beam tests. The milled material was treated with different amounts of cement and bitumen emulsion. Tests from the same aggregate reported in reports CR2001/32 and CR2001/69 were used in the analysis of some of the results in this report.

The results indicate that the addition of bitumen emulsion to the material improves the flexibility of the material, while the addition of cement contributes to the strength. Low percentages of emulsion did not have a significant effect on the flexibility, while cement contents lower or equal to the Initial Consumption of Cement (ICC) did not significantly affect the strength. Evaluation of the material under a optical microscope showed that the bitumen is distributed through the material very well and that there is a good agreement between the distribution obtained in the laboratory and that obtained in the field.

Keywords: deep in situ recycling, cement treated gravel, bitumen emulsion treated gravel

Proposals for implementation: Report supplied to client for implementation

Related documents:

1. Long, FM, HL Theyse, **Laboratory Testing for the HVS Sections on Road P243/1**, CR-2001/32
2. Robroch, S**, Laboratory testing on Foamed Bitumen and Cement Treated Material from HVS Test Section on Road P243/1**, CR-2001/69

Signatures:				
K Wolhuter	HL Theyse	BMJA Verhaeghe	S Roets	PJ Hendricks
Language Editor	**Technical Reviewer**	**Programme Manager**	**Info Centre**	**Division Director**

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. General Background

This technical 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 program is to produce guideline documents and design methods for DISR using bituminous emulsion and foamed bitumen for use by the road-building industry. These guideline documents and design methods will ensure optimal designs reducing the risk of premature failure and increasing the probability of optimal performance.

The assessment process will mainly use techniques that include laboratory testing and Heavy Vehicle Simulator (HVS) testing. This is to determine the benefits of DISR combined with bituminous emulsion and foamed bitumen and to create a knowledge base from which guideline documents and design methods will be developed. The main aspects that will be investigated include the engineering properties (such as the bearing capacity, 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 the cold treatment processes and all aspects that impact on the above such as design, construction and maintenance.

1.2. Objectives and Project Deliverables

The laboratory work discussed 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 with the HVS. The laboratory tests performed for this research are part of the larger framework of testing. Some previous tests, discussed by Long and Theyse (2002) and Robroch (2002) are also discussed in relation to the newly performed tests.

The objective of this research is to gain an understanding of the engineering and performance properties of pavements treated with bitumen emulsion, which understanding can ultimately be used to develop a comprehensive structural design procedure for the South African Mechanistic-Empirical Design Method.

1.3. Benefit to the Road Authority

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

2. MATERIALS

For this project, only one type of aggregate was used for testing. The aggregate was milled from a DISR site on Road P243/1. Some laboratory tests had previously been carried out on this aggregate. The bitumen and the cement used in the tests described in this report are the same as used in the previous tests, described by Long and Theyse (2002).

2.1. Aggregate

Only ferricrete milled from the HVS test site by a Wirtgen deep in situ recycler was used in the laboratory testing. The aggregate consisted of an old cement treated ferricrete base, the multiple seal surfacing and some material from the untreated subbase. The main engineering properties of the aggregate are presented in Table 1 with the grading of the material in Figure 1.

The detailed properties of the aggregate are presented by Long and Theyse (2002).

Table 1. Main Engineering Properties of Aggregate Used in Laboratory Testing

Material property	Value
Maximum dry density	2 013 kg/m^3
Optimum moisture content	11.5 to 12.5%
Plasticity index	7
CBR @ 98% compaction of AASHTO density	56.0
CBR @ 95% compaction of AASHTO density	23.0
CBR @ 93% compaction of AASHTO density	17.5
CBR Swell	0.6%
Grading modulus	2.13

2.2. Binders

The bituminous binder used was a 60% stable grade cationic emulsion while the cement was an Alpha CEM I, 42.5 MPa. This was the same cement and emulsion as used in the previous tests, although procured at different times.

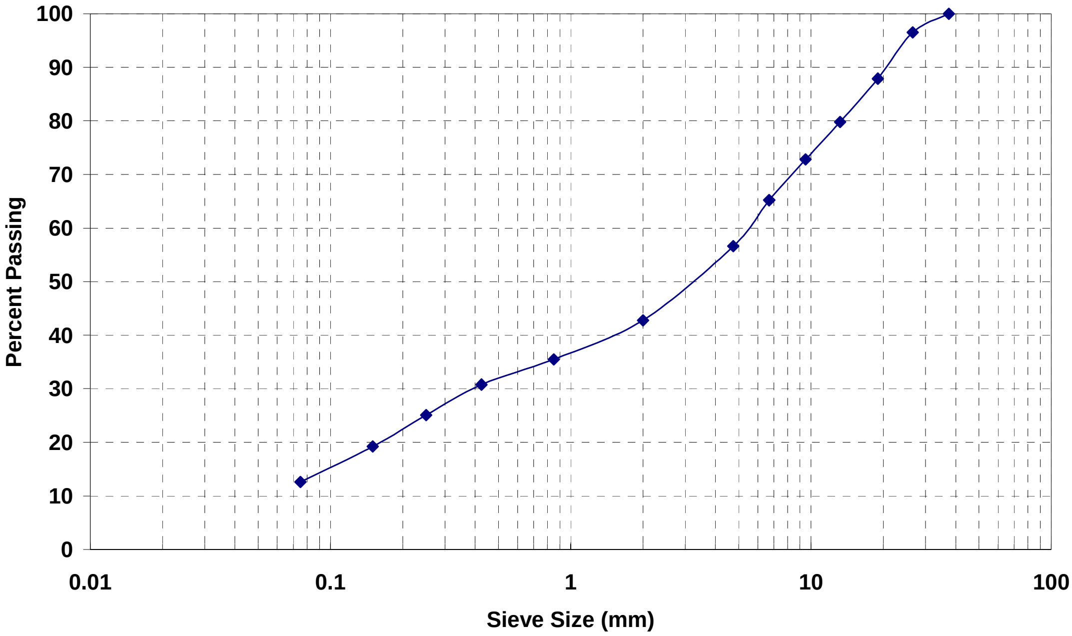


Figure 1. Grading of Ferricrete Used in Laboratory Testing

3. LABORATORY TESTS

3.1. Testing Program

The tests discussed in this report are the Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS), flexural beam fatigue, and California Bearing Ratio (CBR) tests. Various samples were examined under an optical microscope and pictures were taken. The test framework is presented in Table 2.

Table 2. Foamed Bitumen and Cement Content Combinations

		Net Bitumen content (%)			
		0	**0.6**	**1.8**	**3.0**
Cement content (%)	**0**	CBR**	CBR UCS ITS	CBR UCS ITS Flexural beam	CBR UCS ITS Flexural beam
	1	UCS ITS Flexural beam**	UCS ITS	UCS ITS Flexural beam	UCS ITS Flexural beam
	2	UCS ITS Flexural beam*	-	UCS ITS Flexural beam*	UCS ITS Flexural beam*

* The UCS, ITS and flexural beam fatigue tests for these materials were performed in the earlier work by Long and Theyse (2002).

** The CBR, UCS, ITS and flexural beam fatigue tests for these materials were performed in the work of Robroch (2002) on foam bitumen materials.

3.2. Specimen Preparation, Compaction Process and Curing

3.2.1 Specimen Preparation

Mixing was performed in the laboratory and all samples were prepared according to TMH1 (NITRR: 1986).

3.2.2 Compaction

The UCS, ITS and CBR were compacted to 100% Modified AASHTO, following the standard procedures from TMH1 (NITRR: 1986). The beams for the flexural beam fatigue test were compacted in the beam mould in three layers, where each layer received 56 blows with an AASHTO hammer. After this, the material was compacted to a standard height of 75 mm using a compression apparatus with a maximum effort of 275 kN.

3.2.3 Curing

The effect of different curing processes and curing times was not investigated in this research. The curing method used is thought to simulate the conditions in the field as accurately as possible to ensure that accurate structural design input parameters could be obtained from these tests. Except for the untreated CBR specimens, all the specimens were cured for 28 days at ambient temperature. All specimens, except the beams, were cured in plastic bags. The beams were sealed in a chamber, and were dried out at a later stage to establish the correct moisture content. The UCS and ITS specimens were also dried out, where necessary, to obtain the target saturation level. The target testing moisture content was calculated from the initial moisture content and the weight of the sample, and was the moisture content that could be expected in the field.

4. MICROSCOPIC PICTURES

A knowledge of the microstructure of a material is necessary for a clear understanding of its behaviour and performance. For this purpose, the materials 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 in the sample, which was not an ideal situation.

Figure 2. Basic Set Up of the Optical Microscope

For this project, a stereo optical microscope capable of between 7 and 90 times magnification was used. A digital video camera is mounted on top of the microscope. State of the art software provides the feature of taking perfectly focused, three-dimensional pictures at high magnifications.

Photos were taken after different curing times to see if any changes in the material could be observed. It was impossible to identify the growing of the cementitious bonds with time. This could be because of the relatively small amount of cement (1%) and the texture and composition of the ferricrete that sometimes led to a confusing image.

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

4.2. Pictures 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 emulsion and a drum for milling and mixing. On the pictures, it is clear that this method gives a fine distribution of the bitumen throughout the mix (Figure 3). The presence of cement can be seen as the whitish crystals while the bitumen is the black speckles.

Figure 3. Sample from the HVS site, 50 times magnification

The material mixed in the laboratory showed a similar distribution of bitumen through the mix (Figure 4). The cement is not clearly visible on the laboratory sample, but traces of it can be seen on the right of the picture.

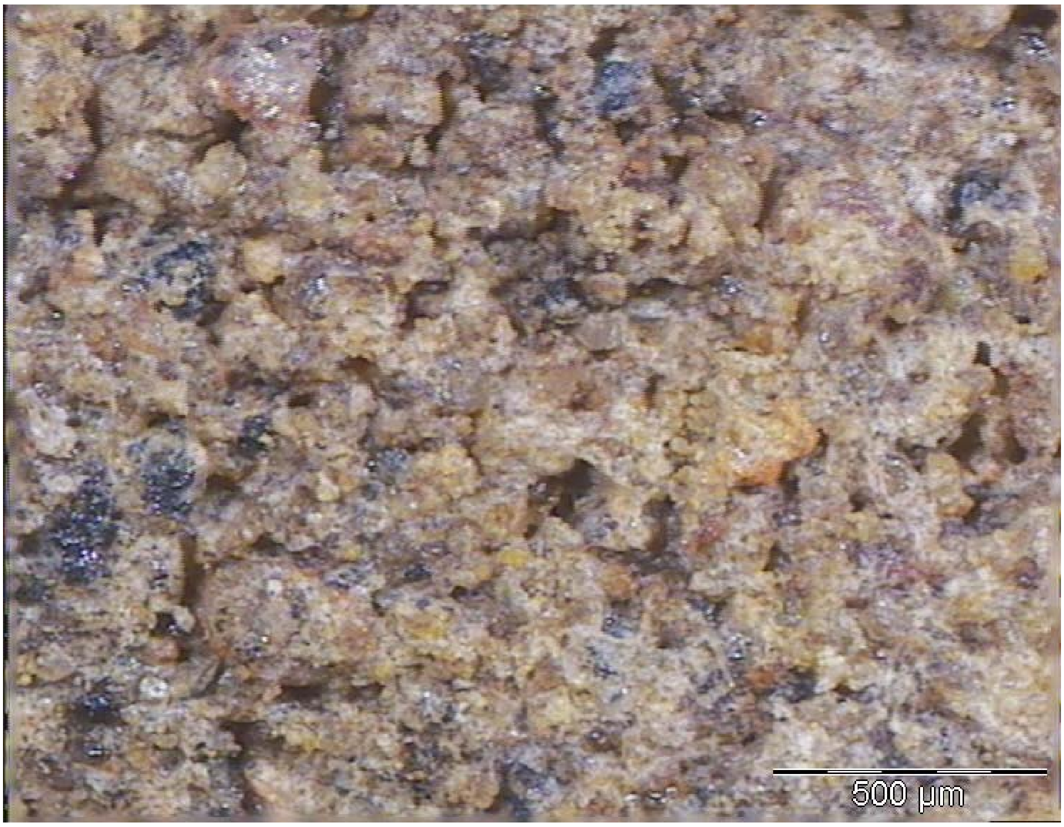


Figure 4. Sample from laboratory (2% cement, 1.8% net bitumen), 32 times magnification

It was very difficult to observe whether the bitumen tends to stick to the coarser or to the finer particles in the mixture. From Figure 4 it is clear that the size of the bitumen emulsion particles in the mix is less than 100 micron in diameter and it can be concluded that the bitumen from the emulsion might tend to stick to the finer particles in the mix. It appears that the texture of the mixture observed under the microscope tends to be more uniform when cement is present in the mix.

Some additional photos with various bitumen and cement contents, as well as from the HVS site are shown in Appendix A.

5. LABORATORY TESTING

Four different laboratory tests were performed on the materials: UCS, ITS, flexural beam and CBR tests. For an overview of which tests were performed on each material combination, see Table 2.

5.1. California Bearing Ratio (CBR)

The CBR test is method A8 in TMH1 (NITRR: 1986). The CBR test was only performed on the materials that did not contain cement, i.e. untreated gravel and gravels with 0.6, 1.8 and 3 per cent net bitumen.

Three tests per material combination were performed at a density level of 100 % Modified AASHTO. The intention was not to determine the relationship with density, but to get an idea of the quality of the material and the influence of the addition of bitumen emulsion on the strength of the material.

Table 3 presents a summary of the CBR results while the complete results are attached in Appendix B. The averages are shown in Table 3 for a penetration of 2.54 mm, which is generally used for assessing the quality of the materials.

Table 3. Summary of CBR Test Results

	Net Bitumen Content			
	0%	**0.6%**	**1.8%**	**3.0%**
CBR at 100% Mod AASHTO	9.6*	13.9	12.7	25.1

*From the work of Robroch (2002)

The CBR result for the untreated material is significantly lower than previous tests (shown in Table 1). The values shown in Table 3 were for samples compacted at a moisture content of 12.8 %. To investigate the large differences in the results, and the possible effect of the moisture content, a range of untreated specimens were prepared at moisture contents ranging from 7.3 to 12.6 %. These results are shown in Figure 5 as the repeat tests. Also shown in the figure are the three original specimens averaged to obtain the CBR value of 9.6 shown in Table 3. The moisture content determination was also repeated, and was of the order of 9.2 %. These results demonstrate that if the specimens shown in Table 3 had been compacted at a lower moisture content, it is likely that the CBR values would be closer in value to those shown in Table 1.

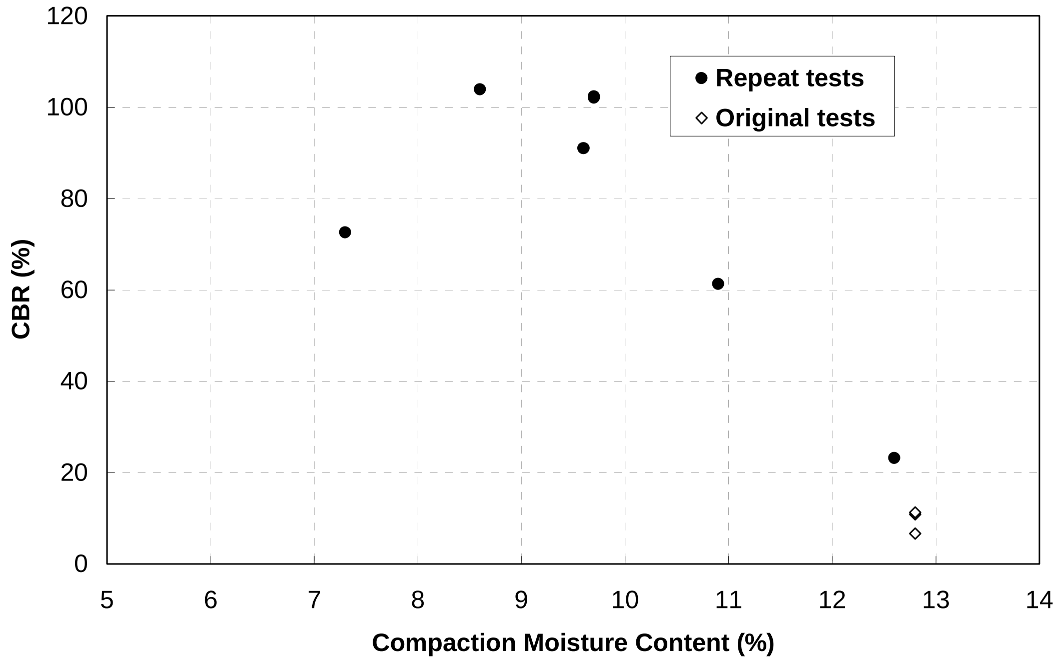


Figure 5. CBR Results from Untreated Specimens

As shown in Table 3, the CBR of the treated materials are higher than for the untreated material. However, at the high moisture contents, low and medium net bitumen contents (0.6 % and 1.8 %) do not seem to have a significant influence on the CBR of the material. The sample with 3 % net bitumen does show a significant increase in strength although it is not adequate for base layers according to the CBR requirement of 80 at 98 % Modified AASHTO compaction for natural materials as described in TRH14 (CSRA: 1985). Had the material being compacted at a lower moisture content, it is likely that the requirement would have been met.

5.2. Unconfined Compressive Strength (UCS)

The UCS tests were done at 100% modified AASHTO compaction with moisture contents as close to the optimum moisture content (12.5 %) as possible. The samples were cured for 28 days at ambient temperature and sealed in a plastic bag to prevent excessive loss of moisture. No rapid curing processes were used. A summary of the UCS tests results is presented in Table 4. Figure 6 illustrates the effect of various net bitumen and cement contents on the UCS. Detailed results are included in Appendix B.

Table 4. Summary of UCS Test Results (kPa)

		Net Bitumen Content (%)			
		0	**0.6**	**1.8**	**3.0**
Cement content (%)	**0**	-	159	132	316
	1	305**	548	545	788
	2	3198*	-	2375*	1645*

* From the work of Long and Theyse (2002)
** From the work of Robroch (2002)

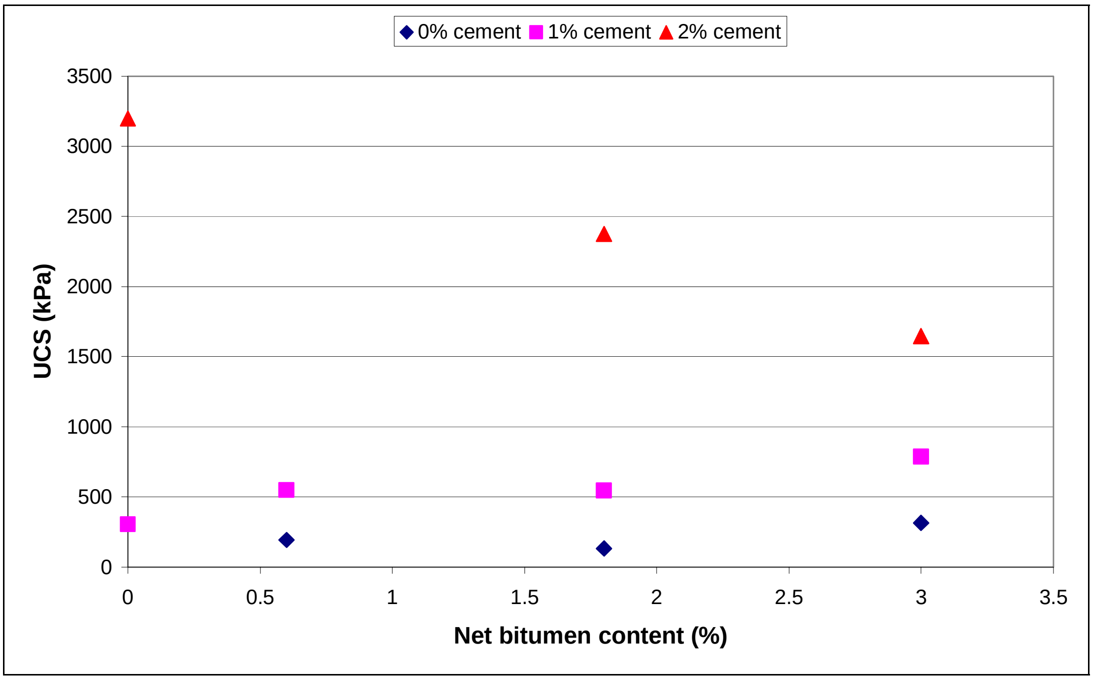


Figure 6. Influence of Cement and Net Bitumen Contents on the UCS

From Figure 6 it is clear that an increase in the bituminous binder had little effect on the UCS of this material at low cement contents, but led to a reduction in the UCS at higher cement contents.

For the mixes with 2 % cement, the UCS decreased with an increase in net bitumen content. For the mixes with 1 % and 0 % cement, there was a slight increase in the UCS with an increase in the net bitumen content. The difference between the 1 % and 0 % cement contents is relative small, indicating that 1% cement does not add significant strength to the material. Initial Consumption of Cement (ICC) tests showed that the ICC of the materials is of the order of 1 %. In the mixes with 1% cement, the hydration reaction from the cement does not occur.

The reduction of the UCS for the emulsion treated specimens with 2 % cement could be the result of some lubricating action of the bitumen, which increases with increases in the bitumen content, or that some of the bitumen encapsulates the cement particles, leaving less cement to participate in the hydration reaction.

5.3. Indirect Tensile Strength Test (ITS)

Indirect tensile strength (ITS) tests were performed on the same mixes as the Unconfined Compressive Strength tests. A summary of the results is given in Table 6 with the complete results in Appendix B. For these mixes, the curing time was 28 days of normal curing at ambient temperature. All the samples were compacted to 100% of modified AASHTO density.

Table 6. Summary of ITS Test Results (kPa)

		Net Bitumen Content (%)			
		0	**0.6**	**1.8**	**3.0**
Cement content (%)	**0**	-	16	24	34
	1	33**	56	65	136
	2	409**	-	325*	230*

* From the work of Long and Theyse (2002)

** From the work of Robroch (2002)

Figure 7 illustrates the effect of various net bitumen and cement contents on the ITS. The ITS test results in Figure 7 follow a very similar trend to the UCS results illustrated in Figure 6.

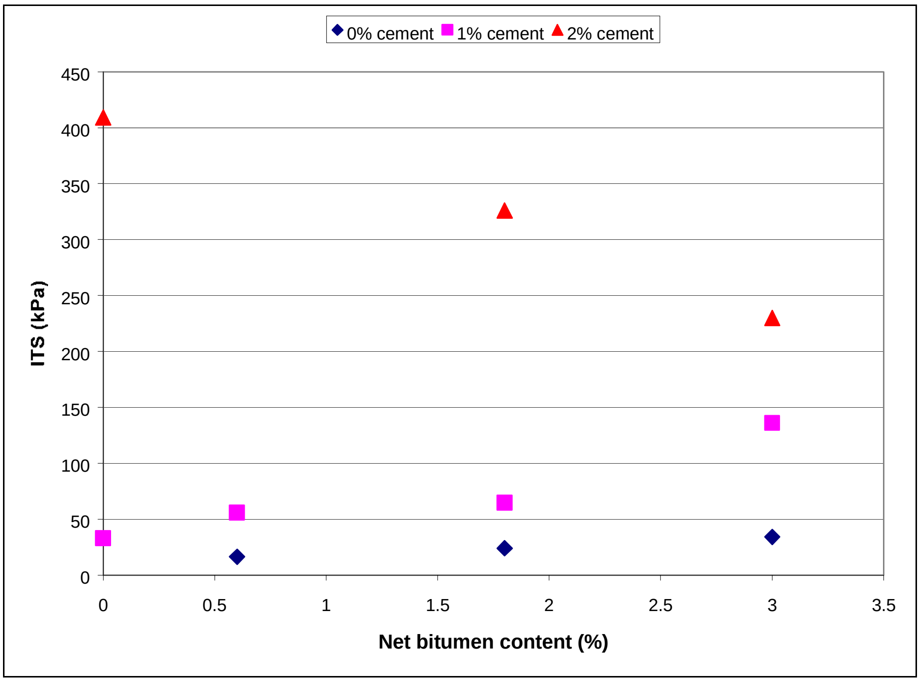


Figure 7. Influence of Cement and Net Bitumen Contents on the ITS

For the sample with 3 % net bitumen, for an increase in cement content from 9% to 1%, the ITS showed a significant increase. This indicates that some cement is necessary to hold the sample together since the addition of only bitumen to the material had virtually no influence on the ITS.

As with the UCS tests, for the mixes with 2 % cement, the ITS decreased with an increase in the net bitumen content. However, there was a slight increase in the ITS with an increase in the net bitumen content, for the mixes with 1 % and 0 % cement. The difference between the 1% and 0% cement content mixes is relatively small, indicating that 1% cement does not add significant strength to the material.

The reduction of the ITS for the 2 % cement samples could be the result of some lubricating action of the bitumen that increases with an increase in the bitumen content. Alternatively, some bitumen may encapsulate the cement particles, leaving less cement for the hydration reaction.

5.4. Flexural Beam Test

The flexural beam test was performed on the different mixes. The test is described in detail by Theyse (2000). The test set-up is shown in Figure 8. The machine imposes a constant displacement of one millimetre per minute.

The data from the flexural beam test consist of a plot of stress versus strain. The turning point on the curve indicates failure of the specimen. The stress at this point is regarded as the stress at break while the strain at this point can be regarded as the strain at break. Theyse (2000) proposed the following mathematical model to fit the data from the beam tests:

$$\sigma = P\left(e^{-D\varepsilon} - e^{-Q\varepsilon}\right) \qquad (1)$$

where: σ = stress

ε = strain

e = natural logarithm (2.718282….)

P, D and Q = regression coefficients

Figure 8. Test Setup of Flexural Beam Test

The first derivative of the function is as follows:

$$\frac{\partial \sigma}{\partial \varepsilon} = P\left(Qe^{-Q\varepsilon} - De^{-D\varepsilon}\right) \tag{2}$$

The turning point of the function, where the stress is a maximum, is obtained by setting the derivative (Equation 2) to zero and solving for ε. The solution for ε is given in Equation 3 and it represents the maximum strain that can be sustained before failure of the sample and is the strain at break of the sample, ε_b.

$$\varepsilon_b = \frac{\ln\left(\frac{D}{Q}\right)}{D - Q} \tag{3}$$

The first derivative of the stress-strain function, as given in Equation 2, also represents the tangential bending stiffness, E_{bend} of the beam. The initial beam stiffness E^i_{bend} may therefore be calculated directly from Equation 2 by substituting zero for ε. This results in the solution given in Equation 4.

$$E^i_{bend} = P(Q - D) \tag{4}$$

By substituting the strain at break calculated from Equation 3 into the original function (Equation 1), the maximum stress σ_{max} can be calculated. The effective stiffness of the beam at failure may then be calculated by dividing the maximum stress (σ_{max}) by the strain at break (ε_b).

The amount of energy required to break the beam gives an indication of the toughness of the material and can be calculated by the integral of the original function between zero and the strain at break:

$$Energy = \int_0^{\varepsilon_b} \sigma \partial\varepsilon = \int_0^{\varepsilon_b} P\left(e^{-D\varepsilon} - e^{-Q\varepsilon}\right)\partial\varepsilon \tag{5}$$

$$= P\left(\frac{e^{-Q\varepsilon_b} - 1}{Q} - \frac{e^{-D\varepsilon_b} - 1}{D}\right) \tag{6}$$

Table 7 and Figures 9 to 11 provide a summary of the flexural beam tests. The larger markers in Figures 9 to 11 are the average values. The complete test results are included in Appendix C.

Table 7. Summary of Flexural Beam Tests

Cement content (%)	Test Parameter	Net bitumen content (%)		
		0	**1.8**	**3.0**
0		-	Samples broke under own weight	
1	Strain at break (με)	96	336	677
	Stress at break (kPa)	38	25	53
	Energy to break (mJ/m^3	2.66	6.48	41.4
	Initial stiffness (MPa)	1 428	235	275
	Stiffness at break (MPa)	496	85	95
2	Strain at break (με)	183*	141*	235*
	Stress at break (kPa)	273*	360*	307*
	Energy to break (mJ/m^3	45.1	32.2	53.2
	Initial stiffness (MPa)	4 921*	4 731*	3 919*
	Stiffness at break (MPa)	1 600*	2 655*	2 200*

* From the work of Long and Theyse (2002)

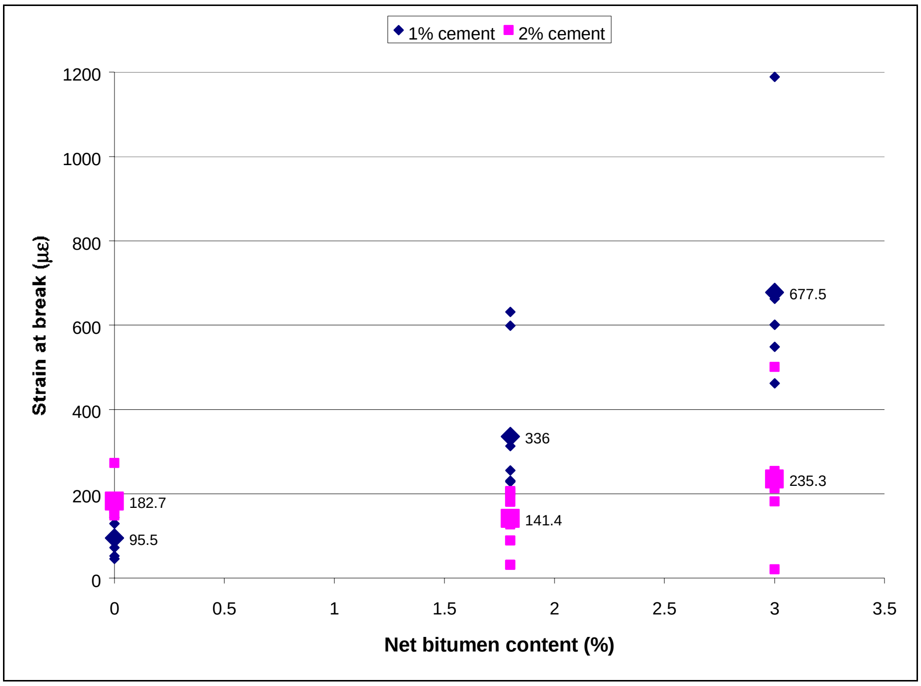


Figure 9. Strain at Break Values from Flexural Beam Tests

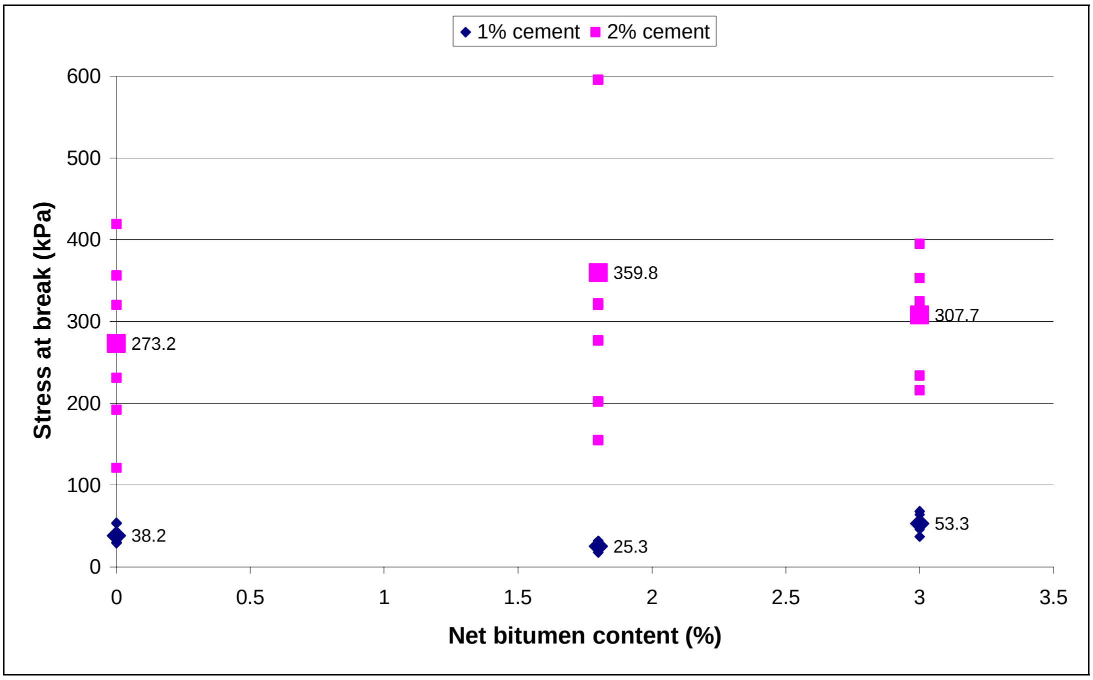


Figure 10. Stress at Break Values from Flexural Beam Tests

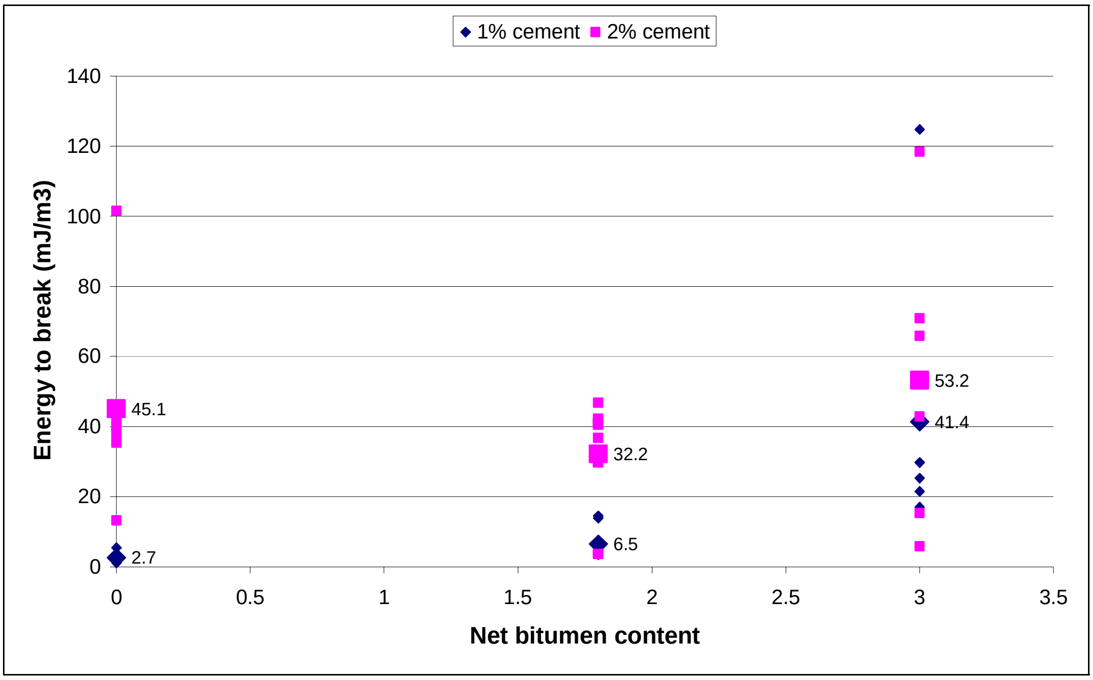


Figure 11. Dissipated Energy from Flexural Beam Tests

The samples with no cement and 0.6% and 1.8% net bitumen broke under their own weight when tested and no strain at break values could be obtained for them. The samples with no cement and 3% net bitumen also broke under their own weight or slowly "flowed" to failure under weight of the 2 kg test equipment weight. This indicates increased flexibility at higher net bitumen contents, but literally no strength.

In general, an increase in bitumen content resulted in an increase in flexibility, or strain at break. It, however, did not seem to significantly affect the stress at break. At lower cement contents, an increase in bitumen content contributed positively to the amount of energy required to initiate failure.

An increase in cement content had a significant effect on the strength of the material in the sense that the stress at break showed a large increase. It reduced the flexibility of the material, with a reduction in the strain at break, when bitumen is present in the material. More energy was required to fail samples with higher cement contents. The cement also contributed significantly to the stiffness of the material. An increase in the cement therefore provides strength to the material but too much cement reduces the flexibiltiy. This should be kept in mind when specifying the UCS in the mix design process where the objective is to optimise both the strength and the flexibility.

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. Three binders used for the cold treatment are cement, foamed bitumen and bituminous emulsion. To understand the behaviour of the material it is necessary to perform both HVS and laboratory testing. HVS tests were performed on Road P243/1 and laboratory tests have been performed in the laboratory at Transportek, CSIR. This report addressed the properties of an emulsion treated ferricrete with various cement and net bitumen contents.

The aim of the laboratory testing was to obtain a material that is representative of the material mixed in the field, with the ultimate goal of relating the results to the field performance and to implement the test results in a practical guideline.

In this report, the results from four widely known laboratory tests, namely the UCS, ITS, flexural beam and CBR test are discussed. These tests are complementary to earlier tests performed on the same aggregate (Long and Theyse: 2002).

Initial Consumption of Cement (ICC) tests on the material indicated that the ICC value of the material was 1%. The ICC, which is closely related to the Initial Consumption of Lime (ICL) is an indication of the minimum amount of cement or lime that is required to satisfy conditions for the cement-hydration reaction to commence (Eades and Grimm: 1964).

From the tests done in this study it appeared that the cement dominates the UCS and ITS at high cement contents (above ICL) and that the addition of bituminous binder reduces the UCS and ITS of the material. At lower cement contents (lower or equal to ICL) the effect of the cement was much less and an increase in bitumen tended to have a slight increase in the UCS and ITS. The cement had little strengthening effect on the material when the ICL requirements were not met, and could therefore explain the greater effect of the bituminous binder on the material at low cement contents. This effect could however be dependent on the type of material. An increase in binder contents in excess of 3% may have a positive influence on the ITS value regardless of the cement content. The material could then behave visco-elastically with similar properties to that of asphalt materials. Additional research is, however, required to prove this theory.

The low UCS, ITS and CBR values for the material with no cement could also be a result of the emulsion not breaking in the samples so that no bitumen was available to bond the particles together. It was not possible to observe under the microscope whether the emulsion had broken. Sufficient cement and time are necessary to ensure proper breaking of the emulsion in a compacted sample or layer.

The increase in flexibility at low cement contents can be ascribed to the fact that the ICL of the material was not met and that the cement reaction that would have contributed to the brittleness of the material had not commenced. The cement increases the strength of the material, but subsequently reduces the flexibility, while the emulsion increases the flexibility but reduces the strength. A delicate balance between the cement and bitumen contents should therefore be aimed for during the mix design process.

No comparison or relationship could be observed between the test results from the Indirect Tensile Strength and the flexural beam test.

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

All the testing has been done on only one material type with one grading. For improved knowledge of the advantages and disadvantages of treating material with bitumen emulsion and cement, different types and gradings of aggregate should be tested.

Recommended strain at break values for input into a structural design procedure obtained from this research are outlined in Table 8. The recommended values assume that the ICL of the material has been met, and would be valid for base materials of G5 to G7 quality. These values were averaged from the laboratory study, described in section 5.4, for the different combinations of cement and net bitumen contents.

Table 8. Recommended Strain at Break Values for Structural Design

Net Bitumen Content	Recommended Strain at Break
1 to 2%	145
2 to 3.5%	230

Note: Cement contents should be slightly above ICL

Additional research to establish a mix design procedure that can be linked to a structural design procedure to ensure the optimum cement and emulsion contents is also recommended.

REFERENCES

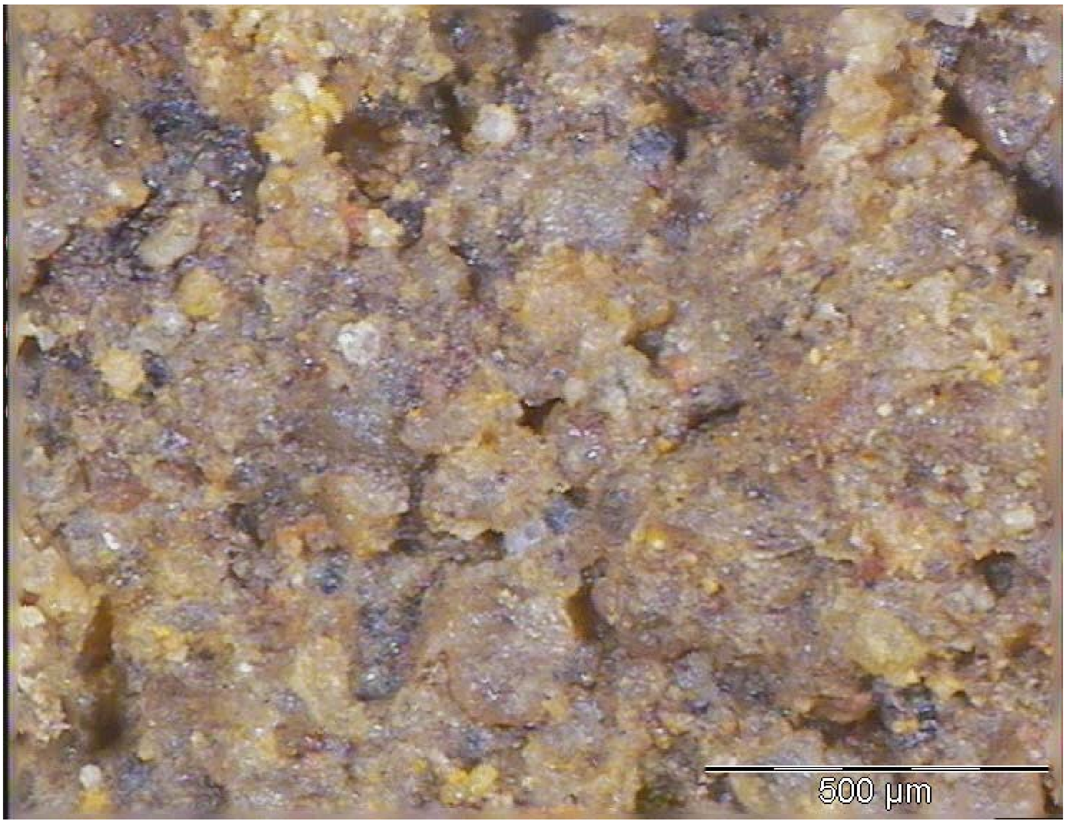
1. LONG FM and THEYSE HL, 2002, *Laboratory testing for the HVS sections on road P243/1*, Contract report CR-2001/32, Transportek, CSIR, Pretoria.
2. ROBROCH SR, 2002, *Laboratory testing on Foamed bitumen and Cement treated material from the HVS test section on Road P243/1*, Contract Report CR-2001/69, Transportek, CSIR, Pretoria.
3. NATIONAL INSTRITUTE OF TRANSPORT AND ROAD RESEARCH (NITRR), 1986, *TMH1: Standard Methods of testing Road and Construction Materials*, 2^{nd} edition, CSIR, Pretoria.
4. THEYSE, HL, 2000, *Laboratory design models for materials suited to labour-intensive construction, Contract report CR-99/38*, Transportek, CSIR, Pretoria.
5. COMMITTEE OF STATE ROAD AUTHORITIES (CSRA), 1986, *TRH14: Guidelines for road construction materials*, Department of Transport, Pretoria.
6. EADES JL and GRIMM RE, 1964, *A quick test to determine the lime requirements for lime stabilisation*, Highway research record no. 139, Washington DC.

APPENDIX A: Microscopic Photographs

Photograph A1. 0.6% net bitumen, 0% cement, 7x magnification

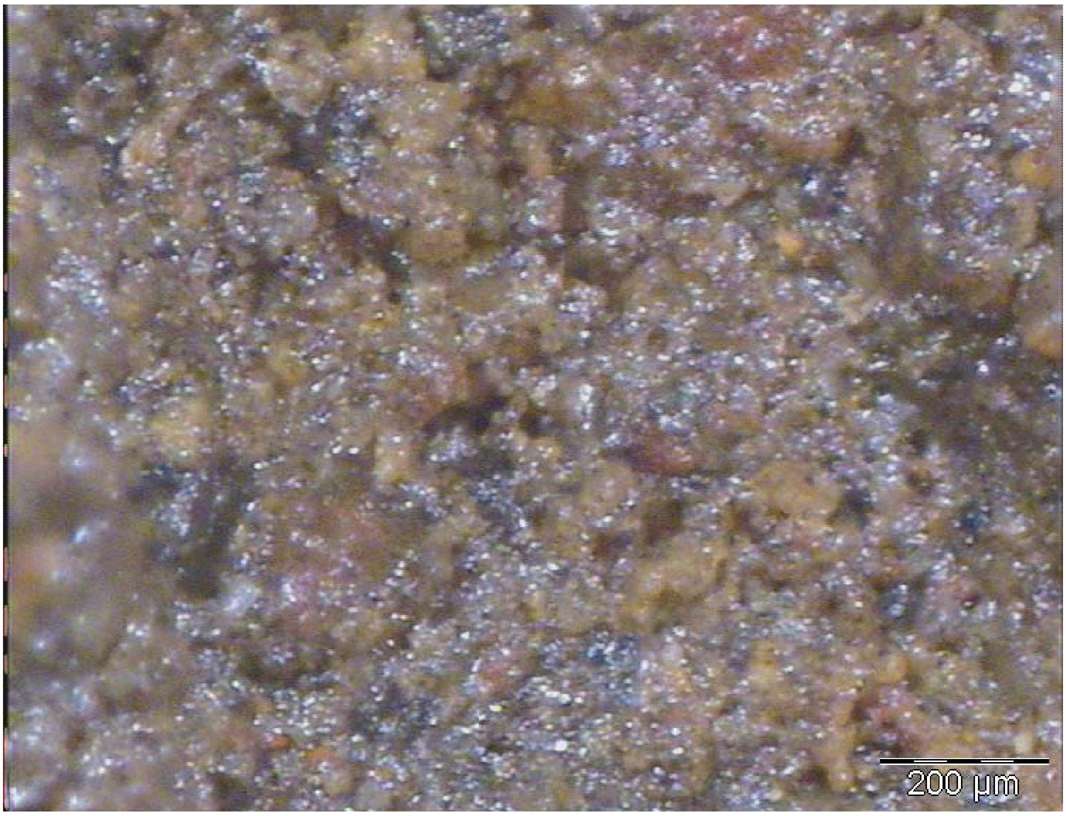
Photograph A2. 0.6% net bitumen, 0% cement, 50x magnification

Photograph A3. 0.6% emulsion, 1% cement, 7x magnification



Photograph A4. 0.6% emulsion, 1% cement, 40x magnification

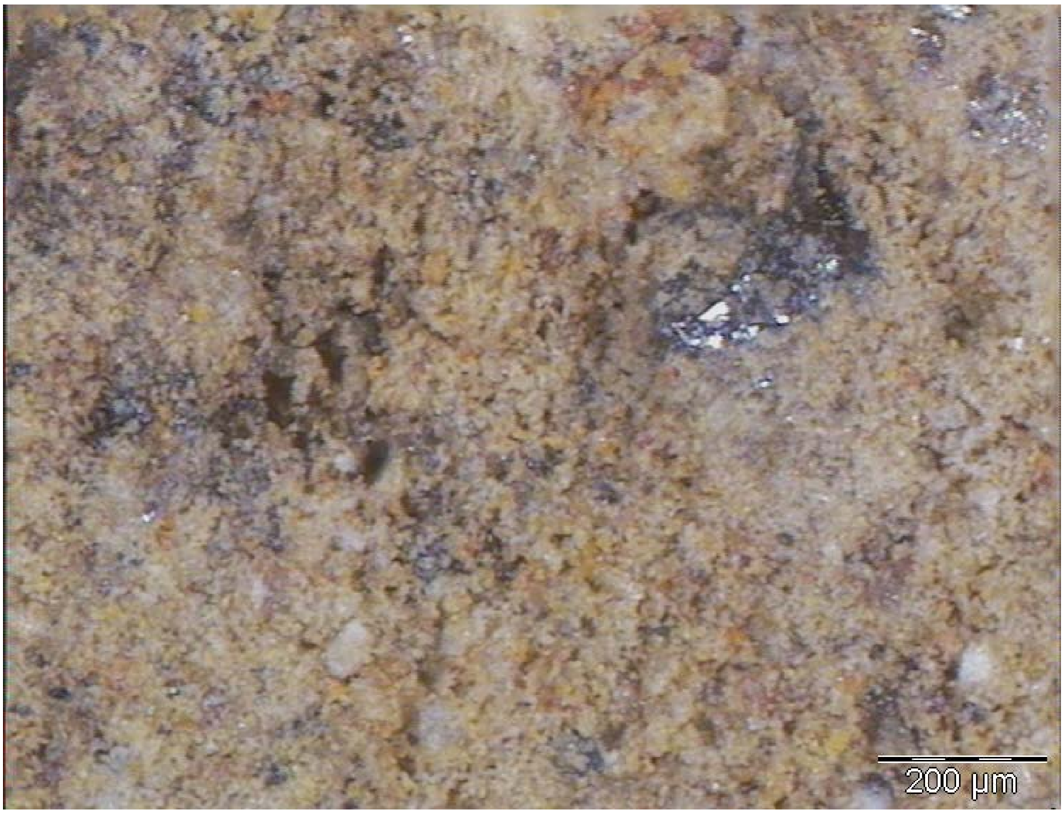
Photograph A5. 1.8% net bitumen, 0% cement, 7x magnification



Photograph A6. 1.8% net bitumen, 0% cement, 50x magnification (sample very wet)

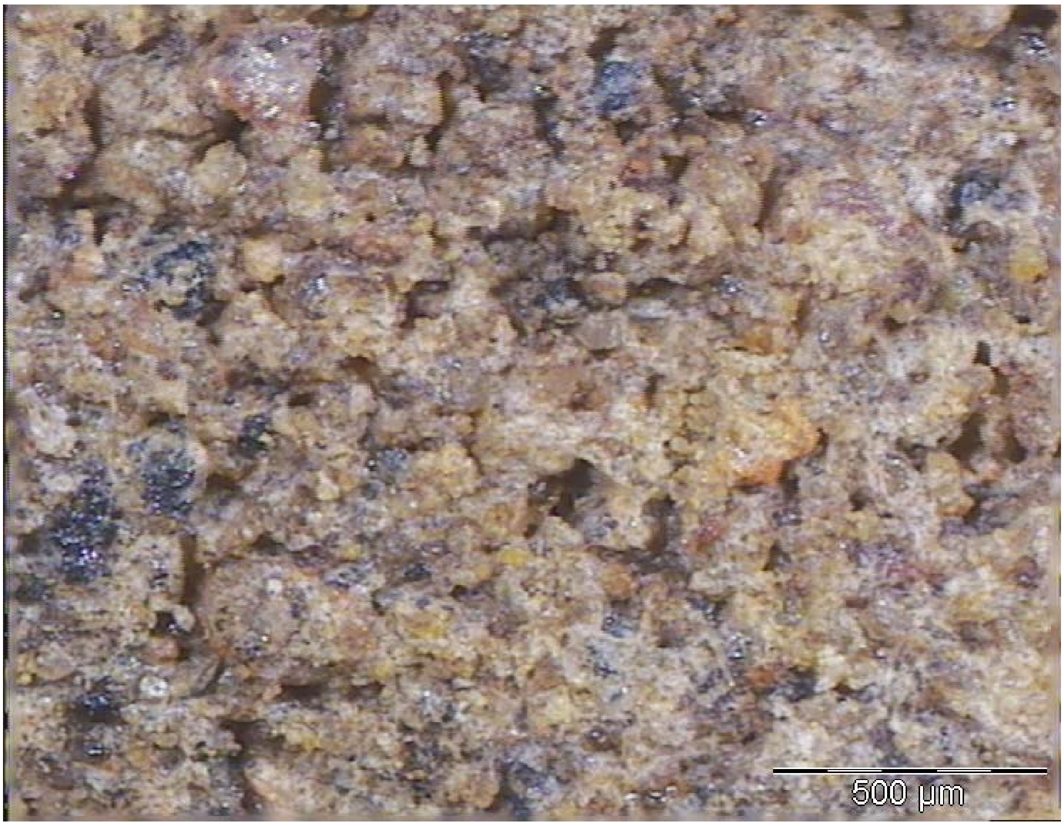
Photograph A7. 1.8% net bitumen, 1% cement, 7x magnification

Photograph A8. 1.8% net bitumen, 1% cement, 40x magnification

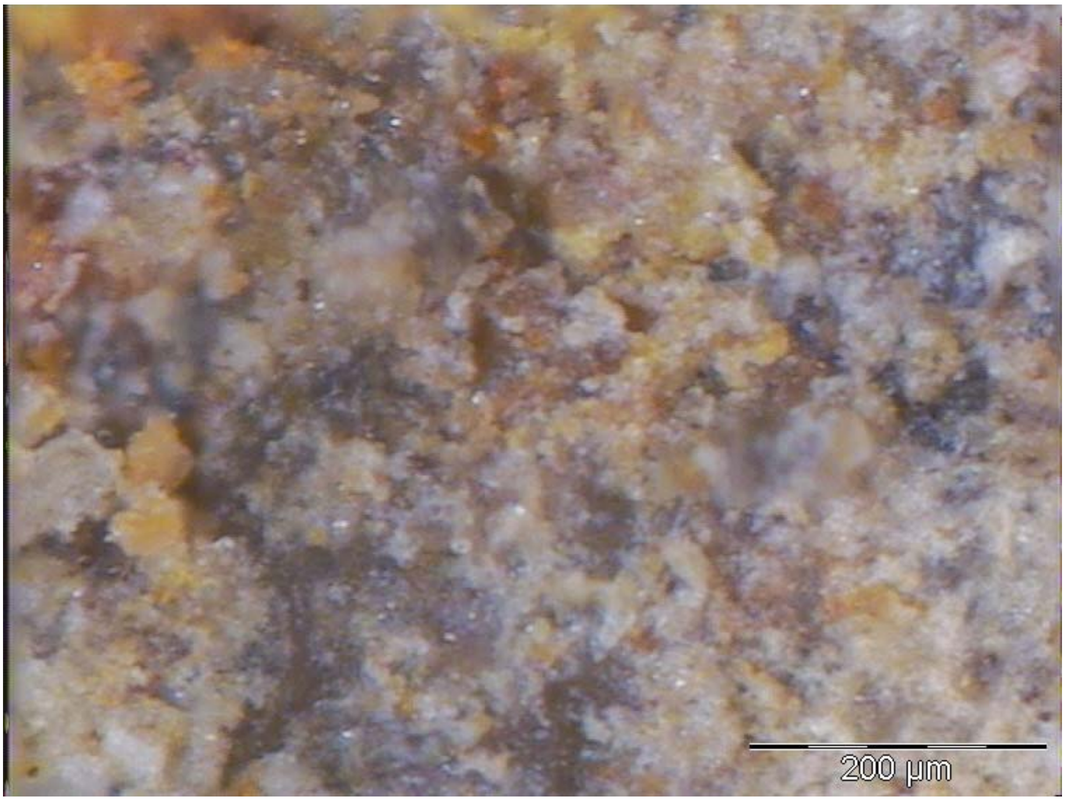


Photograph A9. 1.8% net bitumen, 1% cement, 50x magnification

Photograph A10. 1.8% net bitumen, 2% cement, 7x magnification

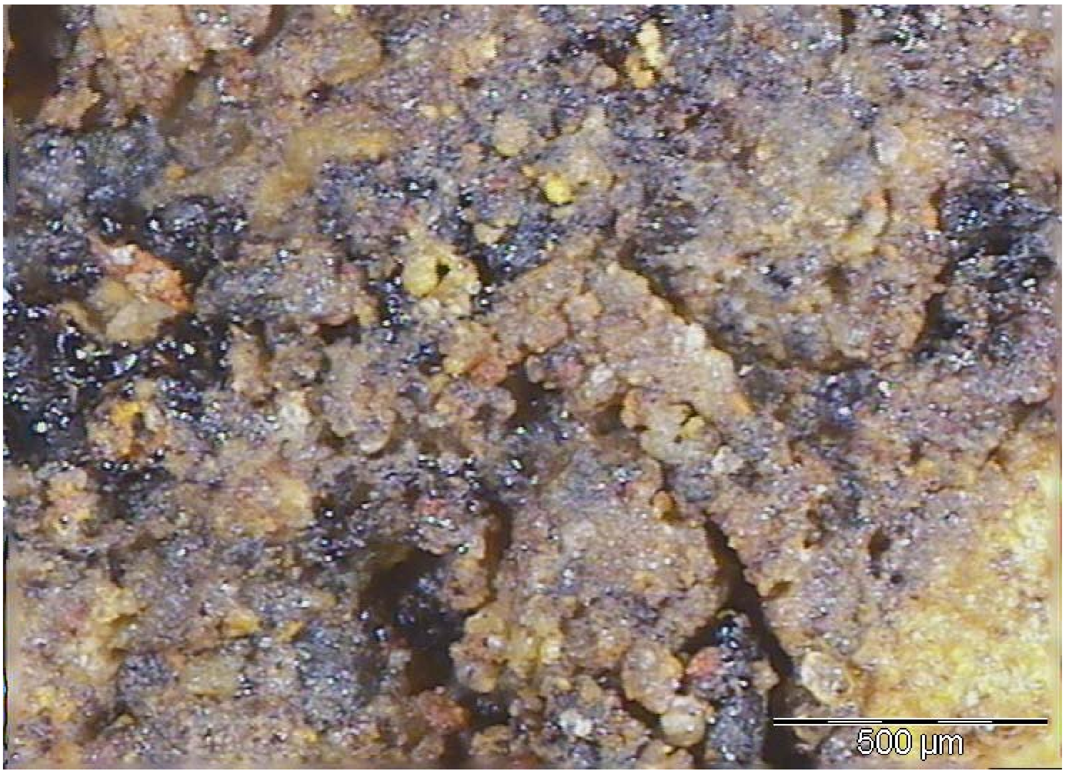


Photograph A11. 1.8% net bitumen, 2% cement, 32x magnification

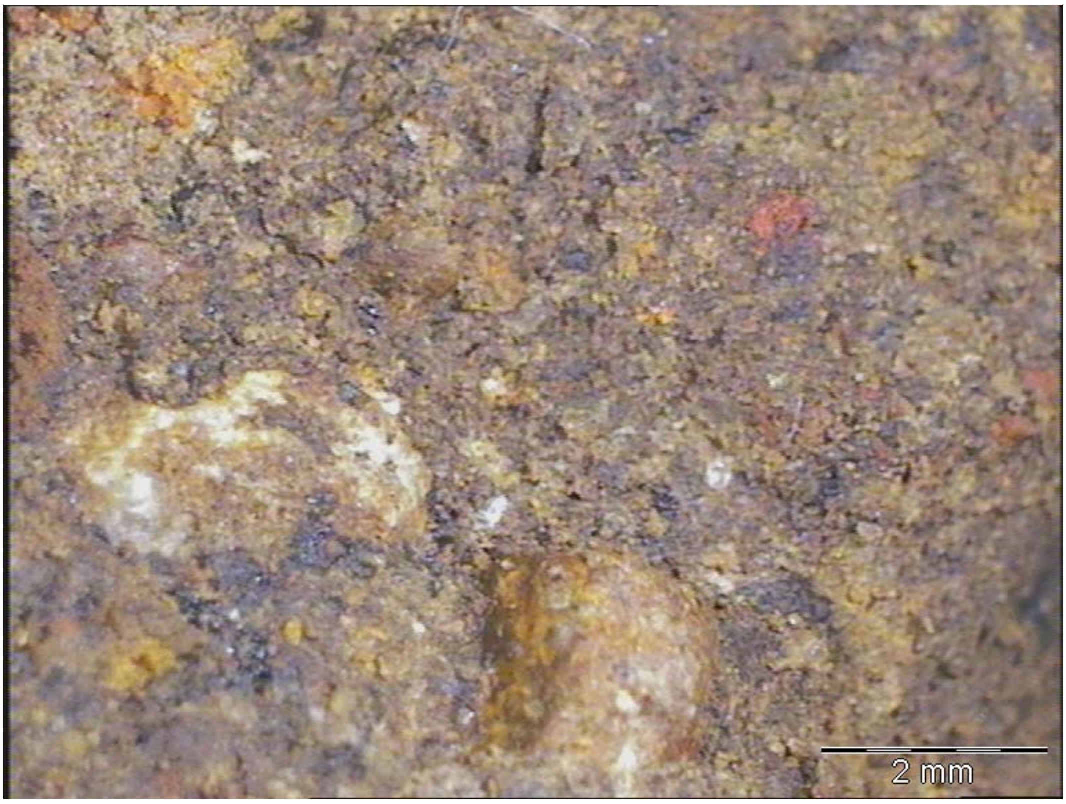


Photograph A12. 1.8% net bitumen, 2% cement, 90x magnification

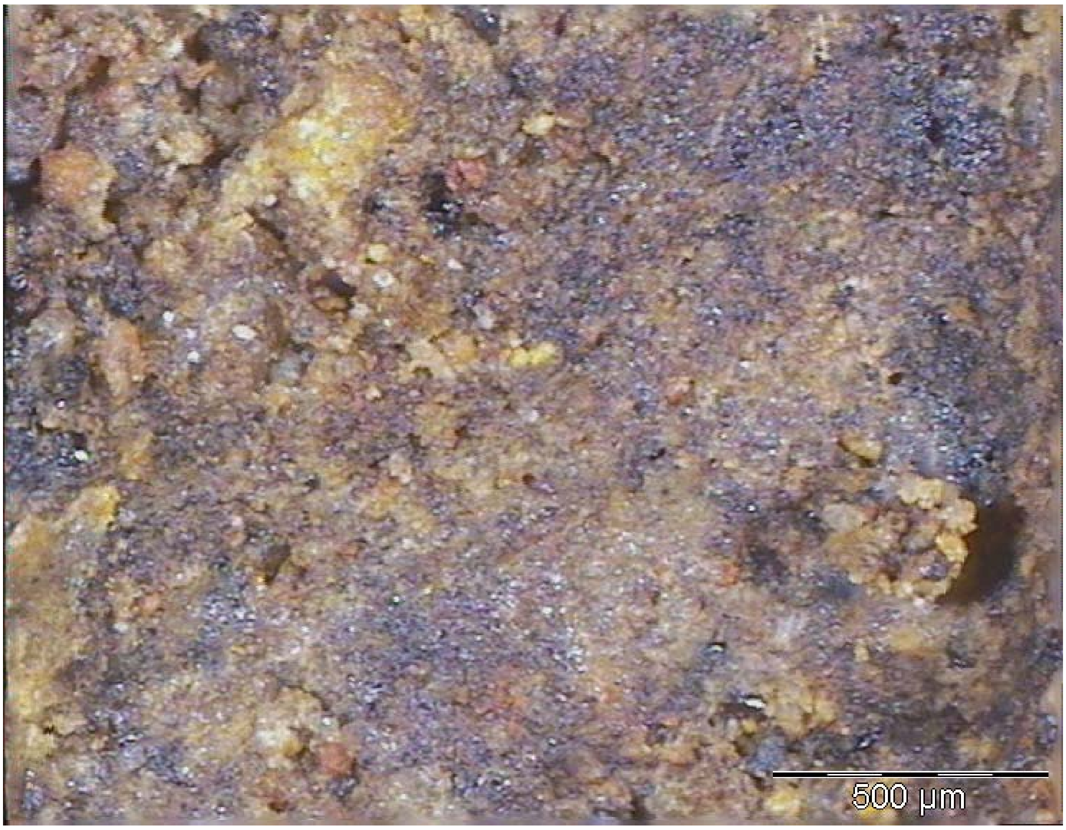
Photograph A13. 3.0% net bitumen, 0% cement, 7x magnification



Photograph A14. 3.0% net bitumen, 0% cement, 32x magnification



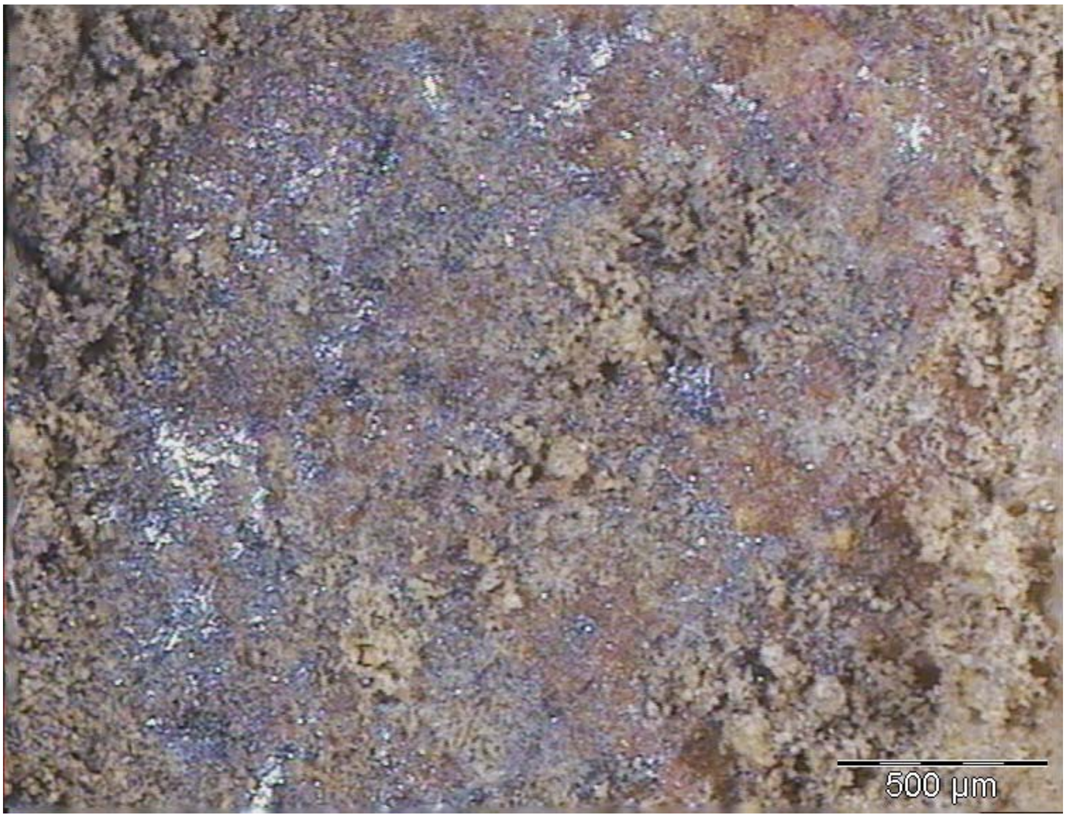
Photograph A15. 3.0% net bitumen, 1% cement, 7x magnification



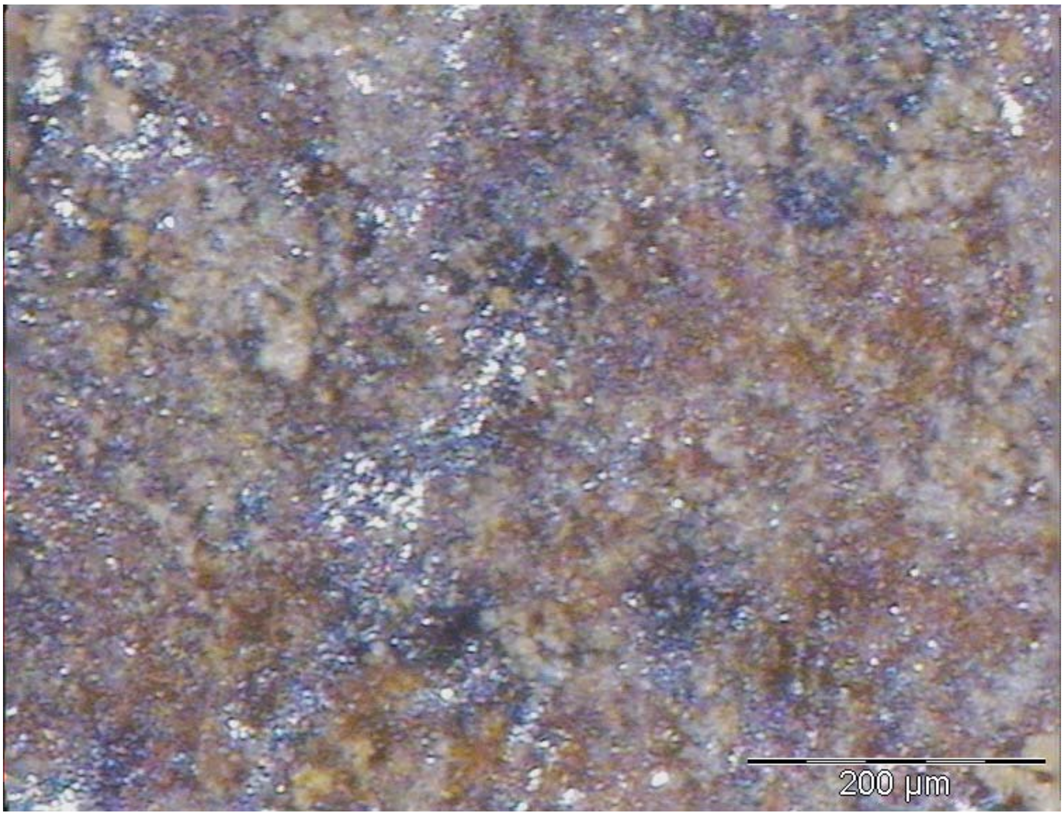
Photograph A16. 3.0% net bitumen, 1% cement, 32x magnification

Photograph A17. 3.0% net bitumen, 1% cement, 7x magnification (note bitumen film around bigger aggregate)

Photograph A18. HVS site sample. Aggregate coated with bitumen, 7x magnification



Photograph 19. HVS site sample. Aggregate coated with bitumen. (Some of the binder has been rubbed off) 25x magnification



Photograph A20. HVS site sample. Aggregate coated with bitumen. (Some of the binder has been rubbed off) 90x magnification

Photograph A21. HVS site sample. Bitumen with cement, 50x magnification

APPENDIX B: Detailed CBR, UCS and ITS Test Results

B1. Soaked CBR Test Results*

Sample Number	Cement Content (%)	Bitumen Content (%)	Moulding Density (kg/m^3)	Moulding Moisture Content (%)	Swell (%)	CBR @ penetration depth		
						2.540 mm	5.080 mm	7.620 mm
10/09/01a	0	0.6	1 991	12.2	0.0	12.1	16.7	19.0
10/09/01b	0	0.6	1 947	12.2	0.0	16.6	17.6	18.4
10/09/01c	0	0.6	1 974	12.2	0.0	13.0	16.3	19.3
4/09/01a	0	1.8	1 940	12.7	0.0	12.9	15.6	18.9
4/09/01b	0	1.8	1 968	12.7	0.0	14.4	18.4	21.7
4/09/01c	0	1.8	1 952	12.7	0.0	10.9	14.9	16.9
11/09/01a	0	3.0	1 982	10.7	0.0	14.2	17.2	2.3
11/09/01b	0	3.0	1 979	10.7	0.2	30.7	43.2	45.2
11/09/01c	0	3.0	1 996	10.7	0.0	30.4	38.2	42.1

* Specimens soaked for 4 days

B2. UCS Test Results

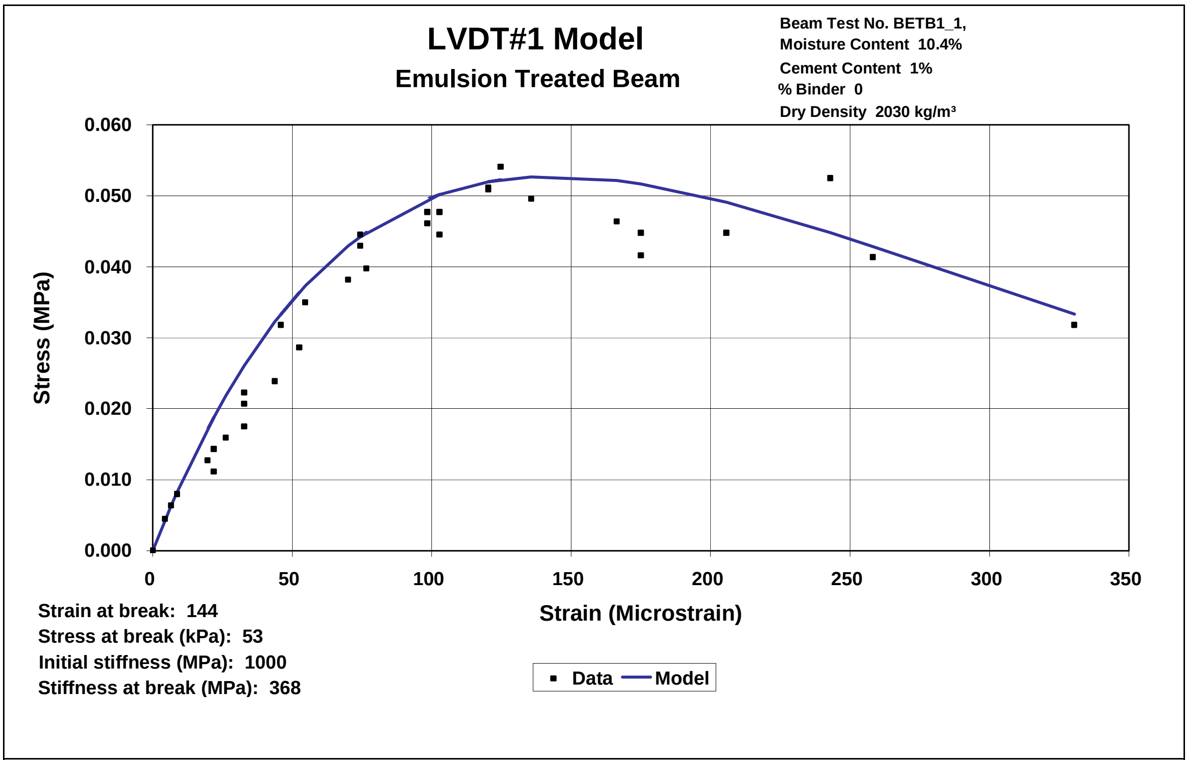
Sample no	Cement content (%)	Bitumen content (%)	Moulding Density (kg/m^3)	Moulding Moisture content (%)	UCS (kPa)
10/09/01a	0	0.6	1 947	12.6	174
10/09/01b	0	0.6	1 980	12.6	137
10/09/01c	0	0.6	1 980	12.6	165
3/09/01g	0	1.8	1 950	11.9	131.6
3/09/01h	0	1.8	1 941	11.9	142.5
3/09/01i	0	1.8	1 924	11.9	120.6
11/09/01a	0	3.0	1 964	11.1	285
11/09/01b	0	3.0	1 938	11.1	280
11/09/01c	0	3.0	1 964	11.1	384
3/09/01a	1	0.6	1 964	12.5	543
3/09/01b	1	0.6	1 943	12.5	510
3/09/01c	1	0.6	1 945	12.5	592
5/09/01d	1	1.8	1 944	12.0	548
5/09/01e	1	1.8	1 949	12.0	543
5/09/01f	1	1.8	1 943	12.0	543
7/09/01a	1	3.0	1 976	10.0	724
7/09/01b	1	3.0	1 991	10.0	658
7/09/01c	1	3.0	1 971	10.0	981

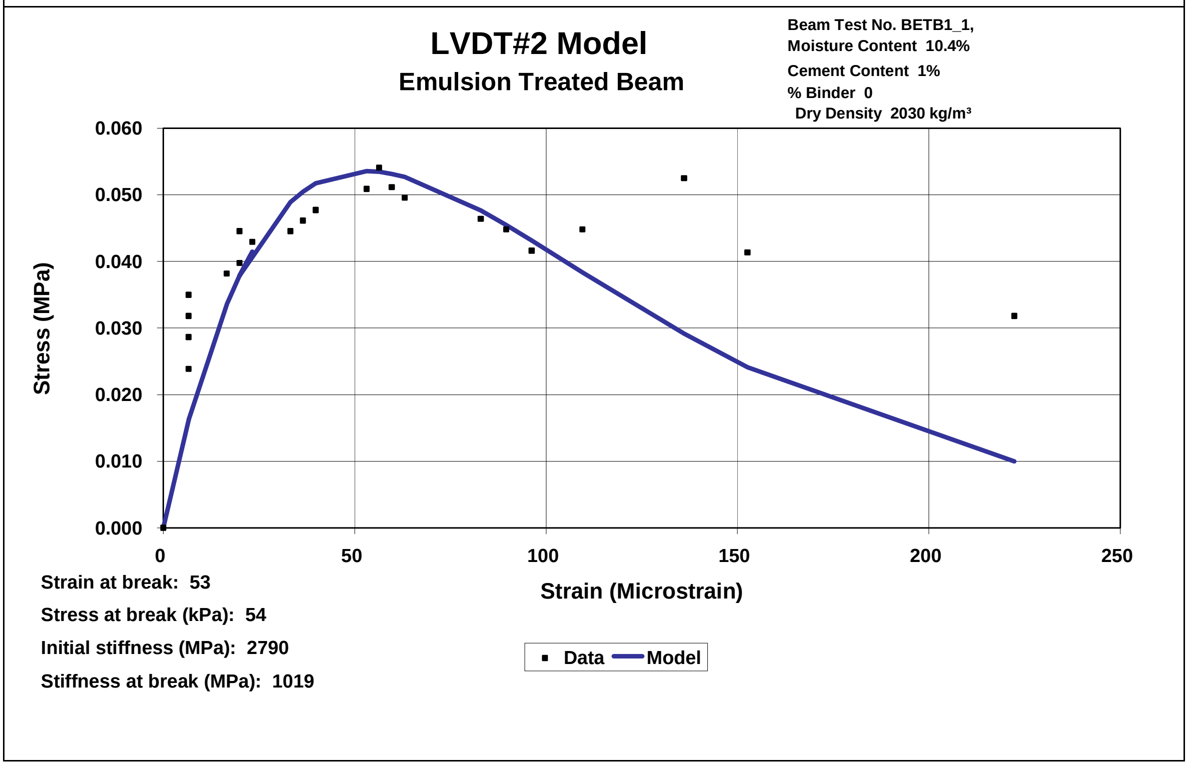
Note: Specimens soaked for 4 days

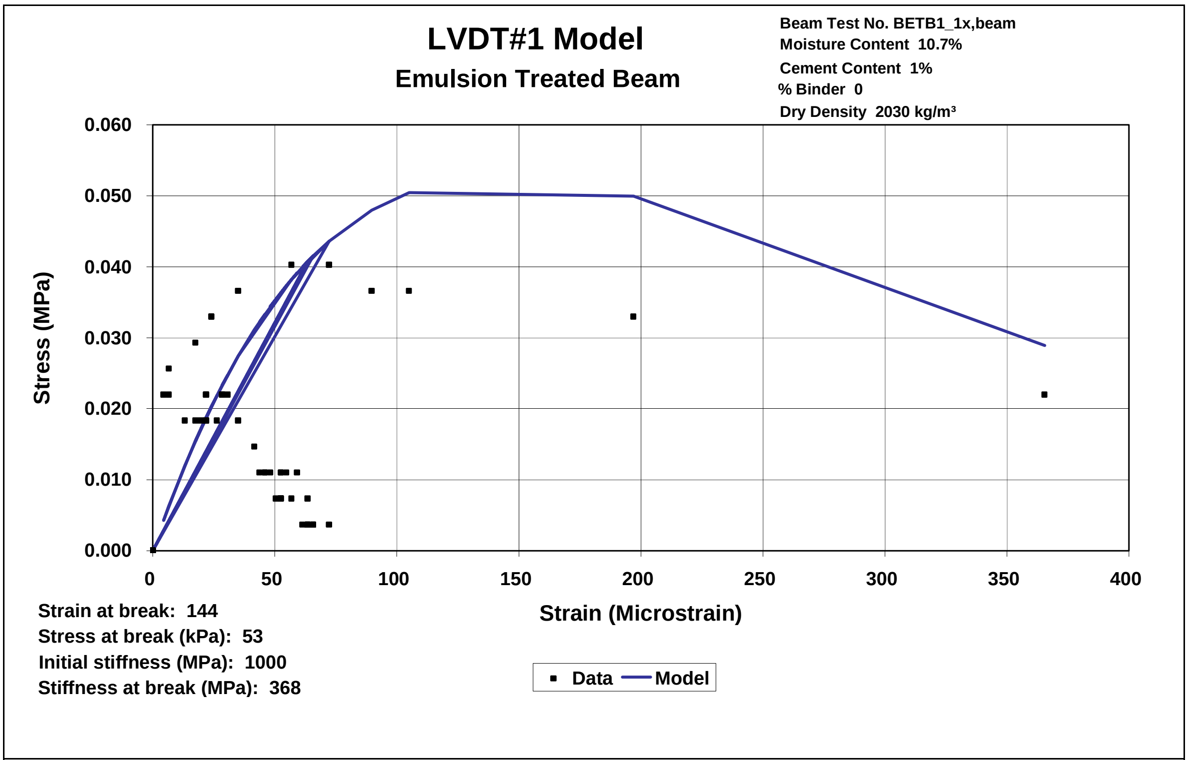
B3. ITS Test Results

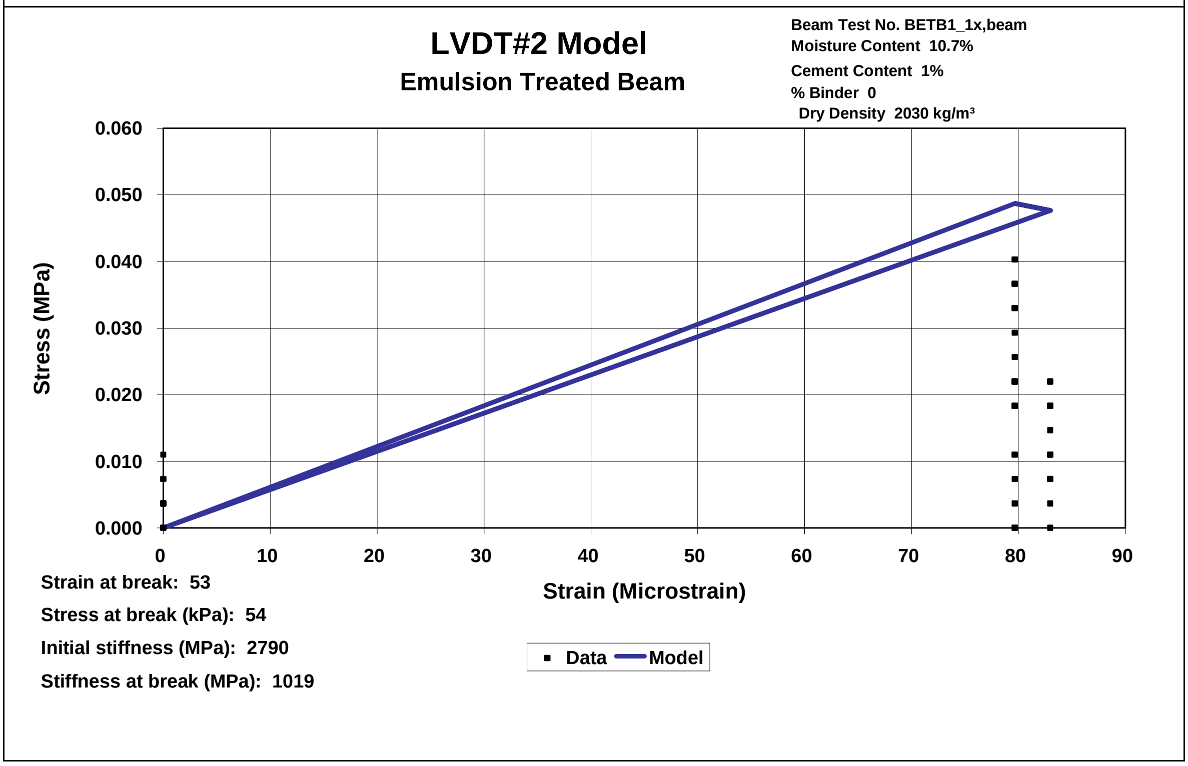
Sample no	Cement content (%)	Bitumen content (%)	Moulding Density (kg/m^3)	Moulding Moisture content (%)	ITS (kPa)
10/09/01d	0	0.6	1 942	12.6	16.4
10/09/01e	0	0.6	1 963	12.6	16.4
10/09/01f	0	0.6	1 972	12.6	16.4
3/09/01a	0	1.8	1 953	12.3	16.4
3/09/01b	0	1.8	1 936	12.3	29.6
3/09/01c	0	1.8	1 949	12.3	26.3
11/09/01d	0	3.0	1 950	11.1	32.9
11/09/01e	0	3.0	1 966	11.1	36.2
11/09/01f	0	3.0	1 978	11.1	32.9
3/09/01d	1	0.6	1 918	12.3	49.3
3/09/01e	1	0.6	1 977	12.3	59.2
3/09/01f	1	0.6	1 932	12.3	59.2
5/09/01g	1	1.8	1 965	12.0	65.8
5/09/01h	1	1.8	1 915	12.0	65.8
5/09/01i	1	1.8	1 945	12.0	62.5
7/09/01d	1	3.0	1 945	10.0	131.6
7/09/01e	1	3.0	1 954	10.0	115.1
7/09/01f	1	3.0	1 957	10.0	161.2

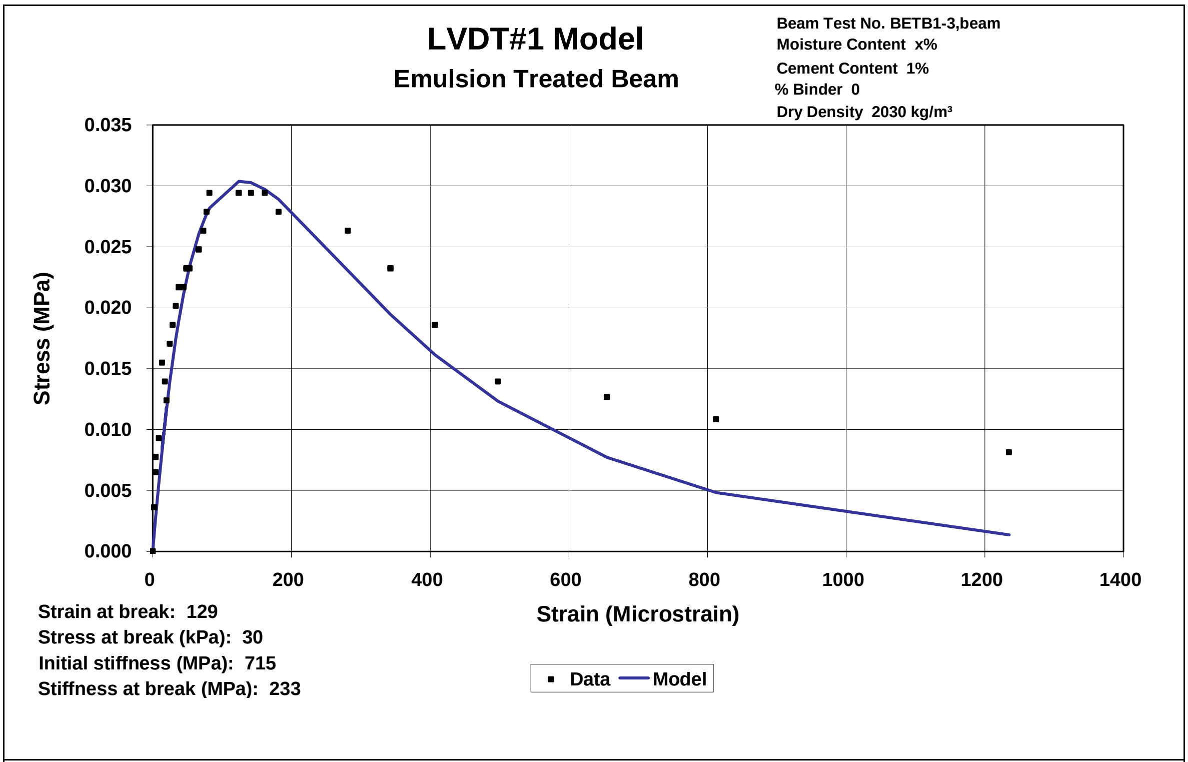
APPENDIX C: Detailed Flexural Beam Test Results

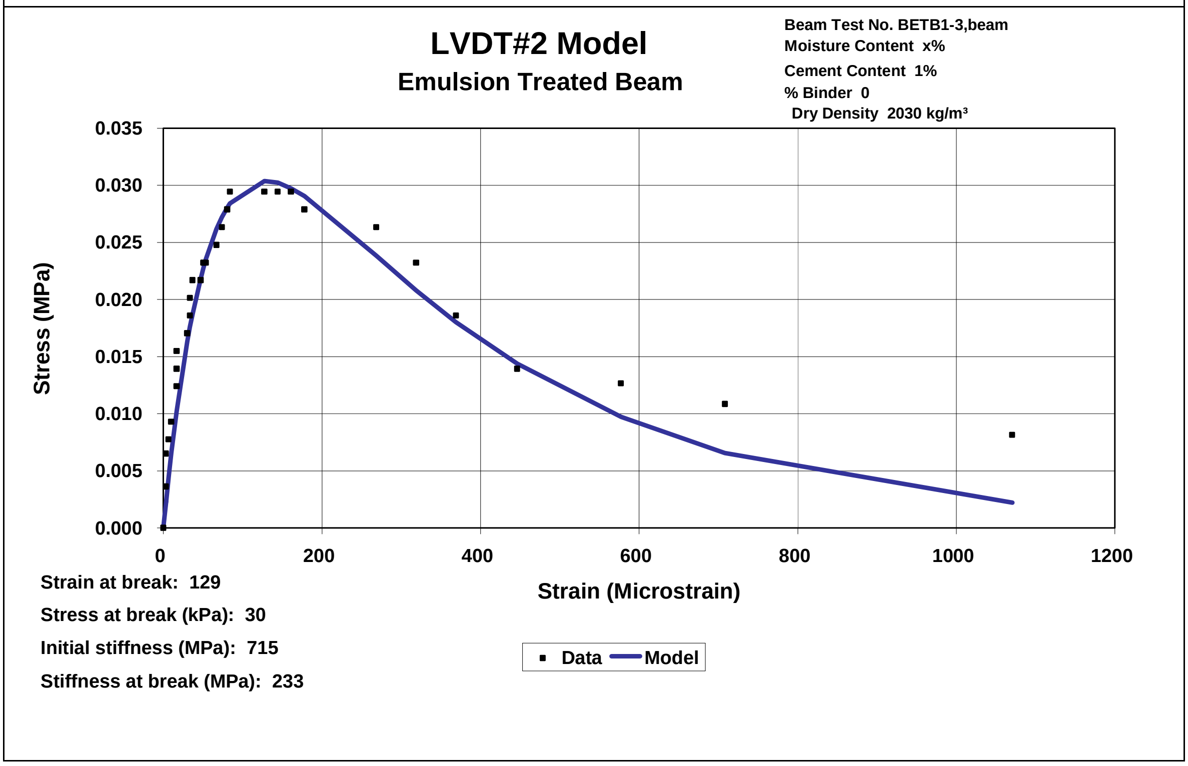

LVDT#1 Model
Emulsion Treated Beam
Beam Test No. BETB1_1,
Moisture Content 10.4%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
50
100
150
200
250
300
350
Strain (Microstrain)
Strain at break: 144
Stress at break (kPa): 53
Initial stiffness (MPa): 1000
Stiffness at break (MPa): 368
Data
Model

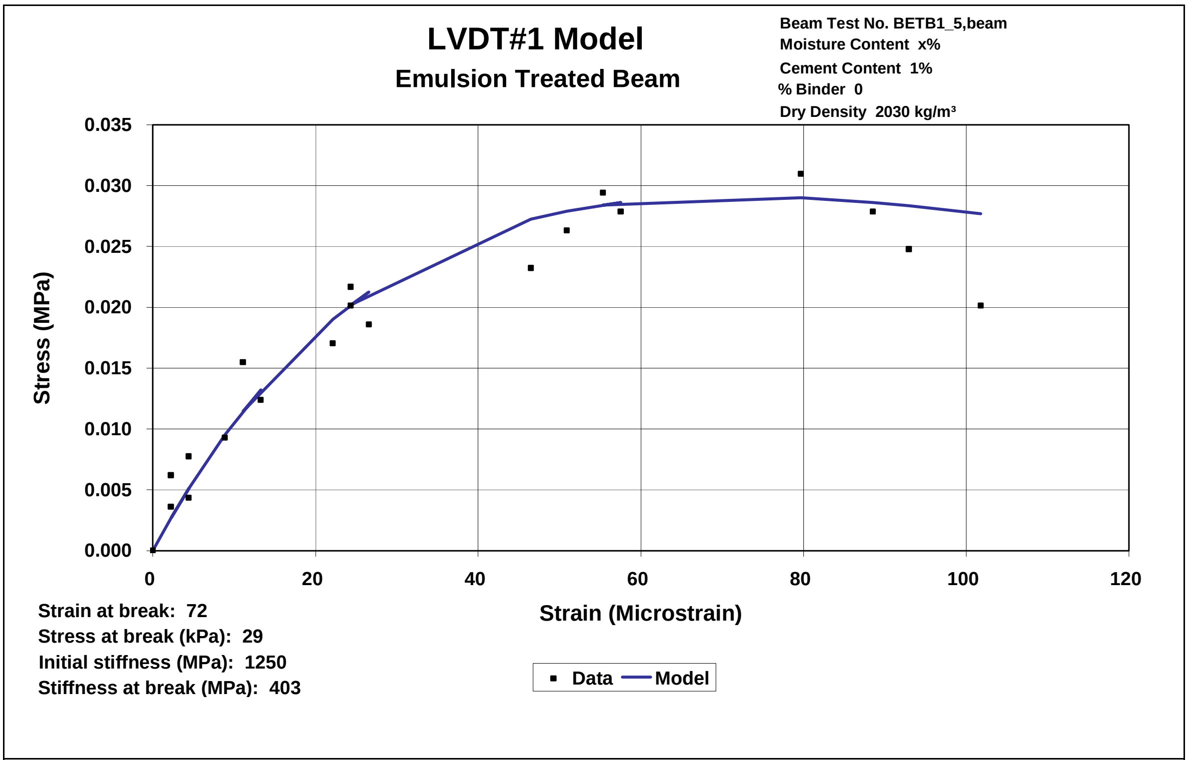

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. BETB1_1,
Moisture Content 10.4%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
50
100
150
200
250
Strain (Microstrain)
Strain at break: 53
Stress at break (kPa): 54
Initial stiffness (MPa): 2790
Stiffness at break (MPa): 1019
Data
Model

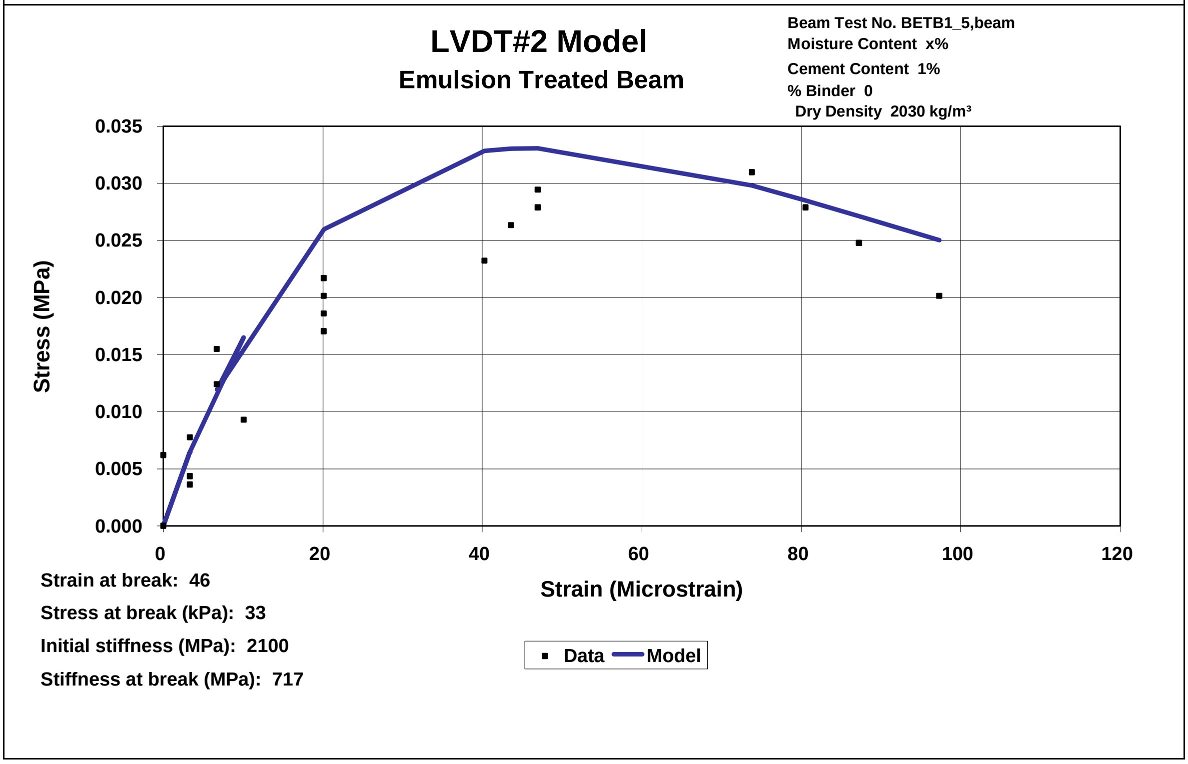

LVDT#1 Model
Emulsion Treated Beam
Beam Test No. BETB1_1x,beam
Moisture Content 10.7%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
50
100
150
200
250
300
350
400
Strain (Microstrain)
Strain at break: 144
Stress at break (kPa): 53
Initial stiffness (MPa): 1000
Stiffness at break (MPa): 368
Data
Model

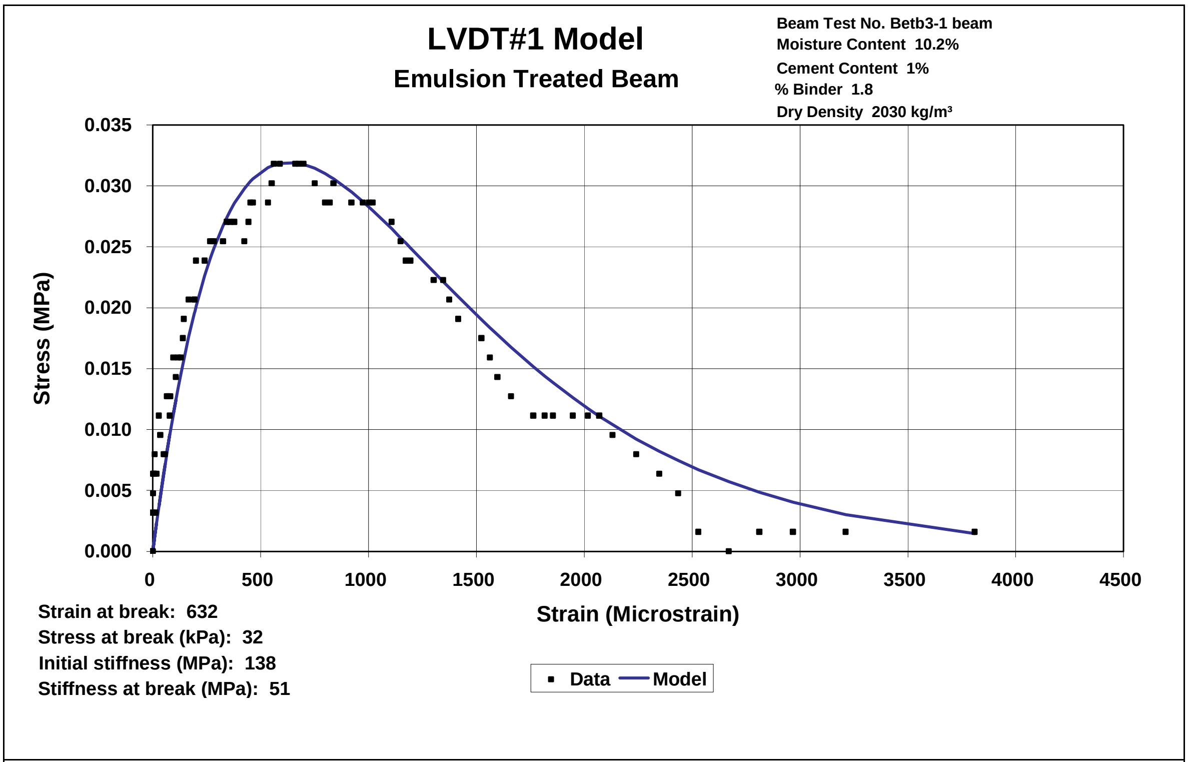

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. BETB1_1x,beam
Moisture Content 10.7%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
10
20
30
40
50
60
70
80
90
Strain (Microstrain)
Strain at break: 53
Stress at break (kPa): 54
Initial stiffness (MPa): 2790
Stiffness at break (MPa): 1019
Data
Model

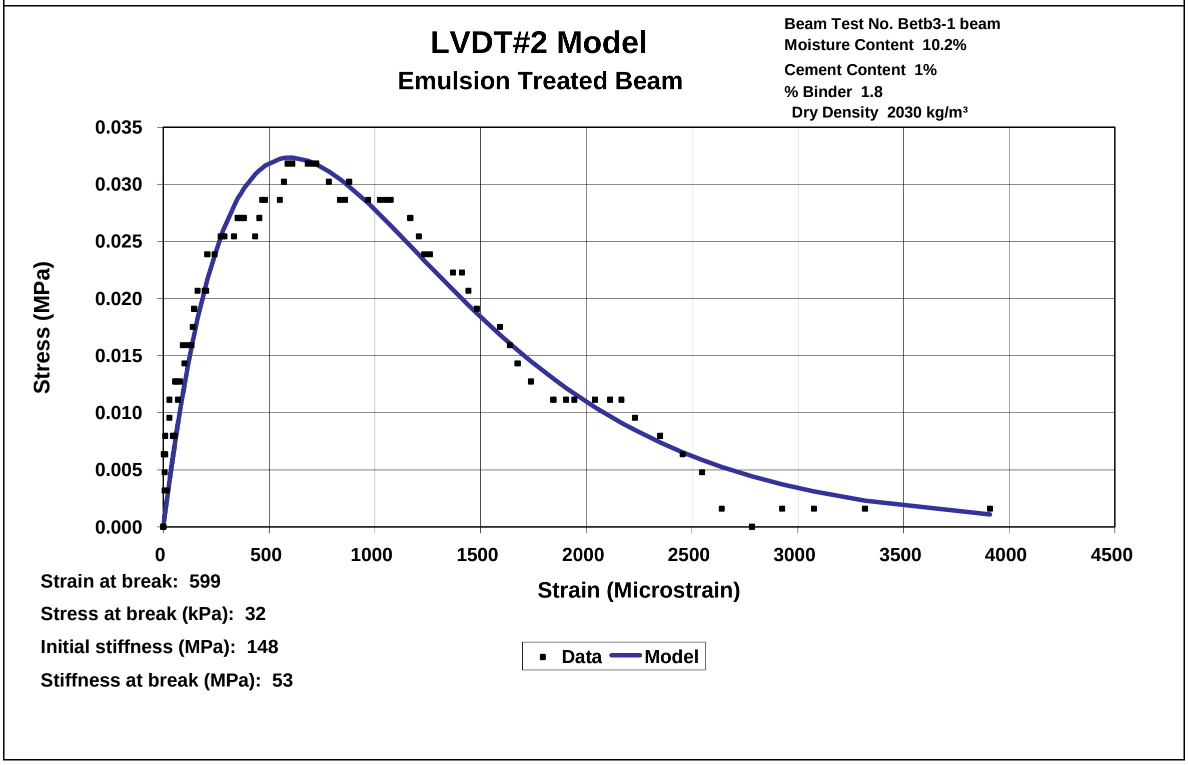

LVDT#1 Model
Emulsion Treated Beam
Beam Test No. BETB1-3,beam
Moisture Content x%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
1400
Strain (Microstrain)
Strain at break: 129
Stress at break (kPa): 30
Initial stiffness (MPa): 715
Stiffness at break (MPa): 233
Data
Model

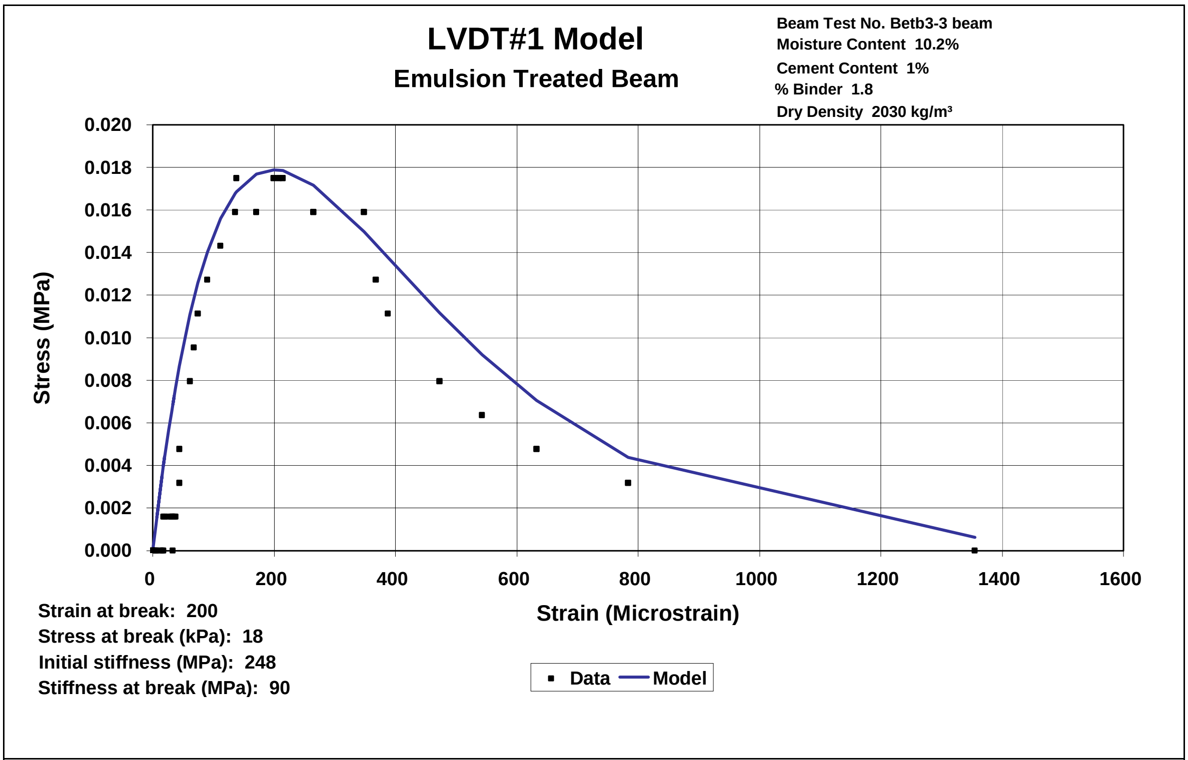

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. BETB1-3,beam
Moisture Content x%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m³
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
Strain (Microstrain)
Strain at break: 129
Stress at break (kPa): 30
Initial stiffness (MPa): 715
Stiffness at break (MPa): 233
Data
Model

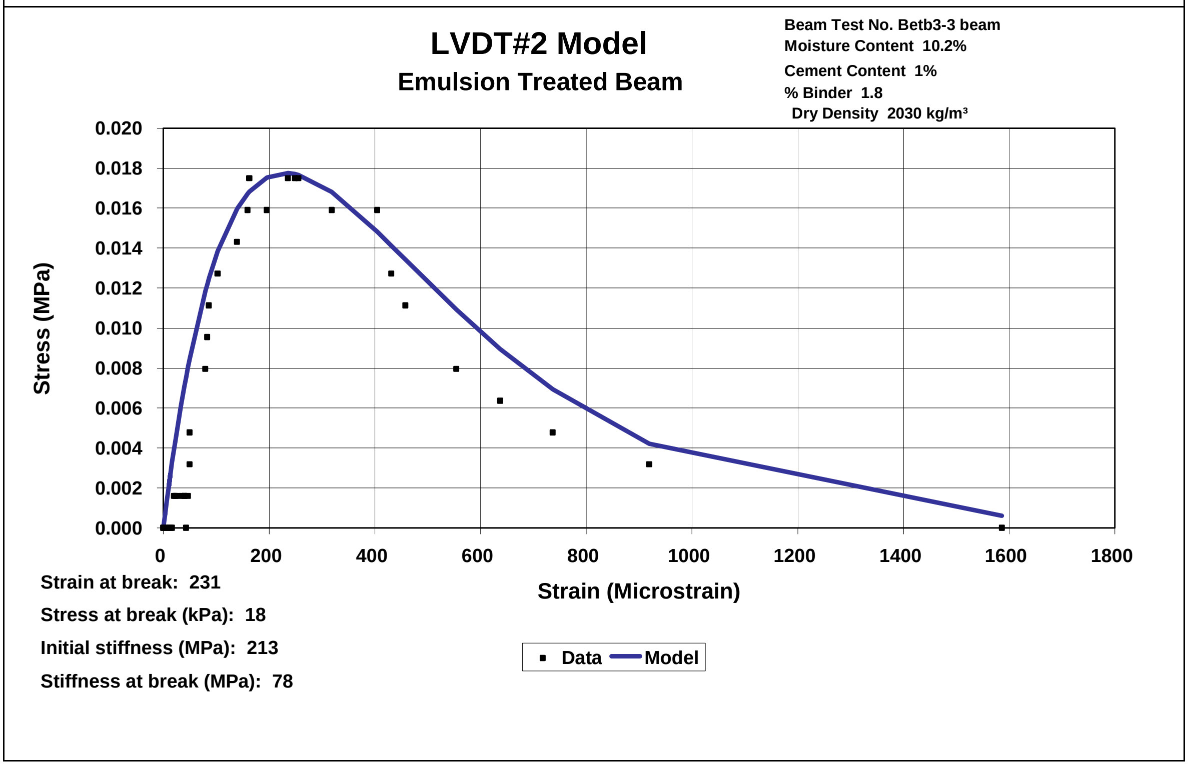

LVDT#1 Model
Emulsion Treated Beam
Beam Test No. BETB1_5,beam
Moisture Content x%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m^3
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
120
Strain (Microstrain)
Strain at break: 72
Stress at break (kPa): 29
Initial stiffness (MPa): 1250
Stiffness at break (MPa): 403
Data
Model

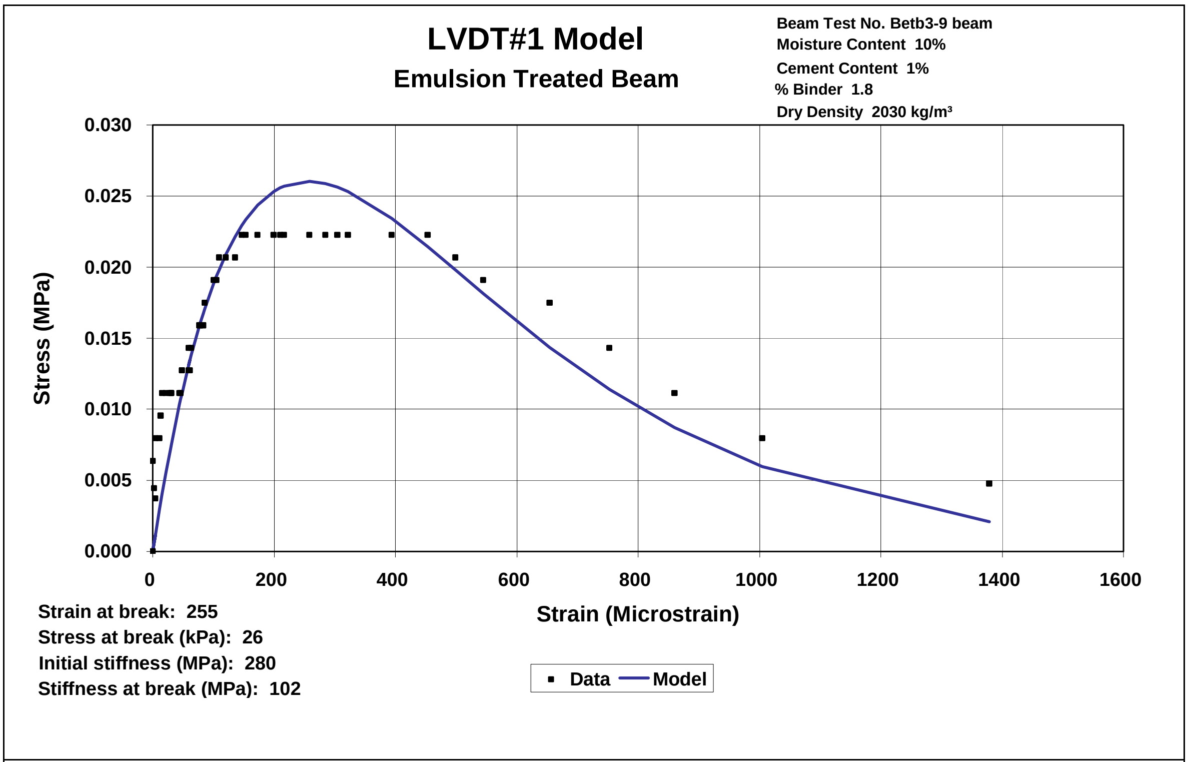

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. BETB1_5,beam
Moisture Content x%
Cement Content 1%
% Binder 0
Dry Density 2030 kg/m^3
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
120
Strain (Microstrain)
Strain at break: 46
Stress at break (kPa): 33
Initial stiffness (MPa): 2100
Stiffness at break (MPa): 717
Data
Model

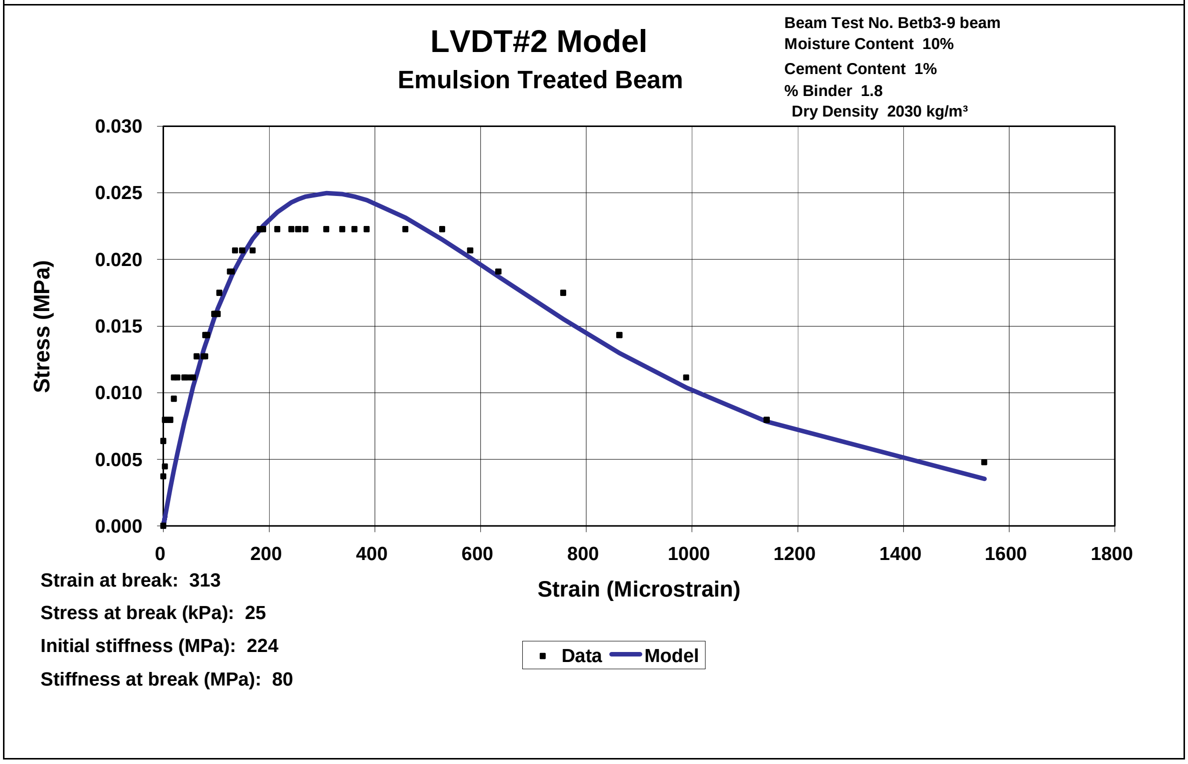

LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb3-1 beam
Moisture Content 10.2%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Strain (Microstrain)
Strain at break: 632
Stress at break (kPa): 32
Initial stiffness (MPa): 138
Stiffness at break (MPa): 51
Data
Model

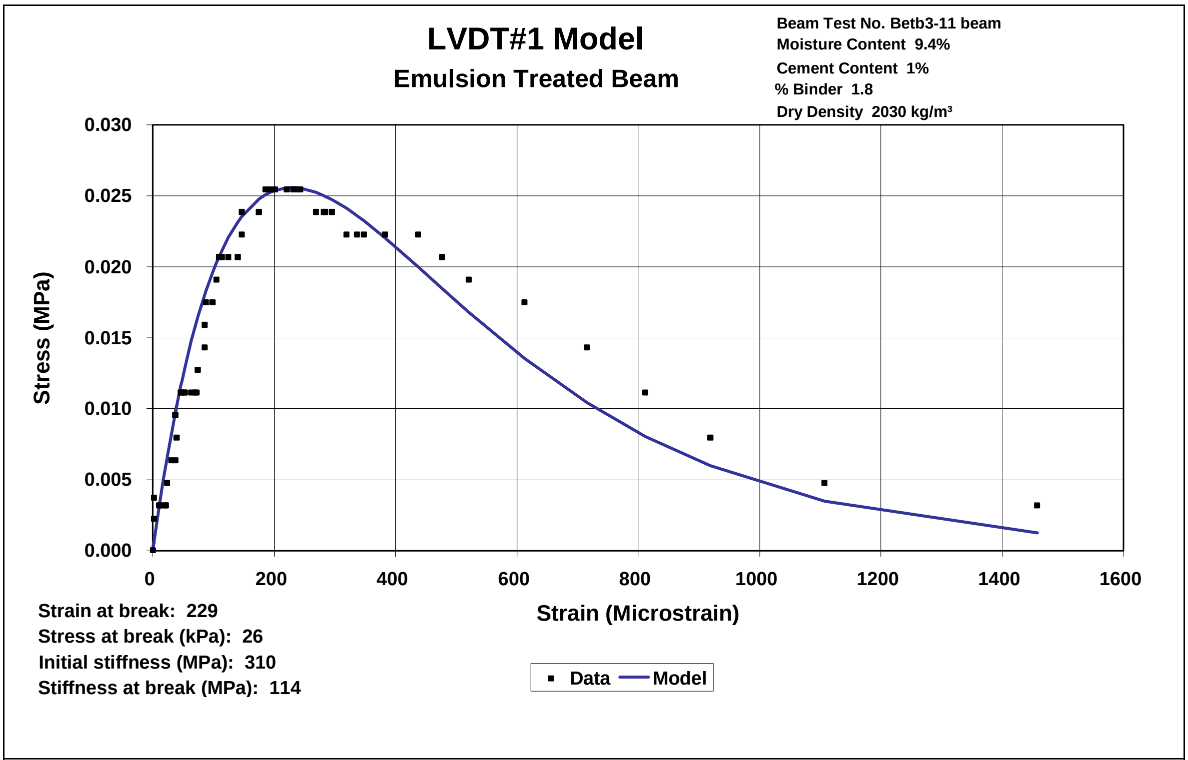

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb3-1 beam
Moisture Content 10.2%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Strain (Microstrain)
Strain at break: 599
Stress at break (kPa): 32
Initial stiffness (MPa): 148
Stiffness at break (MPa): 53
Data
Model


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb3-3 beam
Moisture Content 10.2%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
1000
1200
1400
1600
Strain (Microstrain)
Strain at break: 200
Stress at break (kPa): 18
Initial stiffness (MPa): 248
Stiffness at break (MPa): 90
Data
Model

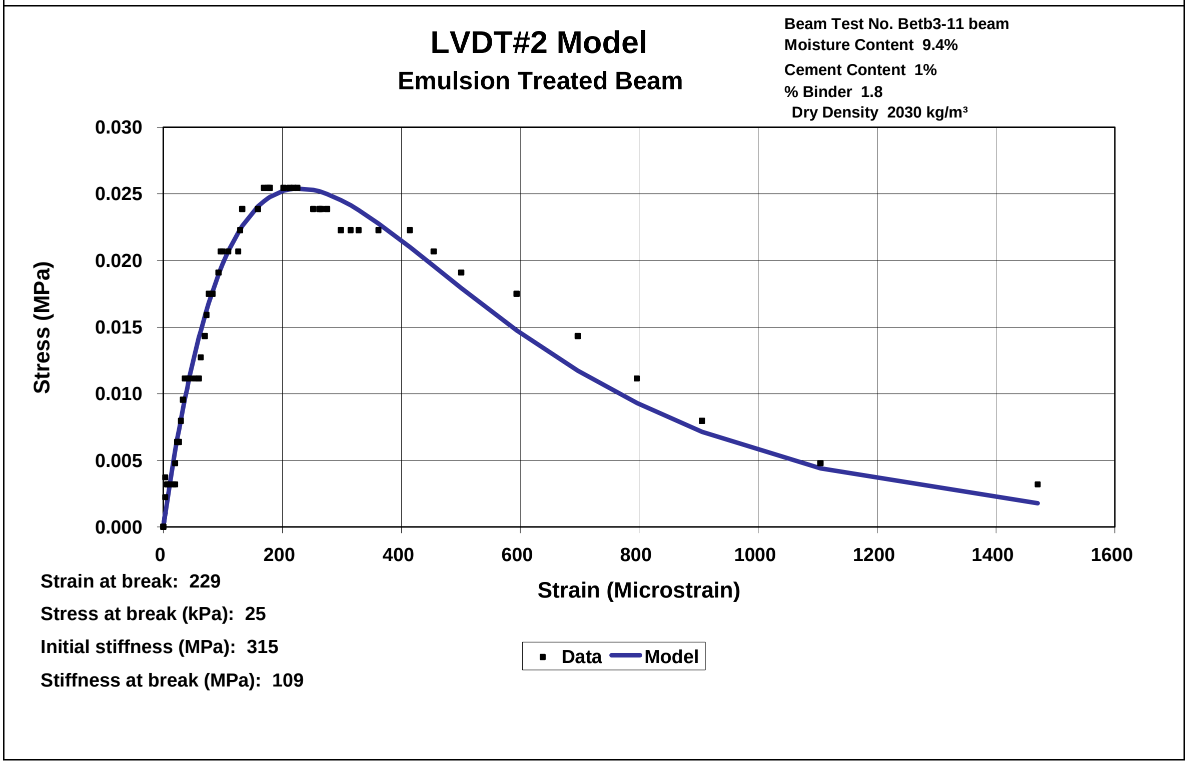

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb3-3 beam
Moisture Content 10.2%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
Strain (Microstrain)
Strain at break: 231
Stress at break (kPa): 18
Initial stiffness (MPa): 213
Stiffness at break (MPa): 78
Data
Model


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb3-9 beam
Moisture Content 10%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
1400
1600
Strain (Microstrain)
Strain at break: 255
Stress at break (kPa): 26
Initial stiffness (MPa): 280
Stiffness at break (MPa): 102
Data
Model

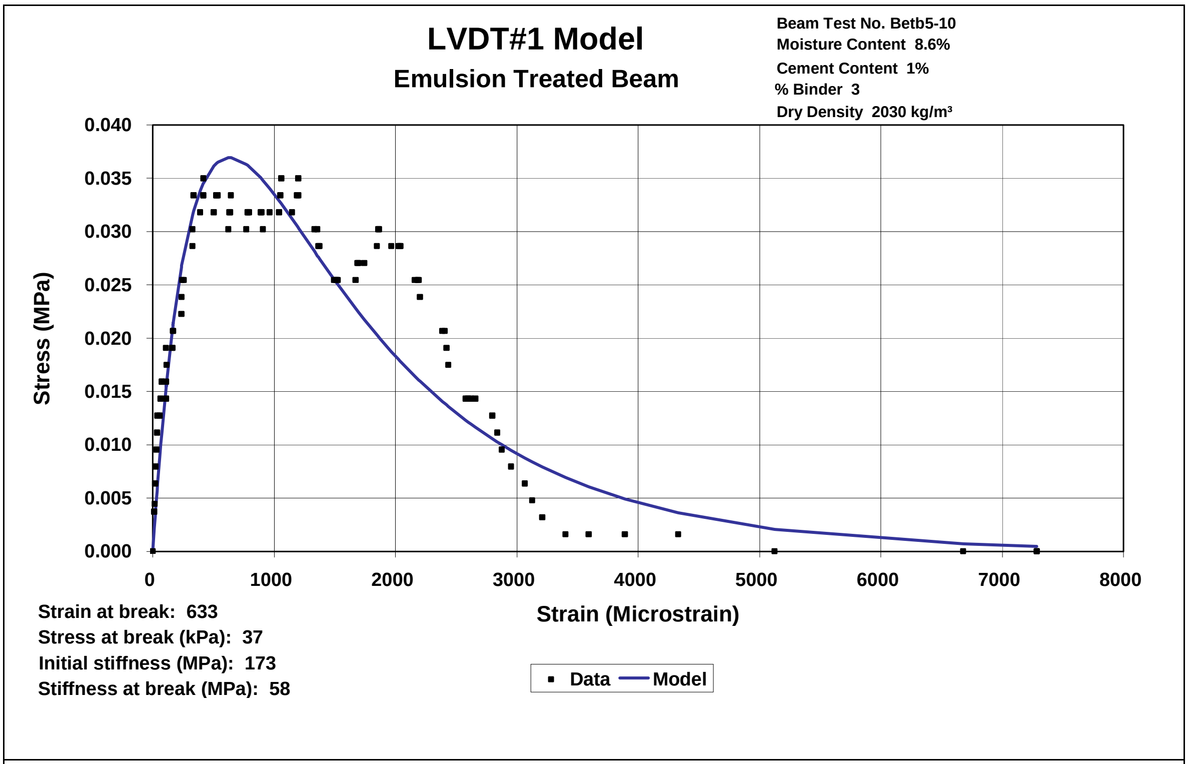

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb3-9 beam
Moisture Content 10%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
1400
1600
1800
Strain (Microstrain)
Strain at break: 313
Stress at break (kPa): 25
Initial stiffness (MPa): 224
Stiffness at break (MPa): 80
Data
Model

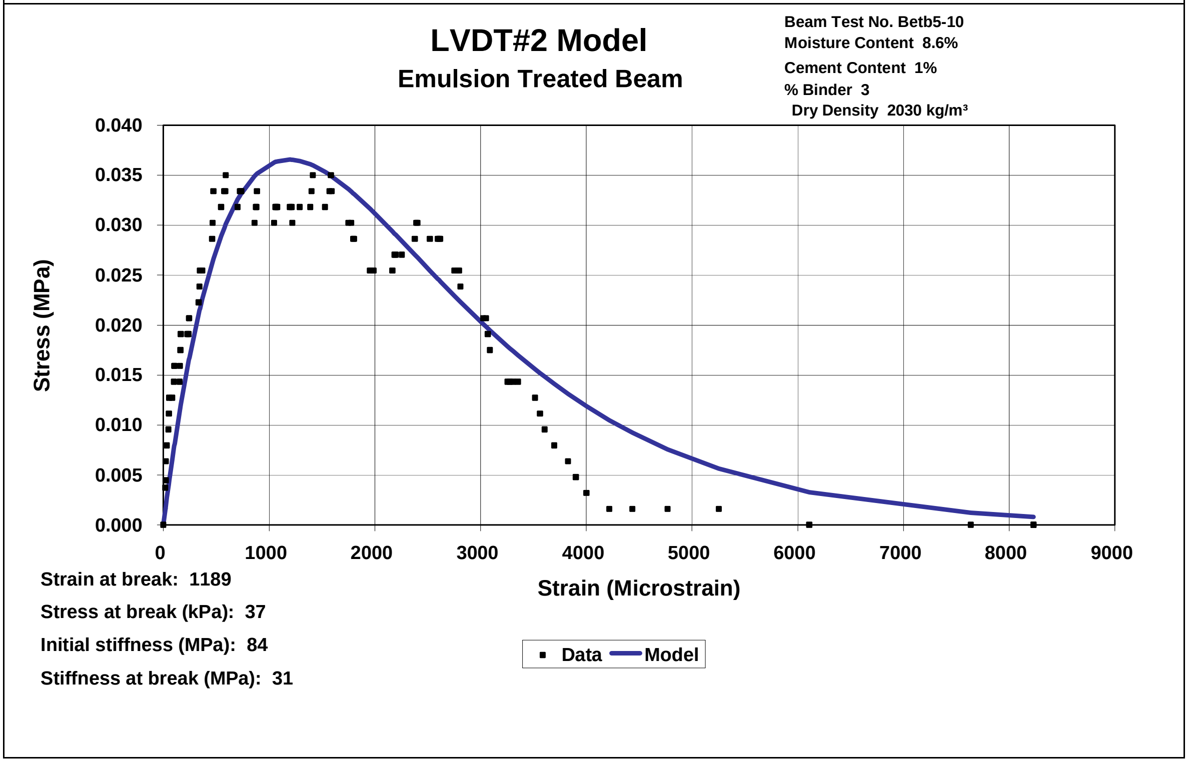


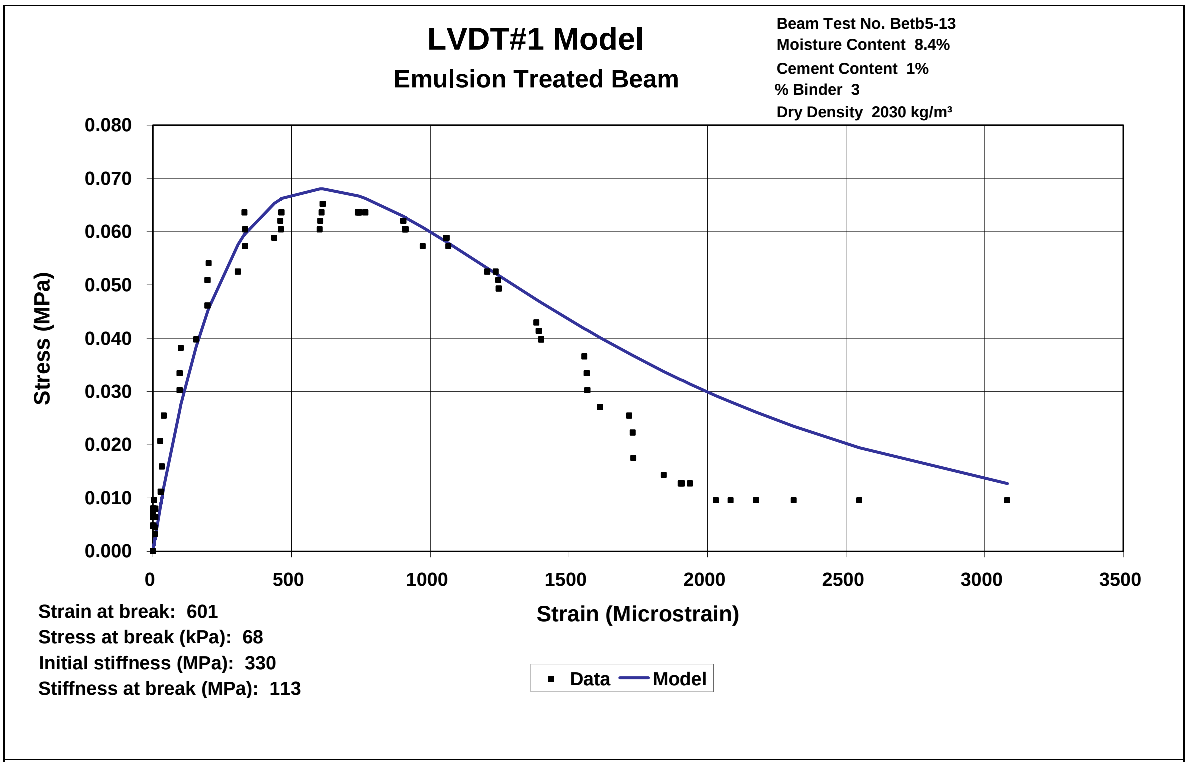
LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb3-11 beam
Moisture Content 9.4%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
1400
1600
Strain (Microstrain)
Strain at break: 229
Stress at break (kPa): 26
Initial stiffness (MPa): 310
Stiffness at break (MPa): 114
Data
Model

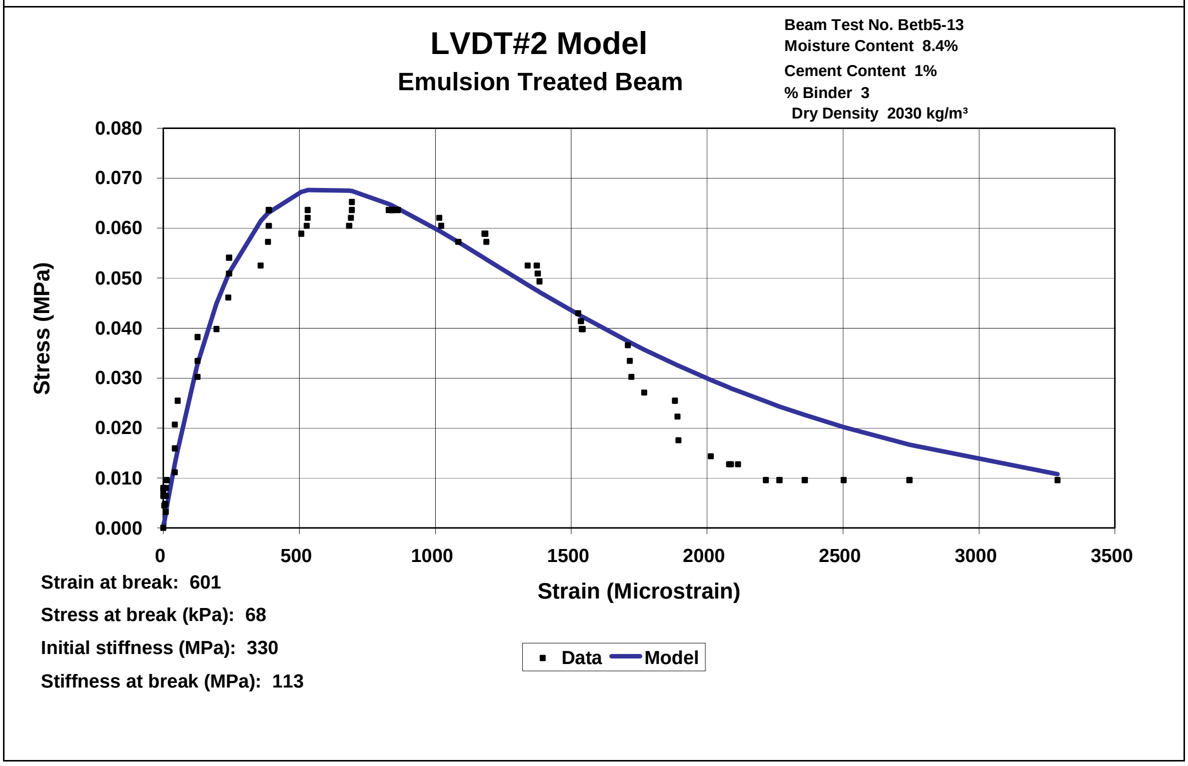


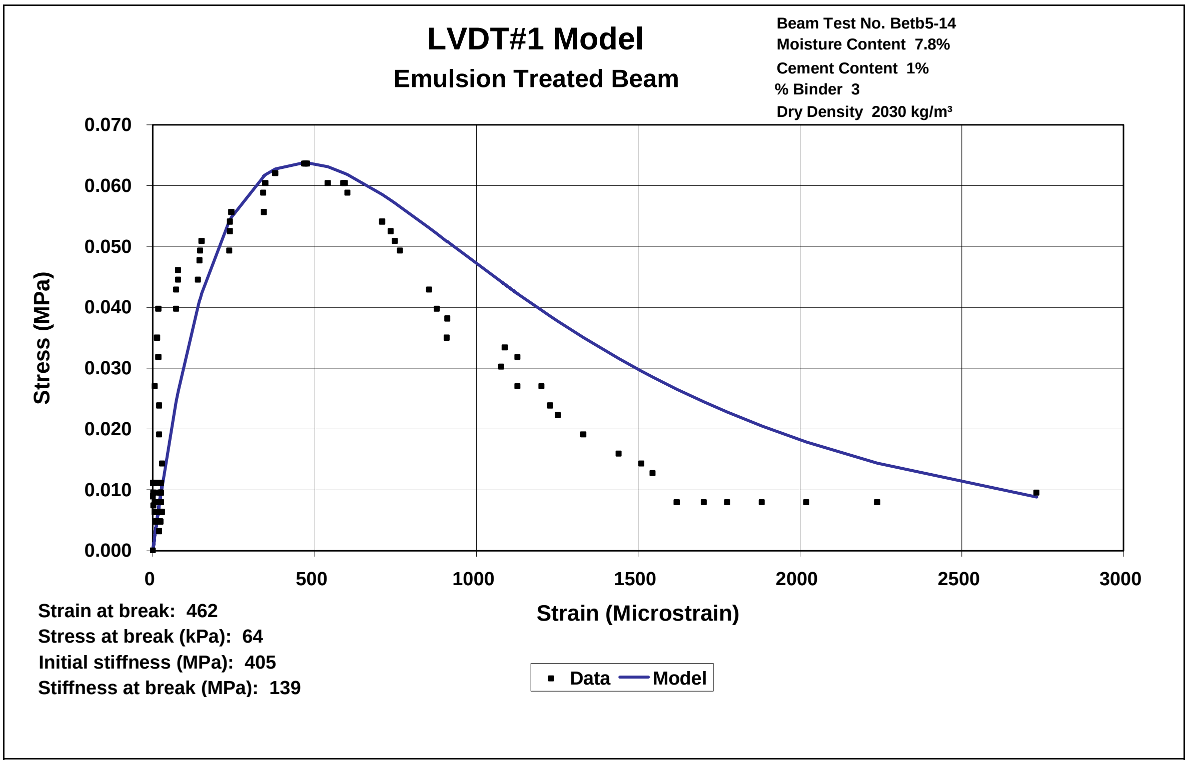
LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb3-11 beam
Moisture Content 9.4%
Cement Content 1%
% Binder 1.8
Dry Density 2030 kg/m³
Stress (MPa)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
1200
1400
1600
Strain (Microstrain)
Strain at break: 229
Stress at break (kPa): 25
Initial stiffness (MPa): 315
Stiffness at break (MPa): 109
Data
Model


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb5-10
Moisture Content 8.6%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Stress (MPa)
0
1000
2000
3000
4000
5000
6000
7000
8000
Strain (Microstrain)
Strain at break: 633
Stress at break (kPa): 37
Initial stiffness (MPa): 173
Stiffness at break (MPa): 58
Data
Model

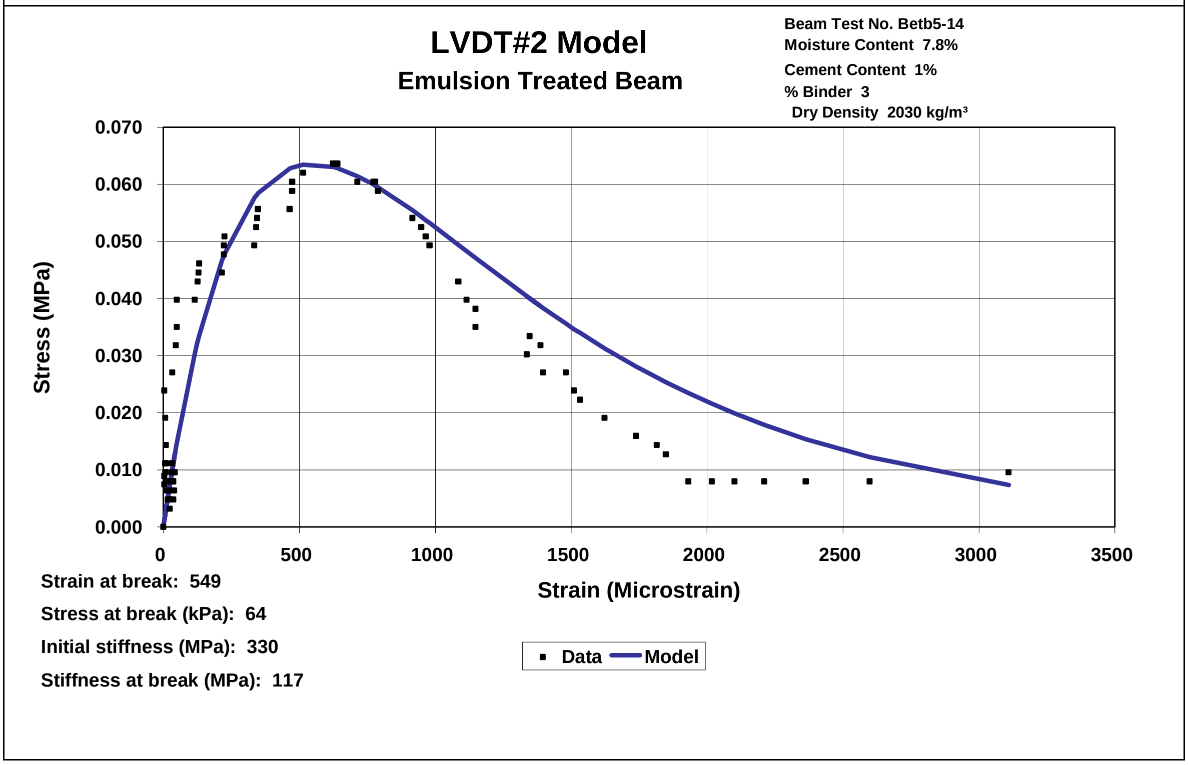

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb5-10
Moisture Content 8.6%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Stress (MPa)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Strain (Microstrain)
Strain at break: 1189
Stress at break (kPa): 37
Initial stiffness (MPa): 84
Stiffness at break (MPa): 31
Data
Model


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb5-13
Moisture Content 8.4%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
Strain (Microstrain)
Strain at break: 601
Stress at break (kPa): 68
Initial stiffness (MPa): 330
Stiffness at break (MPa): 113
Data
Model

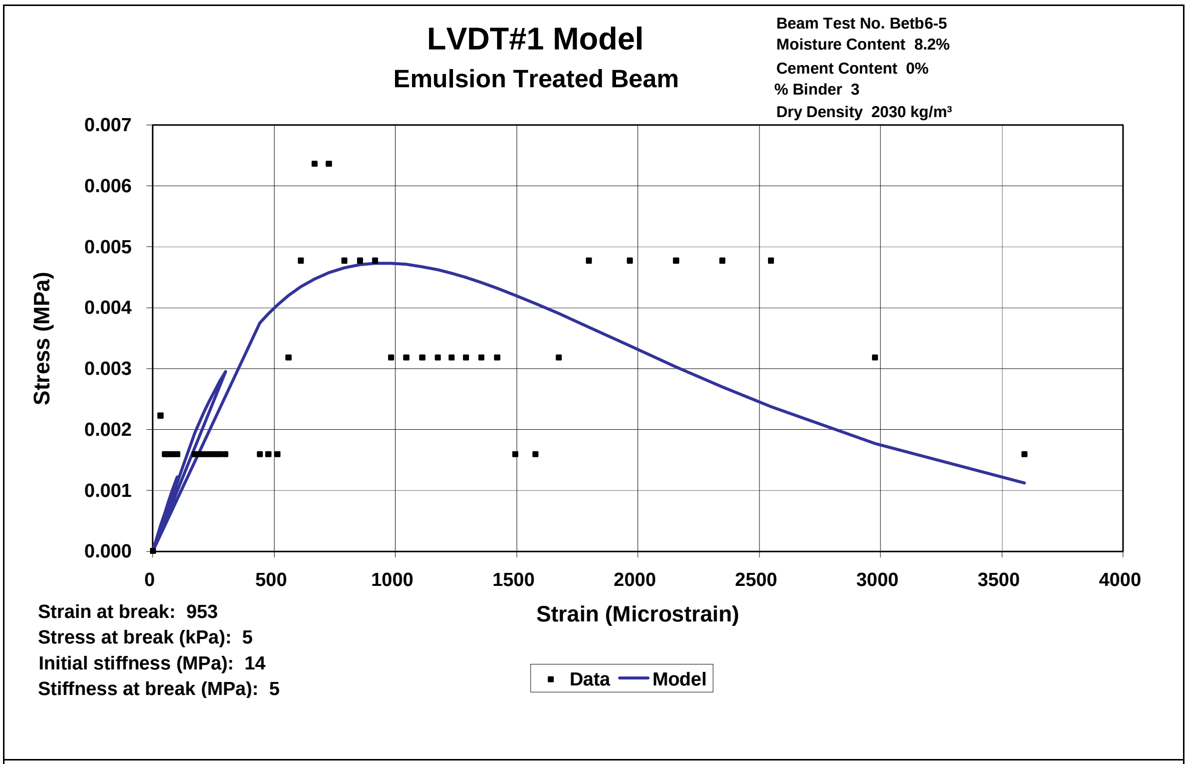

LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb5-13
Moisture Content 8.4%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
Strain (Microstrain)
Strain at break: 601
Stress at break (kPa): 68
Initial stiffness (MPa): 330
Stiffness at break (MPa): 113
Data
Model

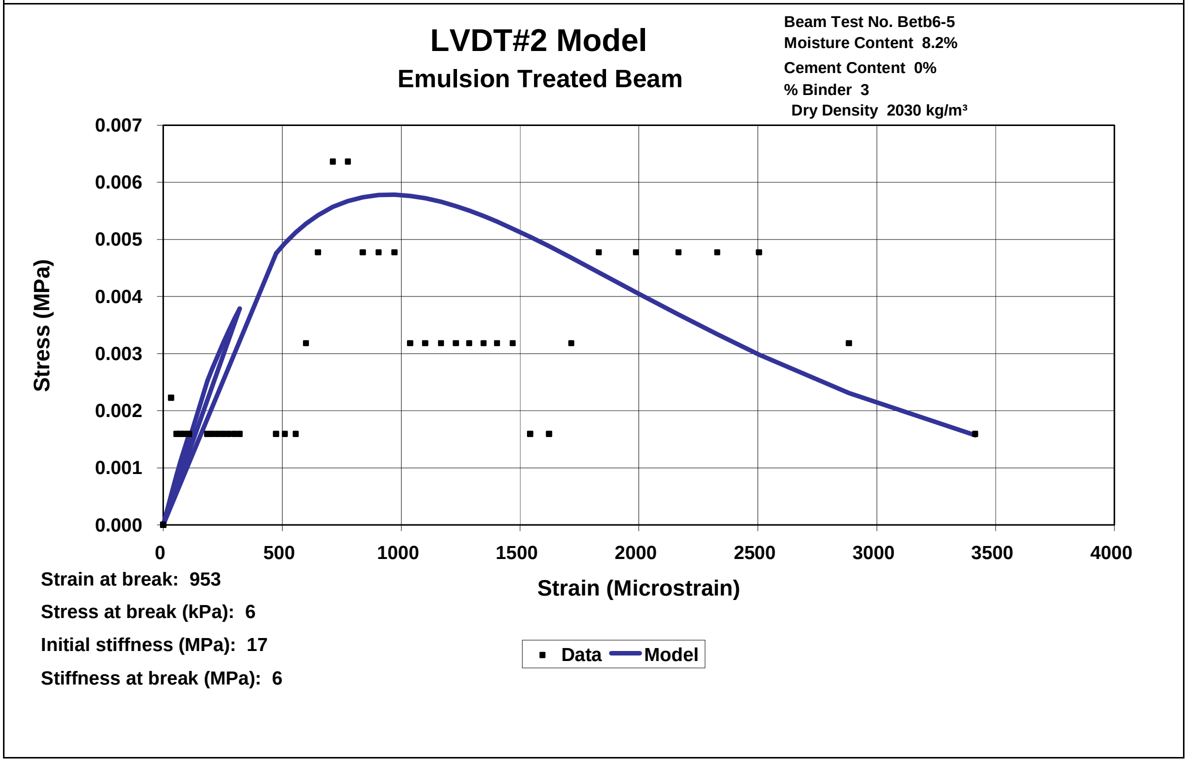


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb5-14
Moisture Content 7.8%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
500
1000
1500
2000
2500
3000
Strain (Microstrain)
Strain at break: 462
Stress at break (kPa): 64
Initial stiffness (MPa): 405
Stiffness at break (MPa): 139
Data
Model



LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb5-14
Moisture Content 7.8%
Cement Content 1%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
500
1000
1500
2000
2500
3000
3500
Strain (Microstrain)
Strain at break: 549
Stress at break (kPa): 64
Initial stiffness (MPa): 330
Stiffness at break (MPa): 117
Data
Model


LVDT#1 Model
Emulsion Treated Beam
Beam Test No. Betb6-5
Moisture Content 8.2%
Cement Content 0%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
500
1000
1500
2000
2500
3000
3500
4000
Strain (Microstrain)
Strain at break: 953
Stress at break (kPa): 5
Initial stiffness (MPa): 14
Stiffness at break (MPa): 5
Data
Model


LVDT#2 Model
Emulsion Treated Beam
Beam Test No. Betb6-5
Moisture Content 8.2%
Cement Content 0%
% Binder 3
Dry Density 2030 kg/m³
Stress (MPa)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
500
1000
1500
2000
2500
3000
3500
4000
Strain (Microstrain)
Strain at break: 953
Stress at break (kPa): 6
Initial stiffness (MPa): 17
Stiffness at break (MPa): 6
Data
Model

APPENDIX D: Work Proposal and Discussion Framework