

## APPENDIX C

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Technical Memorandum

### **Updating Bituminous Stabilized Materials Guidelines: Mix Design Report, Phase II**

#### **Task 3 – Correlation of BSM Stiffness Part I**

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# 1. BACKGROUND AND INTRODUCTION

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## 1.1. Terms of Reference

The stiffness of an engineering material is an important material property that is widely used for the design of structures incorporating such materials. Hence also in pavement engineering the stiffness of the road building materials that make up the pavement structure is used for structural design and pavement modelling. The stiffness (resilient modulus) of a material can accurately be measured in a short duration dynamic tri-axial test.

In the Inception Study (Jenkins *et al.*, 2006) it was discussed that this test is fairly difficult to perform due to the nature of the test and the delicate and sensitive measuring equipment required. One has to consider that the total deformation over the middle third of a 300 mm high test specimen can be as little as 0.1 mm, repeated at 10 cycles per second. This requires a sensitive and high speed data acquisition system. Also, robust LVDT mountings free of any movement are of paramount importance. The test is therefore time consuming and expensive. This factor has been mentioned by Jenkins *et al.* (2007) to be one of the reasons why the resilient modulus is not always included in tri-axial investigation and only monotonic and long duration dynamic tests (permanent deformation) are performed.

It is against this background that in the Inception Study the question was raised whether a simple and reliable alternative exists to provide fundamental stiffness properties that can be used as input in mix design testing and pavement design. This led to the definition of a number research objectives for Phase II of Updating the Bituminous Stabilized Materials Guidelines. These are listed in the following section.

## 1.2. Task Objectives

In the Project Proposal (PP/2005/09/c) for Phase II of Updating Bituminous Stabilized Materials Guidelines the objectives of Task 3 were listed as follows:

- Gather data for several cold mixes from monotonic and dynamic tri-axial as well as flexural stiffness from Four Point Bending Test. Some of the data should be gathered from the CSIR. This will not include additional research testing but rather use of current data;
- Correlate resilient properties from the three tests taking account of the differences in loading rate, temperature, *etc.*;
- Compare stiffness values with representative mix stiffness for equivalent materials in field conditions; and
- Discern which method of testing is most reliable and whether a simple reliable alternative exists.

## 2. STIFFNESS OF BITUMEN STABILISED MATERIALS

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### 2.1. Stiffness from monotonic tri-axial test

#### Introduction

The monotonic tri-axial test is used to determine shear parameters, *i.e.* cohesion and friction angle. Only the maximum stress at failure ( $\sigma_{max}$ ) for a given confining stress ( $\sigma_3$ ) is taken into consideration. Other information that can possibly be extracted from the monotonic tri-axial test is often ignored.

This possible other information from the engineering stress-strain diagram could include tangent and secant moduli. These are both stiffness moduli that can be derived from a monotonic test. The tangent modulus ( $E_{tan}$ ) is defined here as slope of the tangent at the linear part of the stress-strain diagram or where the steepest slope occurs. The secant modulus ( $E_{sec}$ ) is defined here as the slope of the line drawn from the origin of the stress-strain diagram to the point on the curve where the maximum stress occurs. In this project the applied stress ( $\sigma_a$ ) will be used in the determination of the secant modulus and not the major principal stress ( $\sigma_a + \sigma_3$ ). The strain at which the maximum stress occurs defines the strain-at-failure ( $\epsilon_f$ ). These respective parameters are shown in the schematic stress-strain diagram in Figure C-1.

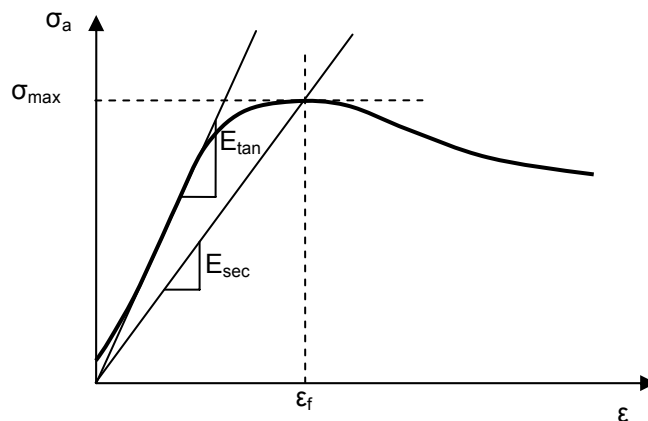


Figure C-1: Stress-strain diagram defining tangent and secant modulus, maximum stress and strain-at-failure

In comparing the stiffness moduli derived from a monotonic tests with resilient moduli derived from dynamic tests, one should keep in mind differences that exist in the test conditions. The main difference is in the rate of loading. The dynamic resilient modulus tri-axial test is carried out at a loading frequency of 10 Hz. The strains observed during the resilient modulus tests in combination with a loading frequency of 10 Hz result in loading rates in the order of 1.0 % strain/sec for the dynamic tests. The strain rate for the monotonic tests is 0.1 % strain/sec. It can thus be concluded that the applied loading rate in a monotonic tri-axial tests is an order of magnitude 10 lower than in a dynamic tri-axial test. This may result in a significant difference in stiffness moduli derived from the respective tests.

Furthermore, it needs to be kept in mind that there is a systematic error between the tangent modulus as derived from the monotonic tri-axial test and the resilient modulus derived from the dynamic tri-axial test. This results from the different manner in which displacements are measured (actuator LVDT *vs.* on-specimen LVDT's).

*Stiffness measurements by University of Stellenbosch*

Ebels (2008) carried out tri-axial tests on a number of BSM's. In summary, the materials tested included two blends of virgin crushed limestone rock and RAP millings with different proportions of each:

- 75% crushed rock and 25% millings (labelled 75C); and
- 25% crushed rock and 75% millings (labelled 75M).

The first blend (75C) was tested both with 1.0 % (m/m) cement as active filler (75C-1) and without any active filler (75C-0). The second blend (75M) was only tested without active filler (75M-0). Three different bituminous binders were used to produce the cold mixes:

- two bitumen emulsions (labelled A and B); and
- one foamed bitumen (labelled C).

The residual binder content (same for all three binders) was 3.6 % for the 75C mixes and 2.4 % for the 75M mixes. This resulted in a testing matrix of nine different mixes.

Monotonic tri-axial tests were carried out 25 °C. A monotonic displacement controlled loading was applied at a rate of 2.6 % axial strain per minute. Four different confinement pressures, *i.e.* 25 kPa, 50 kPa, 100 kPa and 200 kPa, were used as standard procedure. However, for some of the mixes 40 kPa and 60 kPa were used as the two lowest confinement pressures (A-75M-0, C-75C-0, C-75C-1 and C-75M-0). The confinement was applied by controlling the air pressure in the tri-axial cell. The shear parameters of the mixes tested are summarised in Figure C-2.

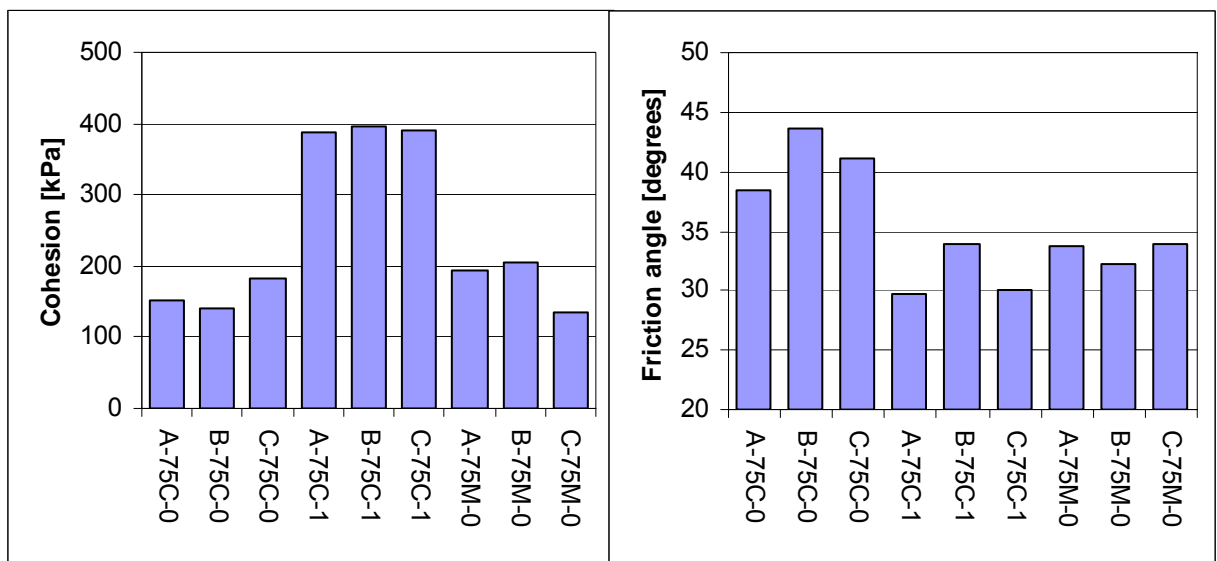


Figure C-2: Summary of shear parameters of mixes tested at Stellenbosch University (Ebels, 2008)

For each of these mixes the tangent and secant moduli were determined and these are in summary shown in Figure C-3 and Figure C-4 respectively.

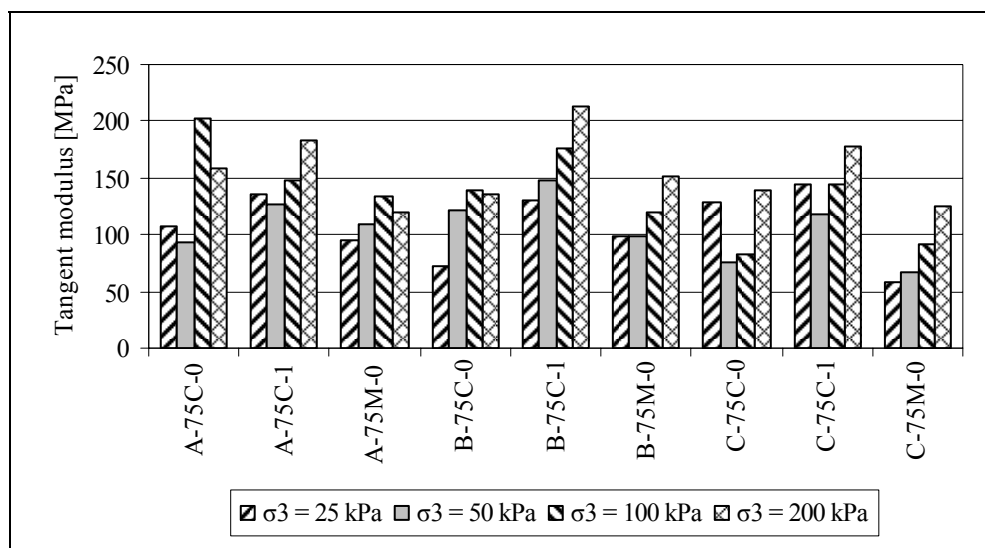


Figure C-3: Tangent modulus per mix and confinement pressure (Ebels, 2008)

It can be seen that the tangent modulus generally varies between 50 MPa and 200 MPa. As the tangent modulus is determined from the linear part of the stress-strain diagram, it should provide an indication of the elastic stiffness modulus of the material. The tangent modulus also shows a stress dependent behaviour, although for some mixes (*eg.* A-75C-0, C-75C-0 and C-75C-1) this trend is less consistent. When comparing the three different blends per binder, the blends with 1 % cement (75C-1) show without exception the highest tangent modulus. The tangent moduli for these three 75C-1 mixes are comparable. There is also a tendency that when comparing the three different blends per binder, the blend with 75 % RAP (75M-0) shows the lowest tangent modulus. Finally, it can clearly be seen that the C-75M-0 mix provides the lowest tangent moduli of all nine mixes.

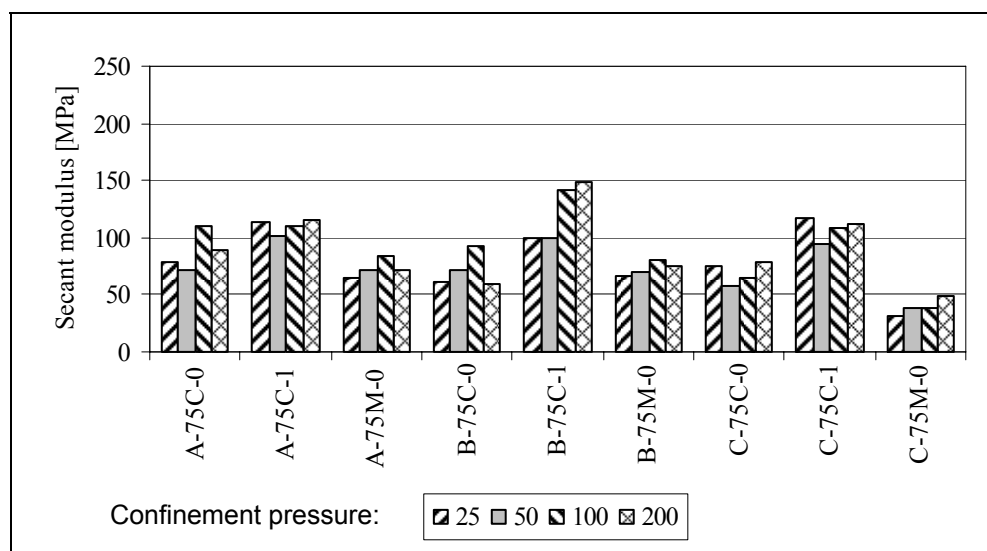


Figure C-4 : Secant modulus per mix and confinement pressure (Ebels, 2008)

As opposed to the tangent modulus, the secant modulus shows no clear stress dependency. This can be explained by the fact that both the maximum stress and the strain-at-failure increase with increasing bulk stress. As both parameters have a similar but opposite effect on the secant modulus, the net effect is little change to the secant modulus. There would also appear to be less variation between the nine mixes when evaluating the secant modulus.

Although the secant modulus does show that the blends with active filler have the highest stiffness per binder and that the C-75M-0 mix shows the lowest secant modulus (as it did for the tangent modulus), Ebels (2008) regarded the secant modulus not to have the potential to evaluate mixes qualitatively nor quantitatively in terms of stiffness.

Stiffness measurements by CSIR

Selected BSM's tested by the CSIR have been analysed under this task. These include crushed stone from the Contermanskloof quarry near the N7 in the Cape region and a 50/50 blend of sand and calcrete sourced from the R22 (P423) in the KwaZulu Natal region. Details on these mixes are given elsewhere (Long and Ventura, 2003; Long and Theyse, 2005). These mixes were selected on the basis that they are comparable to the mixes tested at the Stellenbosch University, *i.e.* high density, medium saturation and 1% cement as active filler.

Following the mix designations used in the CSIR reports, four letter designations are adopted. The first letter indicates the type of material, *i.e.* Q for the crushed stone, S for the sand/calcrete blend stabilised with bitumen emulsion and T for the sand/calcrete blend stabilised with foamed bitumen. The second letter indicates the type of filler. Only mixes with cement added as active filler were used for the comparison here, *i.e.* the second letter is C for "cement". The third letter indicates the filler content. Only mixes 1 % active filler content were used for comparison here, *i.e.* L for "low" (low being 1 %). The fourth and last letter indicates the residual binder content. Three levels are used, *i.e.* low (L), medium (M) and high (H). The mix designations of the mixes used here for comparison are summarised in Table C-1.

Table C-1: Mix designation as used by the CSIR for selected mixes tested at the CSIR (after Long and Theyse, 2005)

Material	Filler	Residual binder content		
		0.6%	1.5%	2.25%
Crushed hornfels	1% cement	QCLL	QCLM	QCLH
		Residual binder content		
Sand/calcrete	1% cement	2.25%	3.5%	5.0%
		SCLL	SCLM	SCLH
Sand calcrete	1% cement	Foamed bitumen content		
		2.25%	4.0%	5.0%
		TCLL	TCLM	TCLH

The shear parameters of these mixes are summarised in Figure C-5 to Figure C-7.

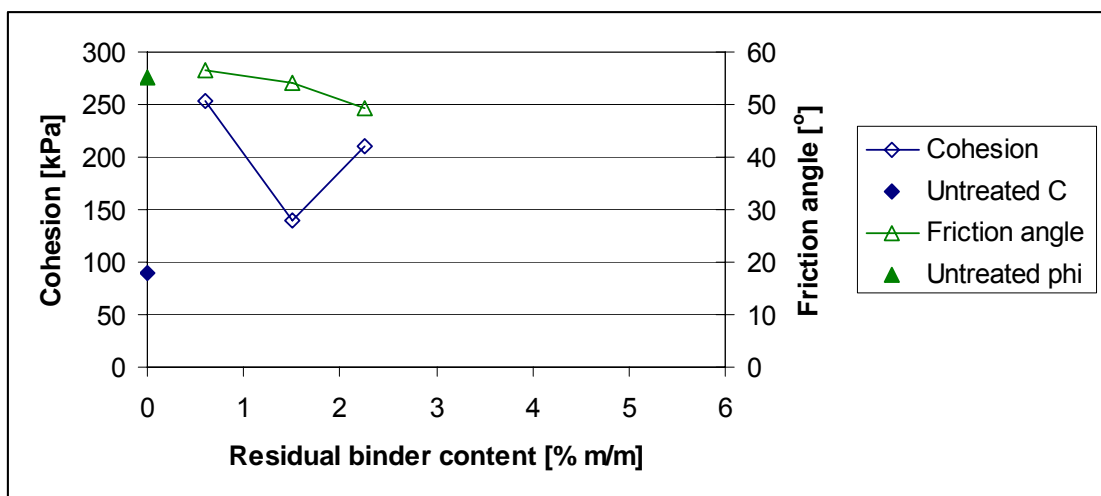


Figure C-5: Shear parameters of crushed stone (QCL mixes) stabilised with bitumen emulsion and 1% cement (data extracted from Long and Theyse, 2005)

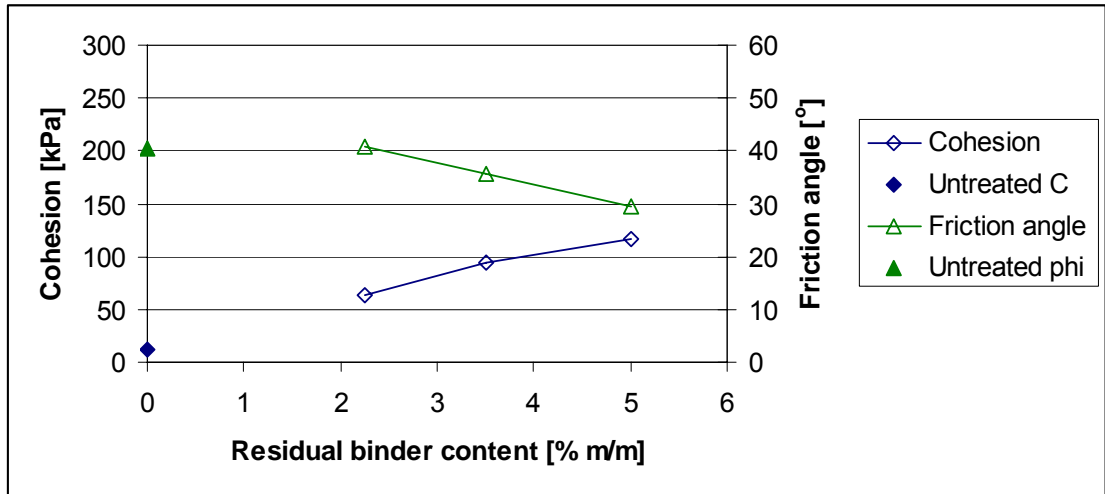


Figure C-6: Shear parameters of sand-calcrete blend stabilised with bitumen emulsion and 1% cement (SCL mixes) (data extracted from Long and Theyse, 2005)

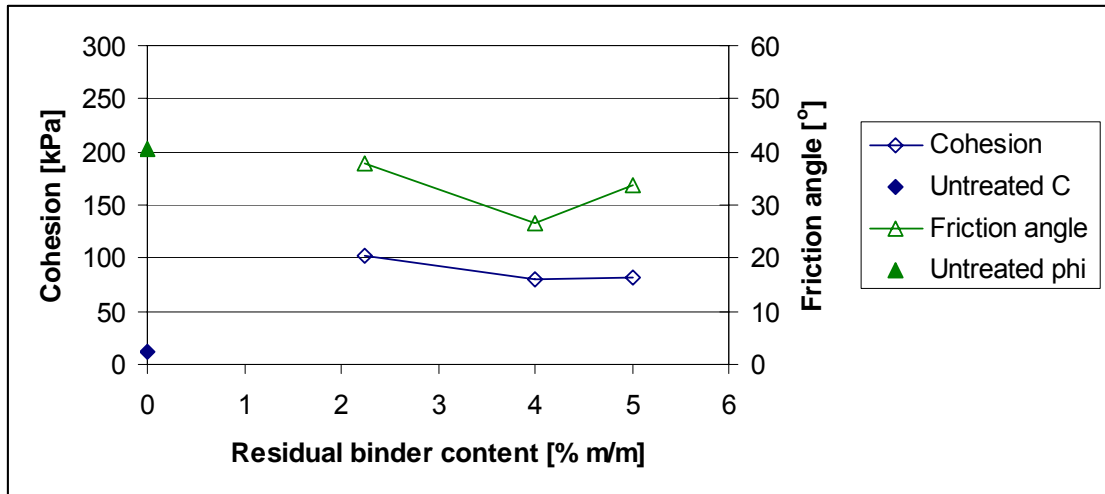


Figure C-7: Shear parameters of sand-calcrete blend stabilised with foamed bitumen and 1% cement (TCL mixes) (data extracted from Long and Theyse, 2005)

The tangent modulus values of the mixes tested by the CSIR are given in Figure C-8. No secant modulus values were provided in the CSIR data. The tangent moduli in Figure C-8 are presented in a manner that they can be compared with the values in Figure C-3 (Stellenbosch data).

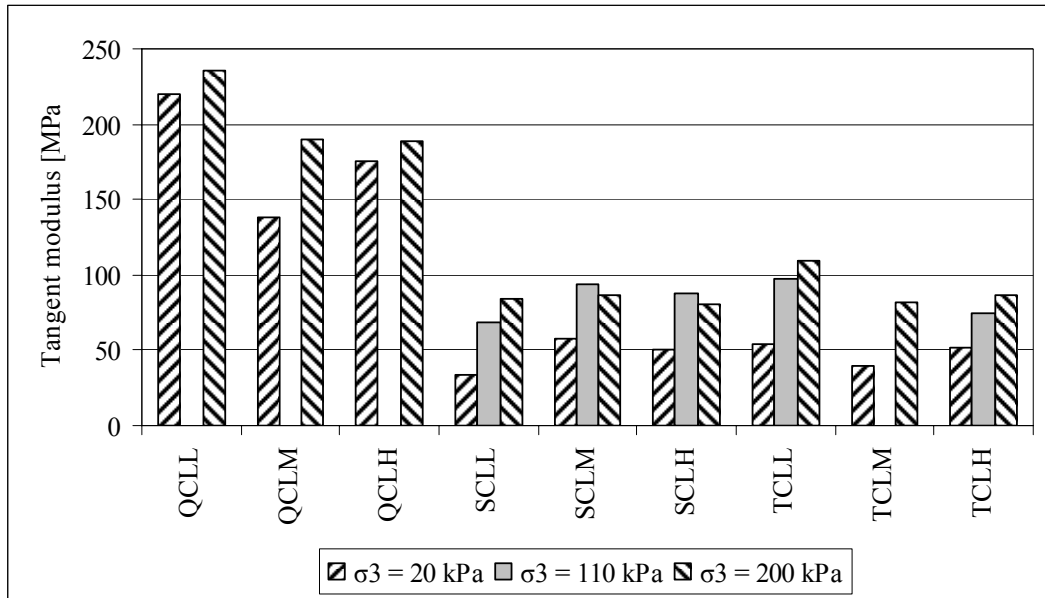


Figure C-8: CSIR mixes; tangent modulus per mix and confinement pressure (data extracted from Long and Theyse, 2005)

It can be seen that the CSIR mixes also show a stress dependency in that the tangent modulus increases with increasing confinement pressure. This is in agreement with the Stellenbosch data. The values of the CSIR tangent moduli are roughly between 30 MPa and 250 MPa, depending on the type of mix. The QCL mixes compare best with the A/B-75C-1 mixes tested at the Stellenbosch University in terms of composition and material quality. It can be seen that the tangent moduli are also comparable.

## 2.2. Stiffness from dynamic tri-axial test

### Introduction

The short duration dynamic tri-axial test is well suited to determine the resilient stiffness of pavement materials. It is also capable of determine the stress dependency of this material property. It is however a test that is typically carried out in a research environment. As such it has been used extensively by many researchers around the world.

From research carried out during the 1960's, Hicks and Monismith (1971) summarised that the resilient response of granular materials under short-duration dynamic loading is significantly influenced by:

- Stress levels (confining pressures);
- Degree of saturation;
- Dry density;
- Fines content (percentage passing 0.075mm sieve); and
- Aggregate properties (density, type, particle angularity, particle texture)

Hicks and Monismith (1971) concluded that the resilient response of untreated granular materials is most significantly affected by the stress level and can therefore be related to the confining pressure,  $\sigma_3$ , or to the bulk stress,  $\theta = \sigma_1 + \sigma_2 + \sigma_3$ , as follows, for as long as shear failure does not occur:

$$M_r = k_1 \sigma_3^{k_2}$$

Eq. C – 1

or

$$M_r = k_3 \theta^{k_4}$$

Eq. C – 2

where	$M_r$	=	Resilient modulus [MPa]
	$\sigma_3$	=	Confinement pressure [kPa]
	$\theta$	=	Bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$ [kPa]
	$k_{1r}, k_3$	=	model coefficients [MPa]
	$k_{2r}, k_4$	=	model coefficients [-]

The model shown in Equation C – 1 is used model for fine-grained soils, while the the model as shown in Equation 2 has been widely accepted to describe the stress-dependent behaviour of a granular material, amongst others for its simplicity. The latter is often referred to as the  $M_r$ - $\theta$  model. On a log-log scale this model represents a linear function, whereby the  $k_{1r}$ -value is a measure of the intersection with the y-axis, while the  $k_{2r}$ -value indicates the slope of the line.

The  $M_r$ - $\theta$  model as shown in Equation C – 2 is used to analyse the stiffness of BSM's will be used for analysis of resilient modulus test results in this study.

The  $M_r$ - $\theta$  model has however certain drawbacks. It is *e.g.* not uncommon for a material to exhibit the following phenomena concurrently:

- An increase in resilient modulus (stiffening) with increasing confinement ( $\sigma_3$ ) at a constant deviator stress ( $\sigma_d$ ); and
- A decrease in resilient modulus (softening) with increasing deviator stress ( $\sigma_d$ ) at a constant confinement ( $\sigma_3$ ).

Both abovementioned changes in the stress conditions result in an increase of the bulk stress  $\theta$ . The  $M_r$ - $\theta$  model can describe overall stiffening (positive  $k_{1r}$ -value) or overall softening (negative  $k_{1r}$ -value), but not stiffening due to increase in  $\sigma_3$  and softening due to increase in  $\sigma_d$  at the same time. Also, the  $M_r$ - $\theta$  model predicts an ever-increasing stiffness with increasing levels of bulk stress. The  $M_r$ - $\theta$  model is therefore fundamentally incorrect. It is however capable of accurately describing the stress-dependent behaviour of certain materials under certain stress conditions and can be applied as long as its users are aware of the limitations.

#### Stiffness measurements by Stellenbosch University

Examples of stress dependent behaviour of BSM's is shown in Figure C-9, Figure C-10 and Figure C-11. Figure C-9 shows stress stiffening behaviour. Some other BSM mixes tested by Ebels (20008) show a different behaviour. This is shown in Figure C-10. The only difference with the mix shown in Figure C-9 is the percentage RAP in the mix and the residual binder content. Figure C-10 shows stress softening instead of stress stiffening behaviour. The latter cannot be described by the  $M_r$ - $\theta$  model and other models need to be developed or adopted for this. The results of the resilient modulus of a mixed granulate BSM tested by Jenkins (2000) at the TUD, but on larger specimens (300mm diameter) as shown in Figure C-11 are included for comparison.

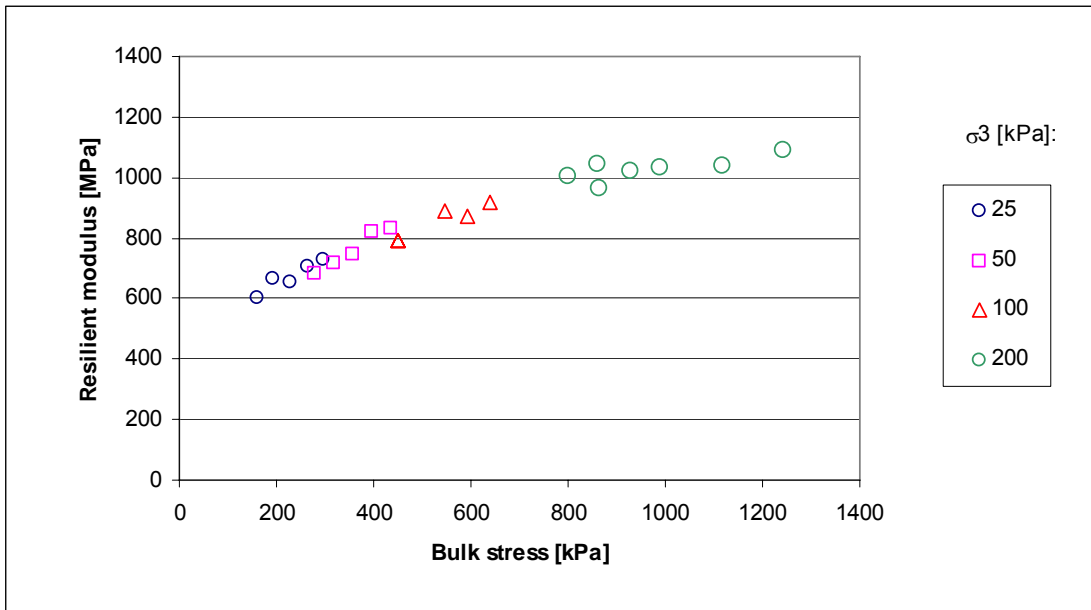


Figure C-9: Stress dependant stiffness behaviour of an emulsion treated granular material; 25% RAP, 3.6% bitumen, 0% cement (Ebels, 2008)

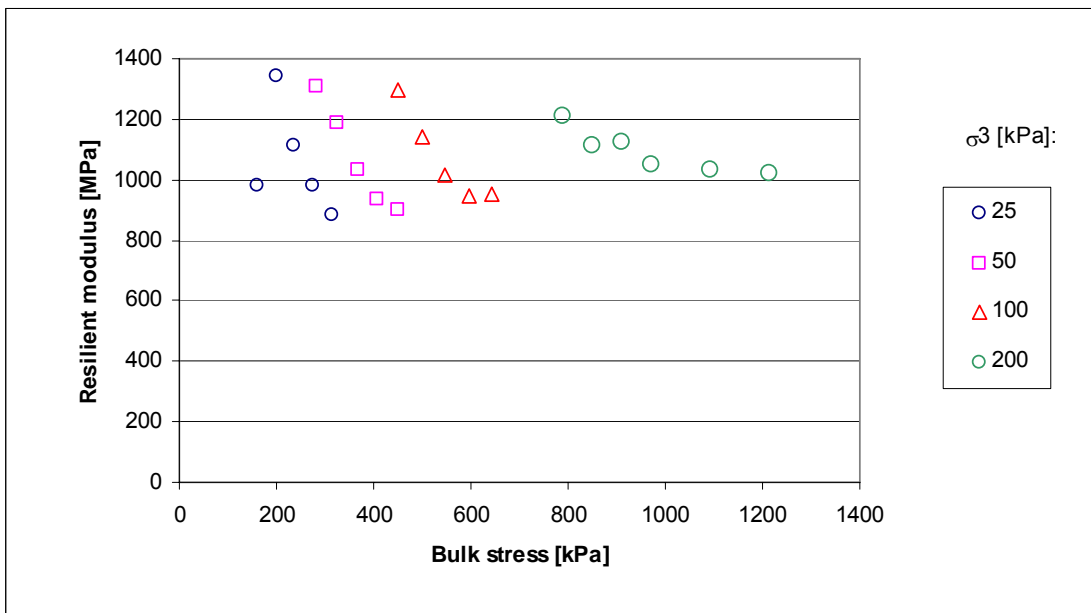


Figure C-10: Stress dependant stiffness behaviour of an emulsion treated granular material; 75% RAP, 2.1% bitumen, 0% cement (Ebels, 2008)

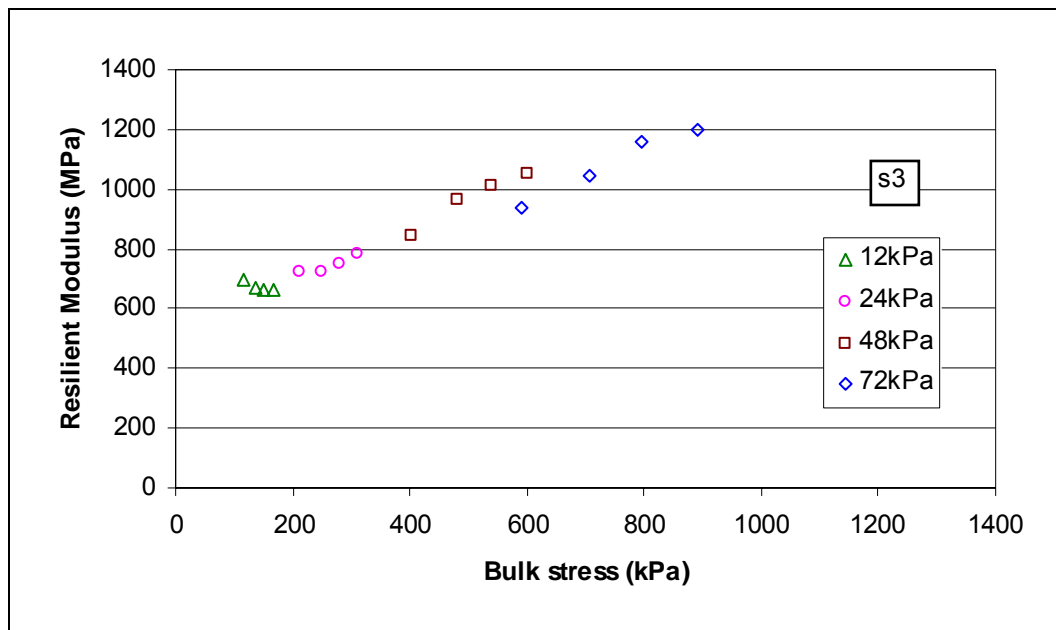


Figure C-11: Stress dependant behaviour of mixed granulate treated with 2% foamed bitumen and 0% cement (Jenkins, 2000)

Ebels (2008) concluded that the resilient modulus the mixes he tested roughly vary from 600 MPa to 1500 MPa, depending on the confinement pressure and applied stress levels. It can be seen that this is in agreement with the range of resilient modulus values found by Jenkins (2000), see Figure C-11. The parameters of the  $M_r$ - $\theta$  model of the BSM mixes tested at the Stellenbosch University are summarised in Table C-2. It can be seen that no good correlation were found with this model for the mixes with a high percentage of RAP (75M-0) and the mixes stabilised with foamed bitumen (binder C). Care needs to be taken when using the model coefficients for these mixes.

Table C-2: Model coefficients  $k_1$  and  $k_2$  ( $M_r$ - $\theta$  model) (Ebels, 2008)

Aggregate blend	Binder	Repeat test	$k_1$ [MPa]	$k_2$ [-]	$R^2$
75C-0	A	a	124.53	0.3008	0.907
		b	134.34	0.2957	0.975
	B	a*	-	-	-
		b*	241.52	0.1641	0.669
		c	132.79	0.3639	0.904
	C	a	744.29	0.0269	0.034
b**		-	-	-	
c		287.2	0.165	0.378	
75C-1	A	a	109.09	0.3676	0.843
		b	193.73	0.2958	0.930
	B	a	1314.2	-0.0042	0.001
		b	427.4	0.1926	0.812
	C	a	997.04	0.0663	0.205
		b	752.38	0.0879	0.308
75M-0	A	a	1238.6	-0.0241	0.013
		b	2805.9	-0.1305	0.257
	B	a	1525.4	-0.0526	0.106
		b	200.51	0.2529	0.175
	C	a	974.29	0.0101	0.002
		b	623.37	0.0656	0.147

Notes \* : Some of the LDVT's out of range or unreliable during the test  
 \*\* : Specimen failed during conditioning

Similar trends as shown in the examples above have been found by the CSIR, TUD and during research at the Stellenbosch University during the 1990's. Although the trends are similar, the absolute values of the resilient moduli differ and are lower magnitude (as low as 200 MPa [Jenkins *et al.*, 2007]). The lower stiffness moduli found by the CSIR may be the result of the fact that only two on-specimen LVDT's are used. These on-specimen LVDT's do not measure only over the middle third, but nearly the full height of the specimen, with a fixed reference being the foot plate of the tri-axial cell. The displacement results of the machine LVDT are also used by the CSIR to determine the stiffness moduli. These displacements would include displacement at the interface of the specimen and the base and top plate as well as the interface between the top plate and loading piston. It may therefore be an overestimation of the actual deformation of the specimen itself. Subsequently, lower stiffness moduli may be found.

Stiffness measurements by the CSIR

The measurement of the resilient modulus at the CSIR forms part of the permanent deformation test. No specific short duration dynamic tri-axial test is carried out to this purpose. The resilient modulus of the selected mixes is summarised in Figure C-12. The confinement pressure ( $\sigma_3$ ) during the dynamic test was always 80 kPa, varying levels of applied stress ( $\sigma_1$ ). The bulk stress  $\theta$  is however not provided in the CSIR data, and therefore no comments on the stress-dependency of the resilient moduli as presented in Figure C-12 can be offered. The values shown are therefore average values of a range of stress dependent resilient moduli that were measured for the particular mixes at certain binder contents.

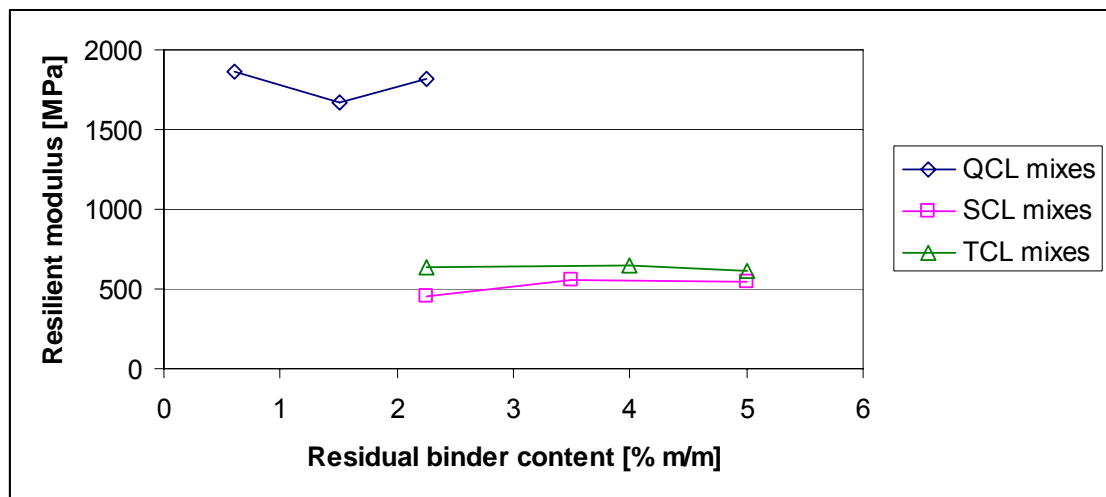


Figure C-12: Resilient modulus of selected mixes tested by CSIR (data extracted from Long and Theyse, 2005)

It can be seen that the stiffness of the BSM appears to be little influenced by the binder content. A clear difference in terms of stiffness can be observed between the crushed stone and the sand-calcrete blend, whereby the former has the higher stiffness. This is in line with the shear strength of the mixes. Ebels (2008) also found a relation between high cohesion, mainly as a result of active filler being added, and the resilient modulus.

It can also be seen that there is little difference between the use of bitumen emulsion and foamed bitumen in the case of the sand-calcrete blend (compare SCL mixes stabilised with bitumen emulsion with TCL mixes stabilised with foamed bitumen). This is in line with findings by Ebels (2008) that when 1% cement is used as active filler, possible differences between type of binders are masked and the cement has a dominating effect on the stiffness of the mix.

### 2.3. Stiffness from four-point beam bending test

Twagira *et al.* (2006) published master curves of the flexural stiffness determined by means of four-point beam testing on the same BSM mixes tested at the Stellenbosch University as described above for the monotonic tri-axial testing. The results thereof are summarised in Figure C-13 - Figure C-15. The time- and temperature dependency of the BSM mixes is evident from the graphs, but the dependency is less then for HMA (Ebels, 2008).

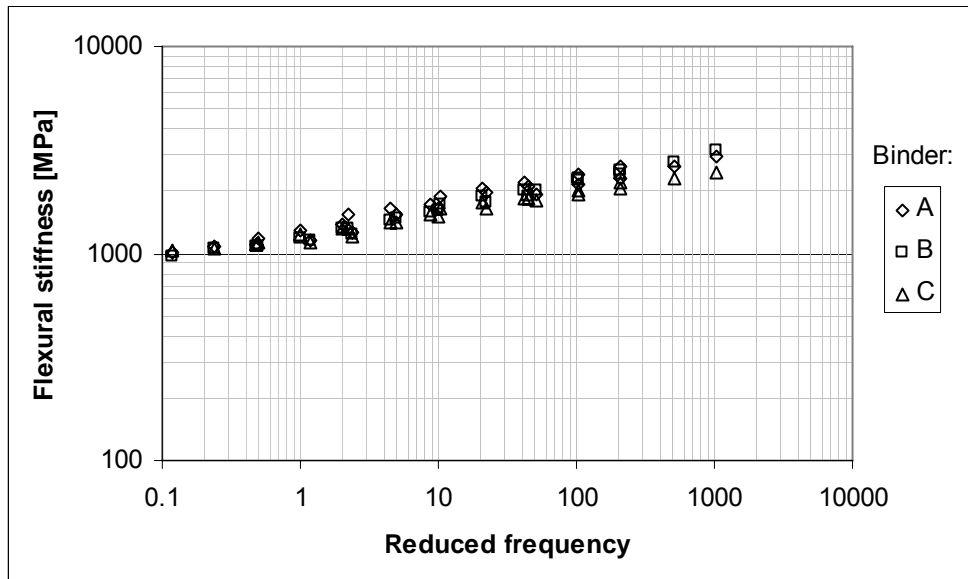


Figure C-13: Master curves per binder type for aggregate blend 75C-0 ( $T_{ref} = 20^{\circ}\text{C}$ )

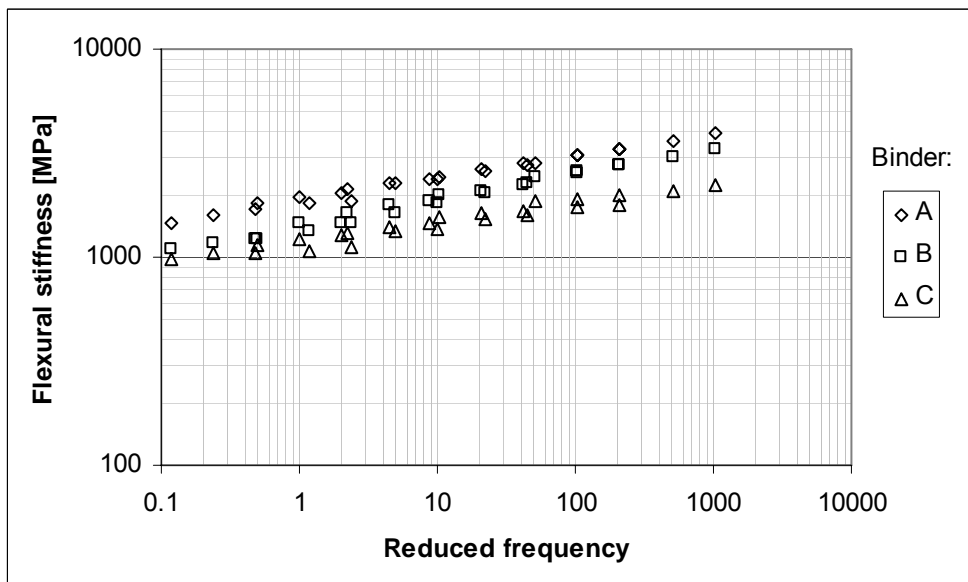


Figure C-14: Master curves per binder type for aggregate blend 75C-1 ( $T_{ref} = 20^{\circ}\text{C}$ )

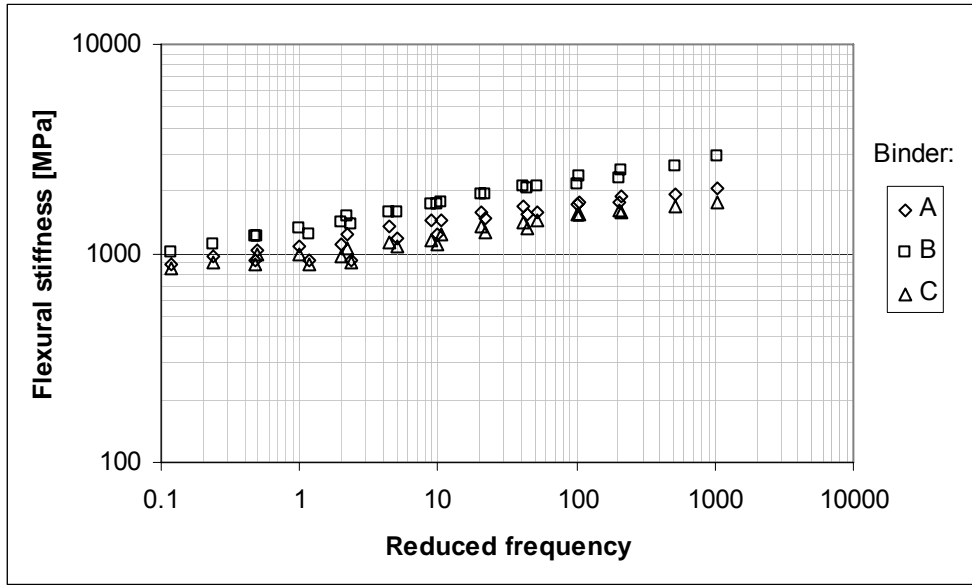


Figure C-15: Master curves per binder type for aggregate blend 75M-0 ( $T_{ref} = 20^{\circ}C$ )

### 3. CORRELATIONS BETWEEN THE DIFFERENT TYPE OF STIFFNESS MODULI

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#### 3.1. Tangent stiffness vs. resilient modulus

The tangent stiffness is determined from monotonic tri-axial testing. Differences in loading conditions, particularly the speed of loading, edge effects and the inclusion of any possible deformation in between the specimen, end plates and tri-axial cell or piston in the monotonic test result in a lower stiffness being measured for the tangent modulus compared to the resilient modulus. There is approximately a factor of 10 difference between the two stiffness values.

The tangent modulus is capable of measuring stress dependent behaviour (tangent modulus increases with increasing confinement pressure) and rank mixes relatively to each other, *e.g.* it shows the influence of active filler and the percentage of RAP in the mix. The trends are however less distinct and consistent as with resilient modulus testing.

The tangent modulus from the monotonic tri-axial test and the resilient modulus (from the CSIR data) are compared with each other here. Per mix the tangent modulus that is compared with the resilient modulus is the average of the tangent moduli at the three different confinement pressures, *i.e.* 20 kPa, 110 kPa and 200 kPa. The resilient modulus is an average of moduli measured over a range of bulk stresses, but all at 80 kPa confinement pressure.

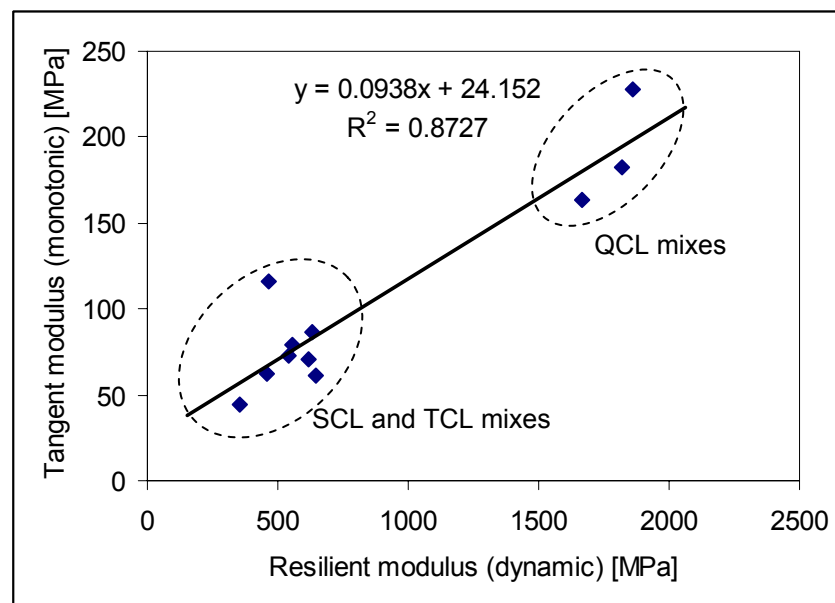


Figure 16: Correlation between tangent modulus from monotonic test and resilient modulus from dynamic test (based on data by Long and Theyse, 2005)

It can be seen that at the face of it a good correlation exists between the tangent modulus that is derived from the monotonic tri-axial test and the resilient modulus that is derived from the dynamic tri-axial test. This in itself is encouraging with a view of using the tangent modulus to characterise BSM stiffness. However, one needs to take into account that the above shown correlation is based on limited data (nine mixes) and that average values are used for both the tangent modulus and the resilient modulus. The spread in the results can be expected to be larger when the individual moduli are compared. It is recommended that this still be done and to include the Stellenbosch University data in the correlation.

It is at this stage not recommended to use the tangent modulus alone to characterise stiffness of BSM's and one should be careful when ranking BSM's based on the tangent modulus.

### 3.2. Resilient modulus vs. flexural stiffness

It is difficult to compare the resilient modulus and the flexural stiffness as one needs to consider the difference between the type of loading (compression *vs.* bending), in specimen geometry and confinement conditions. The resilient modulus was tested at 2 Hz and 25 °C, but over a range of confinement pressures and deviator stress ratios. The flexural stiffness testing was conducted over a range of loading frequencies and temperatures. The flexural stiffness values at 2 Hz and 25 °C are selected for comparison and are shown in Table C-3.

Table C-3: Bending stiffness (4PB) of BSM's tested at 2 Hz and 25°C (Ebels, 2008)

Binder	75C-0	75C-1	75M-0
Emulsion A	1101	1693	929
Emulsion B	1084	1218	1198
Foam C	1107	1049	896

Although the mechanism of the tri-axial test and the four-point beam tests are different (hence the type of stiffness, *i.e.* compression *vs.* bending), the magnitude of the flexural stiffness at comparable temperature and loading frequency appears to be of the same order as the range of resilient modulus values. This would indicate that the resilient modulus values obtained by tri-axial testing can be used as a rough estimate for the bending stiffness, with the latter being used in structural design calculations.

## 4. CONCLUSIONS AND RECOMMENDATIONS

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- Data for several cold mixes tested at both the Stellenbosch University and the CSIR has been gathered. This includes information in the shear strength of the mixes, stiffness derived from the monotonic tri-axial test (tangent modulus), stiffness from the dynamic tri-axial test (resilient modulus) and flexural stiffness from the four-point beam test.
- The tangent modulus shows stress dependency, *i.e.* at higher confinement pressures higher tangent moduli are measured. The tangent modulus can also be used to rank different BSM mixes in a similar order as when the resilient modulus is used. The absolute value of the tangent modulus is however a factor of 10 lower than that of the resilient modulus.
- The tangent modulus and resilient modulus from the same mixes as tested at the CSIR show a good linear correlation, confirming the factor of 10 difference. This correlation is however based on limited data and average moduli. It is recommended that this correlation be extended with more available data.
- At this stage it is however not recommended to use the tangent modulus alone to characterise stiffness of BSM's and one should be careful when ranking BSM's based on the tangent modulus.
- The flexural stiffness values of BSM's tested at the Stellenbosch University using the four-point beam apparatus fall within the range of resilient moduli of the same mixes determined using a tri-axial test. Although the mechanism of the tri-axial test and the four-point beam tests are different (hence the type of stiffness, *i.e.* compression *vs.* bending) the resilient modulus values may provide a rough estimate for the bending stiffness. The latter is normally used in structural design calculations.
- The monotonic tri-axial test is an easy to perform test, but the tangent modulus is less accurate and may show inconsistencies. The resilient modulus dynamic tri-axial test is an extremely difficult test to perform accurately, but the outcome is less variable and fairly reliable. The four-point beam test in itself is an easy to perform test, however, the beam specimen fabrication and preparation is a difficult process. In addition, the variation in the test results of the four-point beam test is generally high due to issues around specimen preparation and quality.

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