09 - 10 October 2012

Real Problems Relevant Solutions

The CSIR Contribution to the Revision of the SA Road Pavement Design Method (SAPDM)

2008 - 2013

Dr James Maina

our future through science

South African Roads…

Some stats - food for thoughts…

- *SA has the 10th largest road network in the world (746,978 km – 80% is unpaved)*
- *Backlog of 10,980 km (paved prov. roads) and 69,216 km (gravel roads)*
- *SANRAL is expected to, eventually, manage 35000km road network - 20000 (strategic) and 15000 (support)*
- *Manpower, tools and knowledge needed to protect the multibillion ZAR worth of investment in transport infrastructure.*

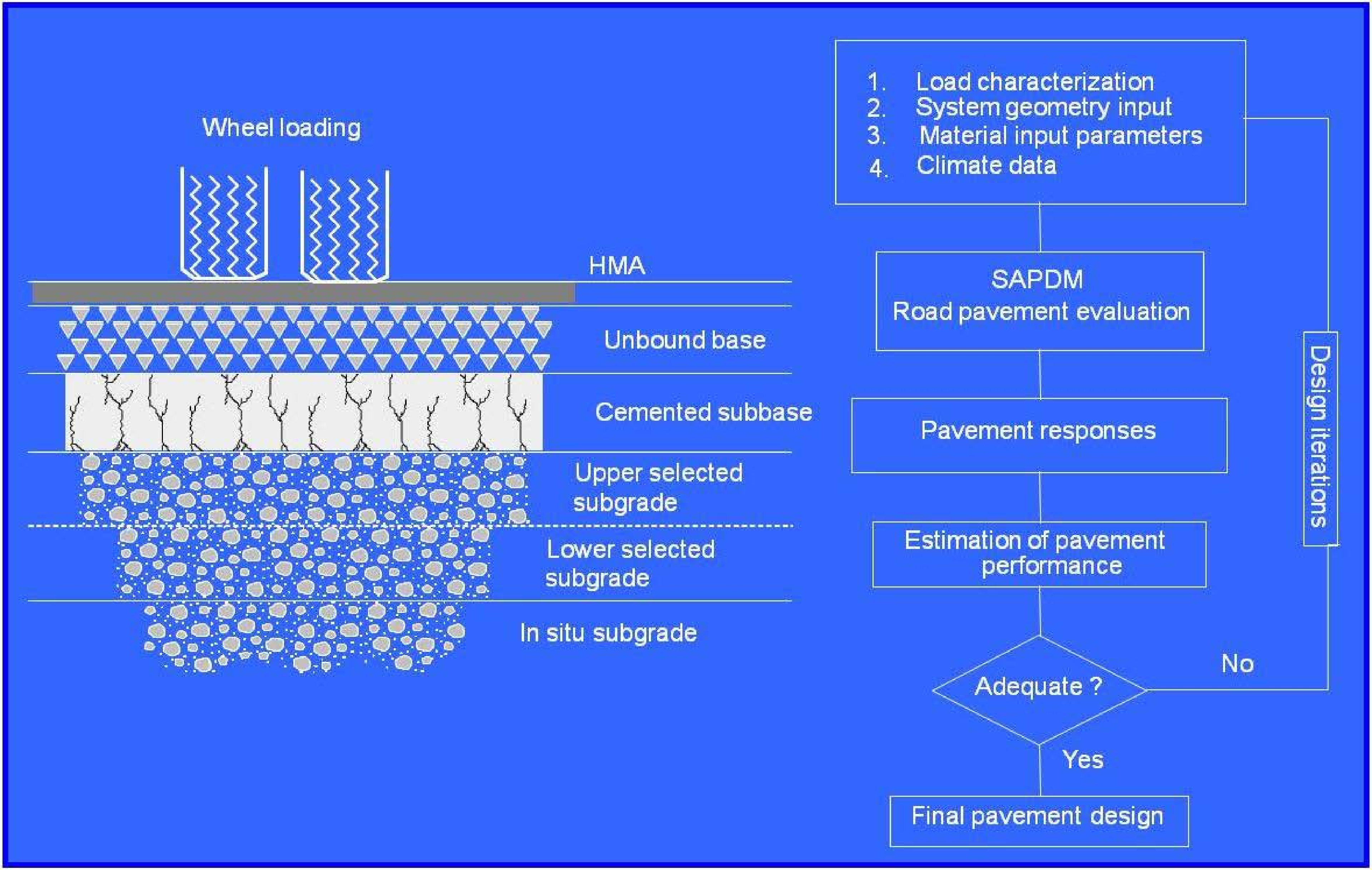
Current South African Mechanistic Design Method for Roads…

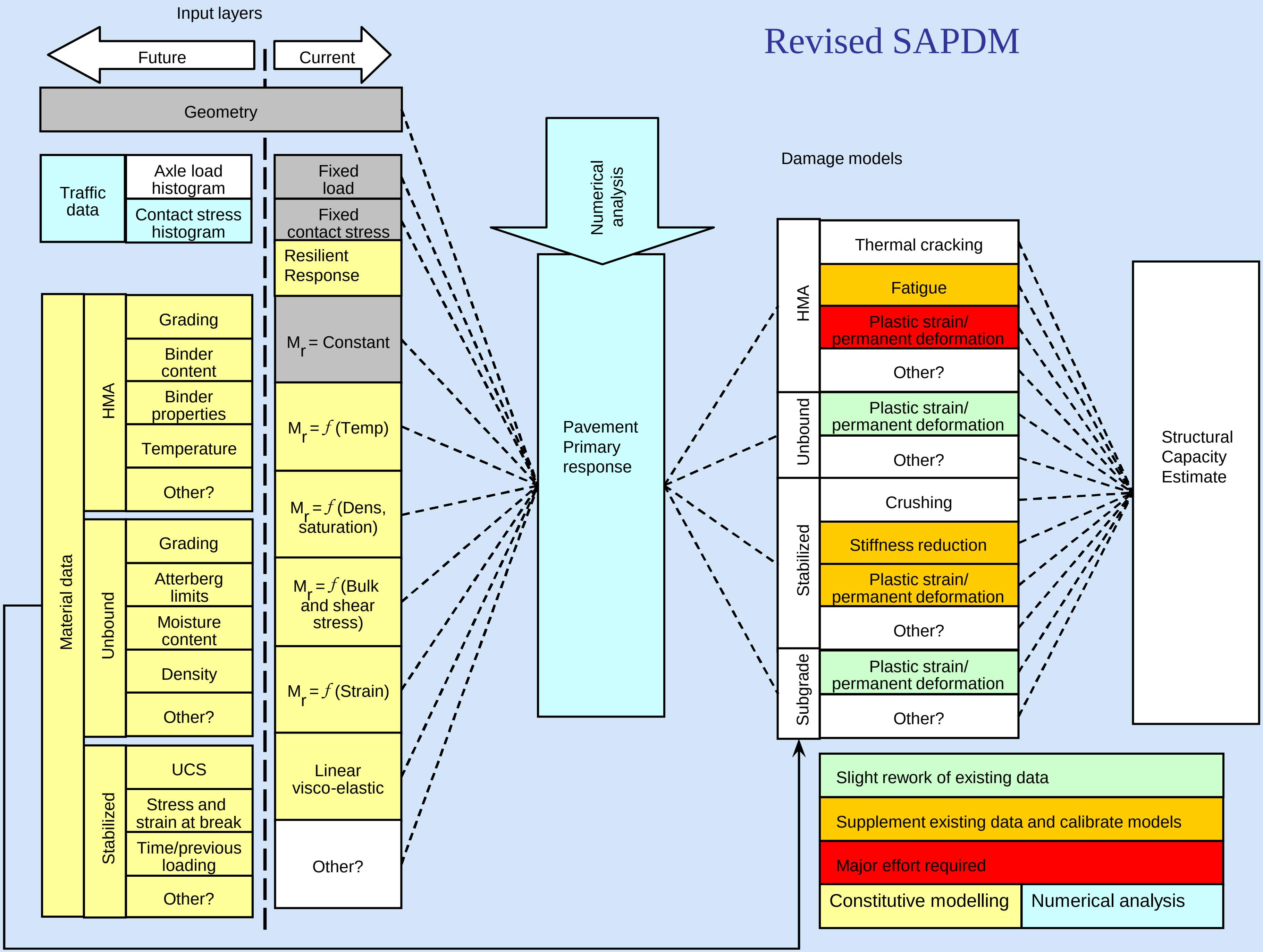
South African roads Design Method

- ***The South African Mechanistic Design Method (SAMDM) used since 1980s in various forms***
  - ***It is mainly based on technology and material performance models developed in the 1970s and 1980s***
  - ***important parts of the method are <u>obsolete and in dire need of serious revision and updating</u> due to:***
    - ***new traffic realities***
    - ***need for the utilization of unconventional materials***
    - ***there are also some genuine concerns regarding the accuracy, reliability and validity of parts of the method***
  - ***Further development of engineering models slowed down because of a lack of funding since early 1990s***

Revision of South African Mechanistic Design Method for Roads…

Pavement design in a nutshell…




Revised SAPDM
Input layers
Future
Current
Geometry
Traffic data
Axle load histogram
Contact stress histogram
Fixed load
Fixed contact stress
Resilient Response
Material data
HMA
Grading
Binder content
Binder properties
Temperature
Other?
Unbound
Grading
Atterberg limits
Moisture content
Density
Other?
Stabilized
UCS
Stress and strain at break
Time/previous loading
Other?
M_r = Constant
$M_r = f$(Temp)
$M_r = f$(Dens, saturation)
$M_r = f$(Bulk and shear stress)
$M_r = f$(Strain)
Linear visco-elastic
Other?
Numerical analysis
Pavement Primary response
Damage models
HMA
Thermal cracking
Fatigue
Plastic strain/ permanent deformation
Other?
Unbound
Plastic strain/ permanent deformation
Other?
Stabilized
Crushing
Stiffness reduction
Plastic strain/ permanent deformation
Other?
Subgrade
Plastic strain/ permanent deformation
Other?
Structural Capacity Estimate
Slight rework of existing data
Supplement existing data and calibrate models
Major effort required
Constitutive modelling
Numerical analysis

Overall objectives for the revision

- *To develop a design method that is:*
  - *Accurate (theory + laboratory testing must agree with reality)*
  - *Impartial in terms of pavement type selection*
    - *Unbound (Crushed stone, natural gravel)*
    - *Stabilised (Cement, Foamed-bitumen, Emulsified-bitumen)*
    - *Hot-mix asphalt (HMA)*
    - *Concrete (not included in flexible pavement design R&D process)*
    - *Recycled asphalt and concrete pavements*
  - *Capable of incremental life cycle performance simulation (structural/functional)*
  - *Comprehensive cost-benefit analysis procedure assessing different life-cycle strategies and including cost and benefits for road users as well as road authorities*
  - *Easy to use and allow for different levels of analysis*

CSIR Contribution to the Revision of South African Pavement Design Method - SAPDM

CSIR Core PG Funded R&D

1. *To review state-of-the-art on bitumen (binders) testing*
2. *To establish optimum test protocols*
3. *Validate test methods/final protocols*
4. *Validate and calibrate selected binders models*

Determination of viscosity

Multiple Methods allowed (but conversion to Poise required)

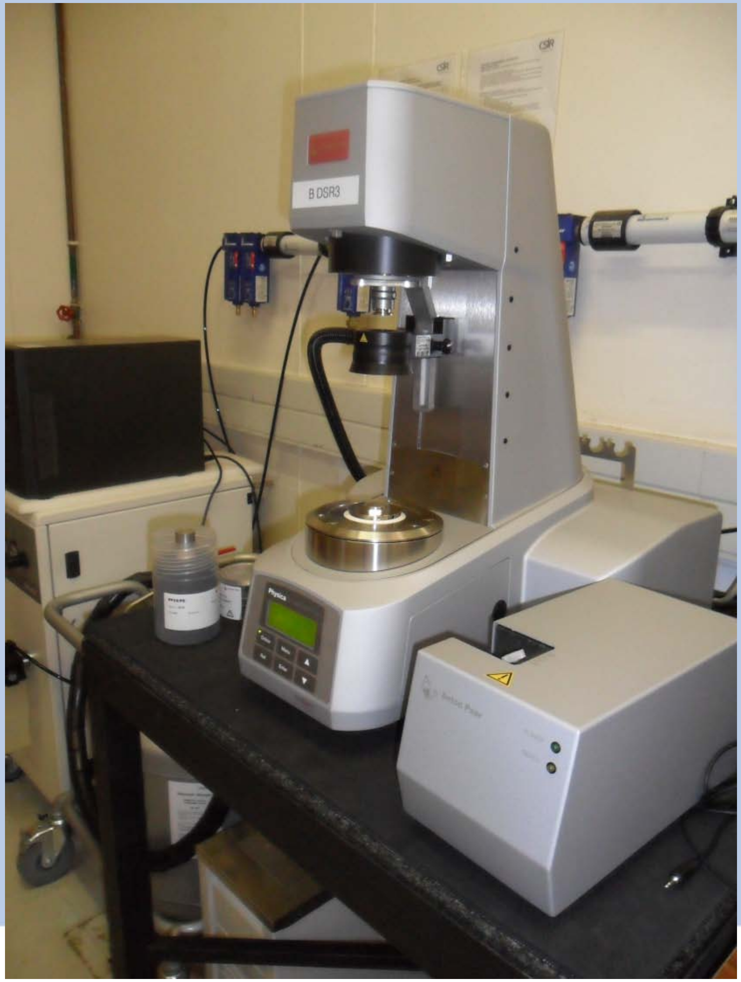
1. *Penetration*
2. *Softening Point*
3. *Kinematic Viscosity*
4. *Absolute Viscosity*
5. *Brookfield Viscosity*
6. *DSR*

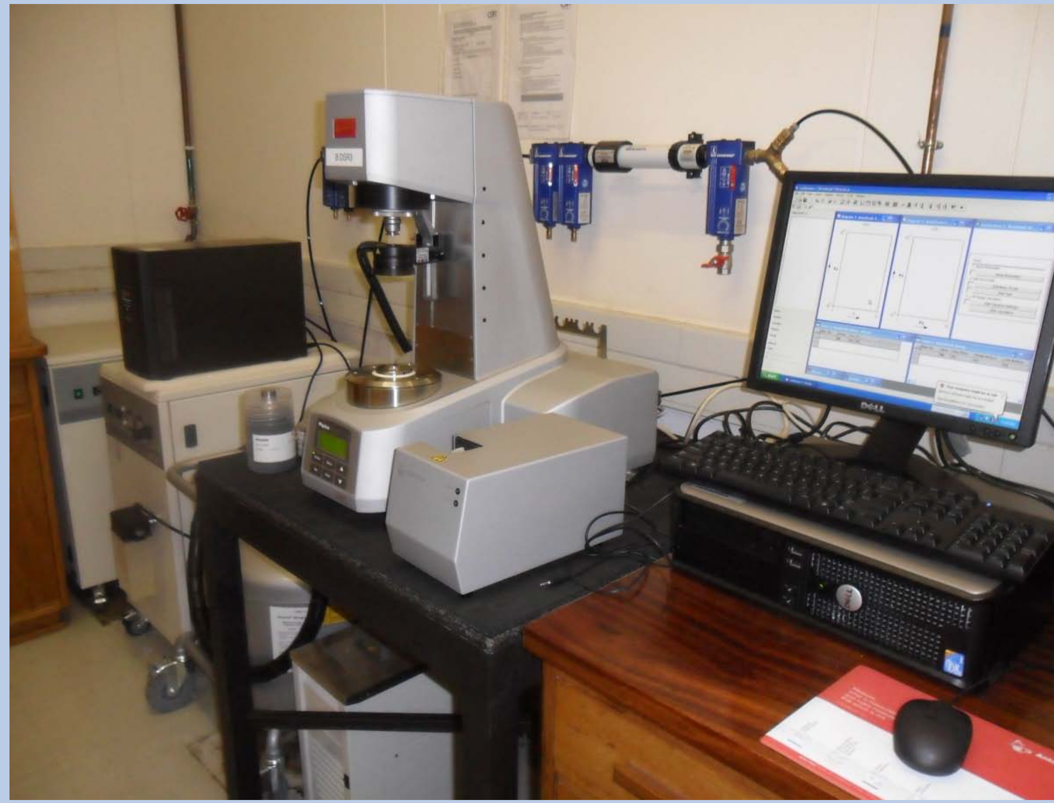
Lab equipment procured to support project

Dynamic Shear Rheometer for binder testing (R680k)

CSIR

Lab equipment procured to support project





Dynamic Shear Rheometer for binder testing (R715k)

Relating Binder viscosity to Mix Stiffness - Witczak

$$\log|E^*| = 3.750063 + 0.029232\,P_{200} - 0.001767\,(P_{200})^2 - 0.002841\,P_4 - 0.058097\,V_a$$
$$-\,0.802208\,\frac{V_{beff}}{(V_{beff}+V_a)} + \frac{[3.871977 - 0.0021\,P_4 + 0.003958\,P_{38} - 0.000017\,(P_{38})^2 + 0.00547\,P_{34}]}{1+e^{(-0.603313-0.313351\log f - 0.393532\log\eta)}}$$

where:

E^* = dynamic modulus, psi.

η = bitumen viscosity, 10^6 Poise.

f = loading frequency, Hz.

V_a = air void content, %.

V_{beff} = effective bitumen content, % by volume.

P_{34} = cumulative % retained on the ¾ in (19.0mm) sieve.

P_{38} = cumulative % retained on the 3/8 in (9.5 mm) sieve.

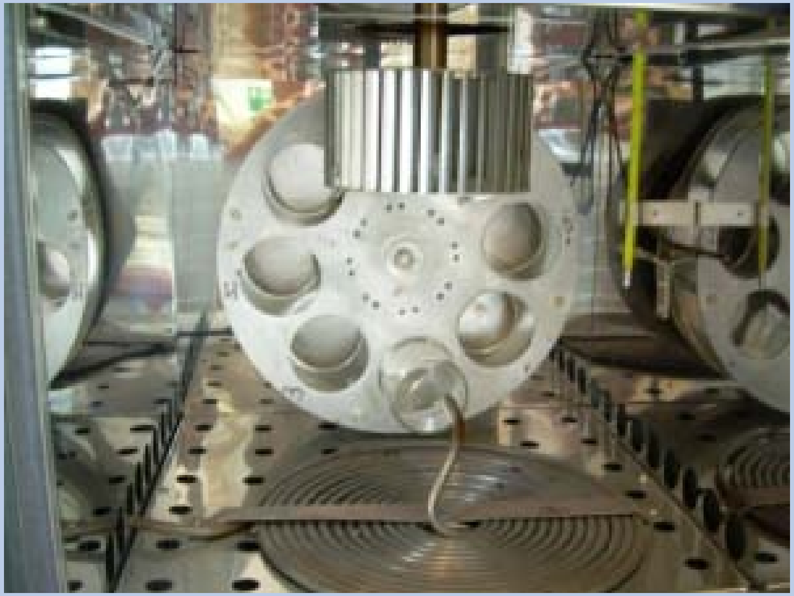
P_4 = cumulative % retained on the No. 4 (4.75mm) sieve.

P_{200} = % passing the No. 200 (75 micron) sieve.

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628}$$

Aging test needs to change for Performance Prediction

- RTFOT currently 163˚C, 85 minutes
- Proposed changes include extended time
- G* is more appropriate than empirical methods such as softening point



Lab equipment procured to support project

Pressure Aging Vessel for binder aging

Proposed Future Binder Spec for South Africa (SABITA)

Binder Class	58 S	64 S	64 H	64 V
Original Binder				
Average 7 day maximum pavement design temperature (˚C)	< 58	< 64	< 64	< 64
DSR |G*|/sinδ _ min 1.0	@ 58˚C	@ 64 ˚C	@ 64 ˚C	@ 64 ˚C
Viscosity Pa.s (DSR) @ 135˚C	≤ 3	≤ 3	≤ 3	≤ 3
Flash Point (˚C)	< 230	< 230	< 230	< 230
Percent Recovery at σ = 3.2 kPa	N/A	N/A	> 15	>30
Storage Stability @ 160˚C Maximum difference between top and bottom	N/A	N/A	0.3 kPa @ 64˚C	0.3 kPa @ 64˚C
RTFOT Binder				
Mass Change (m/m%, max)	0.3			
J_{nr} (at σ = 3.2 kPa)	≤ 4.0 kPa^{-1}@ 58˚C	≤ 4.0 kPa^{-1}@ 64 ˚C	≤ 2.0 kPa^{-1}@ 64 ˚C	≤ 1.0 kPa^{-1}@ 64 ˚C
A, VTS viscosity parameters	report only	report only	report only	report only
Rolling Stones Test (% cover)	40	40	50	60
PAV Binder - @ 100˚C				
DSR |G*|sinδ	Max 5 000 kPa @ 22 ˚C	Max 5 000 kPa @ 22 ˚C	Max 6 000 kPa @ 22 ˚C	Max 6 000 kPa @ 22 ˚C

CSIR SRP Funded R&D

1. *To review state-of-the-art on HMA materials and testing*
2. *To establish optimum test protocols*
3. *Validate test methods/final protocols*
4. *Validate and calibrate selected HMA models.*

SANRAL

1. *Assessment of the proposed protocols to establish the desired critical factors (i.e. test temperature, loading frequency, load magnitude, type and mode of loading, mix variables) on HMA performance and to calibrate and validate the models.*
2. *Extensive laboratory and field testing.*
3. *Finalize formulation of resilient response and damage models for HMA materials.*

Lab equipment procured to support project

Advanced Asphalt Gyratory Compaction Equipment (R470k)

Lab equipment procured to support project

Dynamic modulus & Permanent Deformation Testing Equipment (R1.15m)

Beam Fatigue Testing Equipment (R900k)

Dynamic Modulus Sample Preparation at CSIR:

Gyratory compaction & coring)

The bitumen was a 60/70 penetration grade binder

150 mm dia. x 170 mm GC specimen

100 mm dia. X 170mm high cored from 150mm dia. X 170 mm high)

CSIR BE coring machine

Sample Preparation (Cutting/Sawing)

Cut 10 mm from ends of 100 mm dia. X 170 mm high

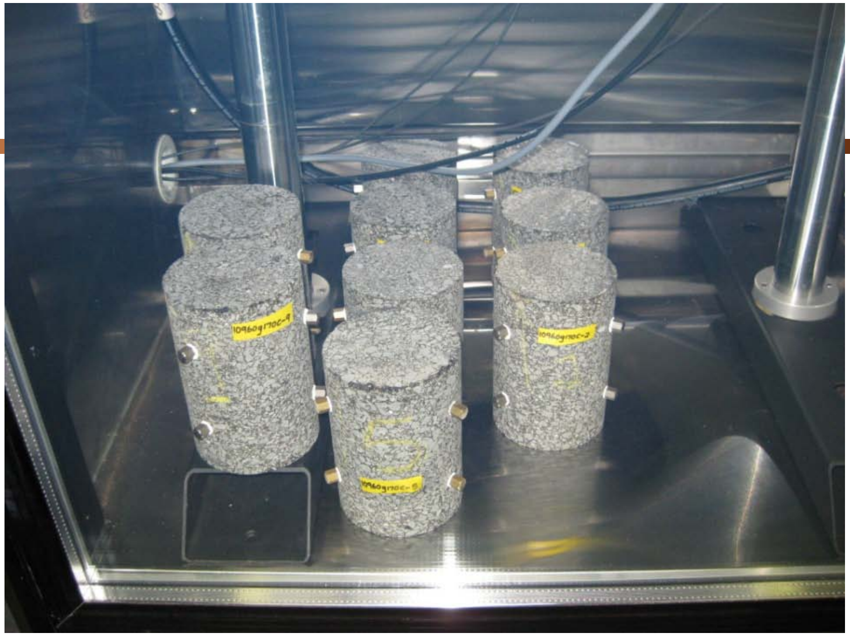
Completed test specimens (100 mm dia. X 150 mm high)

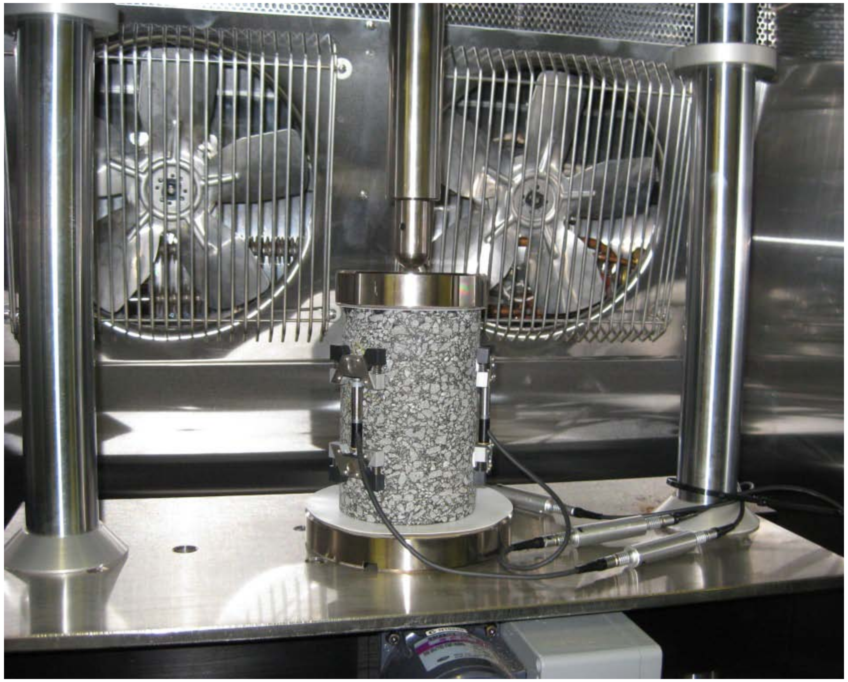
Specimen Instrumentation

Instrumented specimen

Photo of clamping device

Conditioning & Testing





Statistical Analyses: Dynamic Modulus Test Results

Temperature (°C)	Statistics	Frequency (Hz)					
		0.1	0.5	1	5	10	25
-5	MEAN |*E**| (MPa)	25438	28670	29990	32934	34114	35536
	STDEV (MPa)	1223	1315	1353	1452	1451	2027
	COV (%)	4.8	4.6	4.5	4.4	4.3	5.7
5	MEAN |*E**| (MPa)	16958	20678	22236	25963	27436	29421
	STDEV (MPa)	1253	1404	1492	1670	1775	2017
	COV (%)	7.4	6.8	6.7	6.4	6.5	6.9
20	MEAN |*E**| (MPa)	5965	8880	10369	14201	16078	18304
	STDEV (MPa)	521	615	662	652	656	1123
	COV (%)	8.7	6.9	6.4	4.6	4.1	6.1
40	MEAN |*E**| (MPa)	673	1161	1550	2933	3942	5563
	STDEV (MPa)	97	188	260	473	605	748
	COV (%)	14.4	16.2	16.8	16.1	15.4	13.5
55	MEAN |*E**| (MPa)	281	359	419	685	907	1526
	STDEV (MPa)	25	40	51	99	128	258
	COV (%)	8.8	11.1	12.2	14.5	14.1	16.9

Modeling of |E*| Test Results

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log f_r}} \qquad \log f_r = \log f + \log a(T)$$

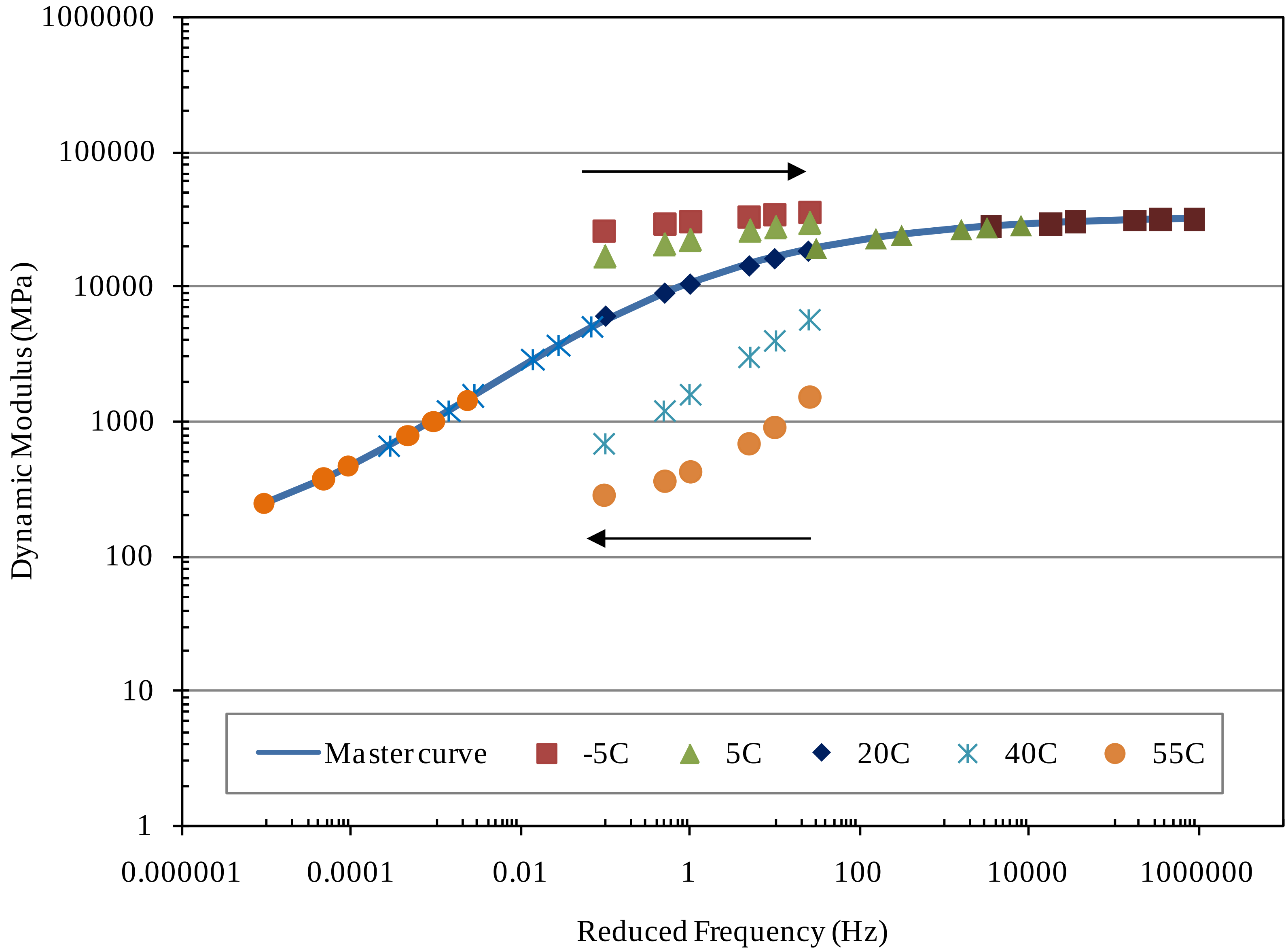
$$\log a(T) = c\left(10^{A+VTS\log T} - 10^{A+VTS\log(527.67)}\right)$$

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\left\{\log(f)+c\left[10^{A+VTS\log T} - 10^{A+VTS\log(527.67)}\right]\right\}}}$$

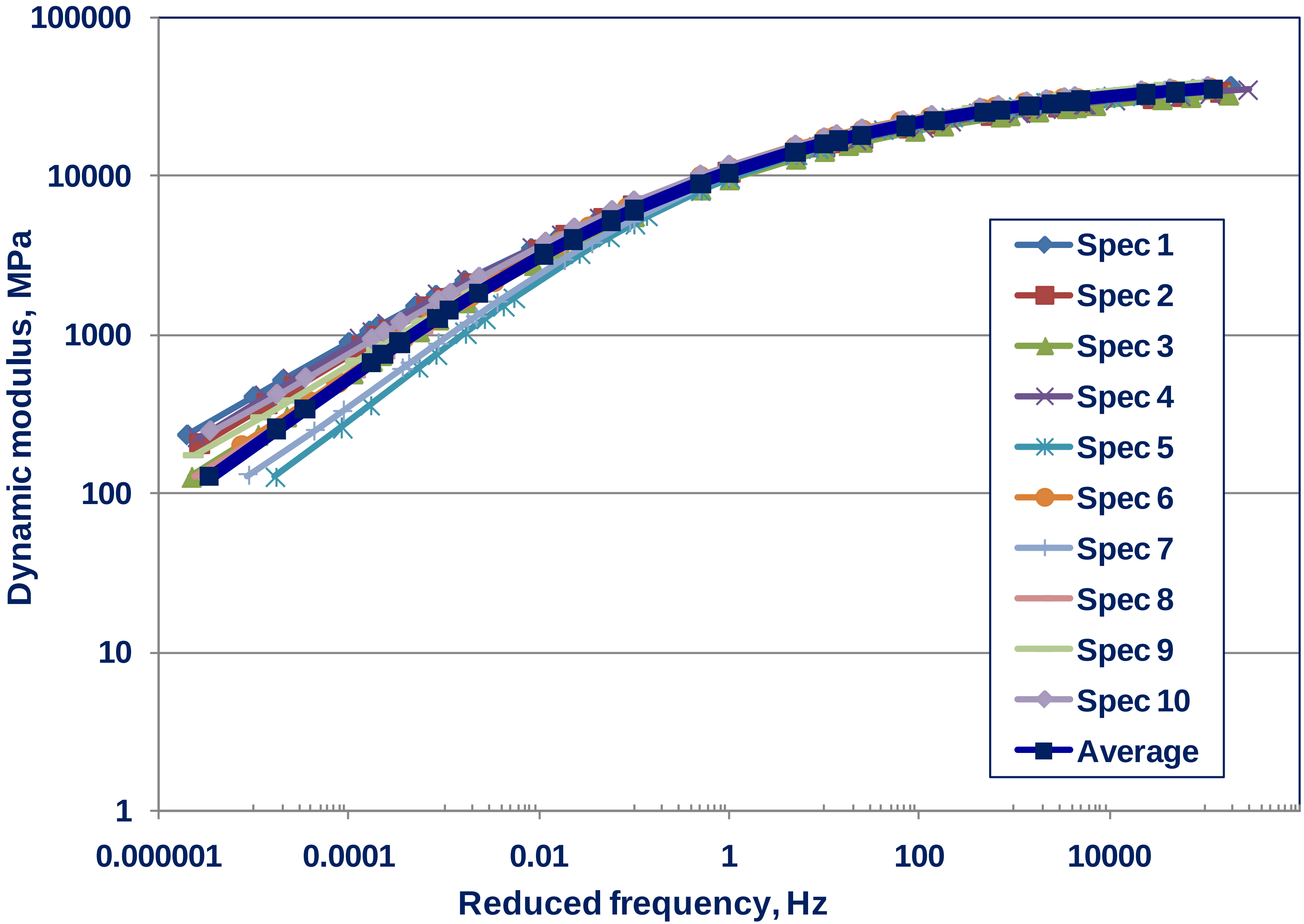
Model results for the asphalt mix tested (using average E values)

	α	β	δ	γ	c
Model Parameters	**2.625**	**-1.451**	**1.892**	**-0.581**	**1.326**

Master Curve & Sigmoidal Model Parameters



Master Curves on Log-Log Scale



CSIR SRP Funded R&D

1. *To review state-of-the-art on unbound materials testing*
2. *To establish testing protocols*
3. *Identify input parameters for response models*
4. *Fine-tune test methods (simplest, most repeatable and reproducible results)*

SANRAL

1. *To assess the proposed protocols for sufficiently wide range of unbound materials.*
2. *Confirmation of proposed laboratory test methods.*
3. *Calibration of density, saturation and stress (including suction pressure) dependent resilient response models.*
4. *Finalize formulation of unbound resilient response and damage models.*

CSIR SRP Funded R&D

1. *To review state-of-the-art on stabilized materials testing*
2. *To establish testing protocols and formulate/re-calibrate models for the determination of the resilient response, yield strength, plastic strain and fatigue.*
3. *To consider modelling of long-term change in characteristics of the stabilized material.*

SANRAL

1. *Assessment of the proposed protocols to establish the desired engineering properties on a set of materials nationally and to calibrate and validate the models.*
2. *Confirmation of proposed laboratory test methods.*
3. *Extensive laboratory and field testing.*
4. *Finalize formulation of resilient response and damage models for stabilized materials.*

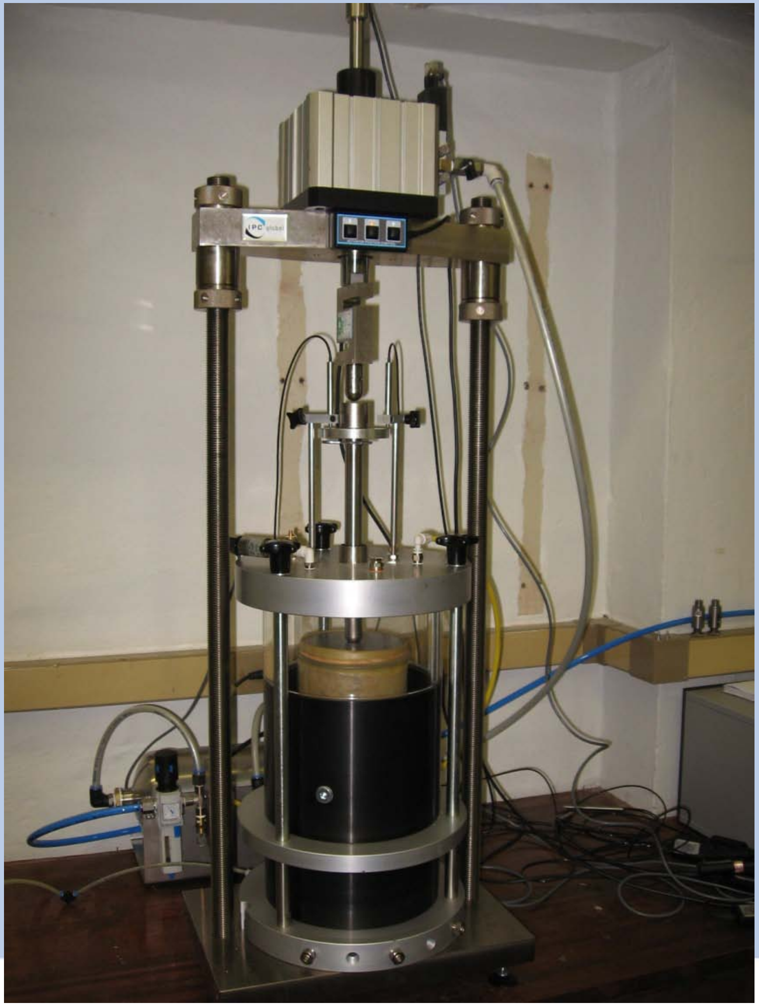
Lab equipment procured to support project

Vibratory hammer for compaction of materials

Lab equipment refurbished to support project

Vibratory table for compaction of materials

Lab equipment procured to support project

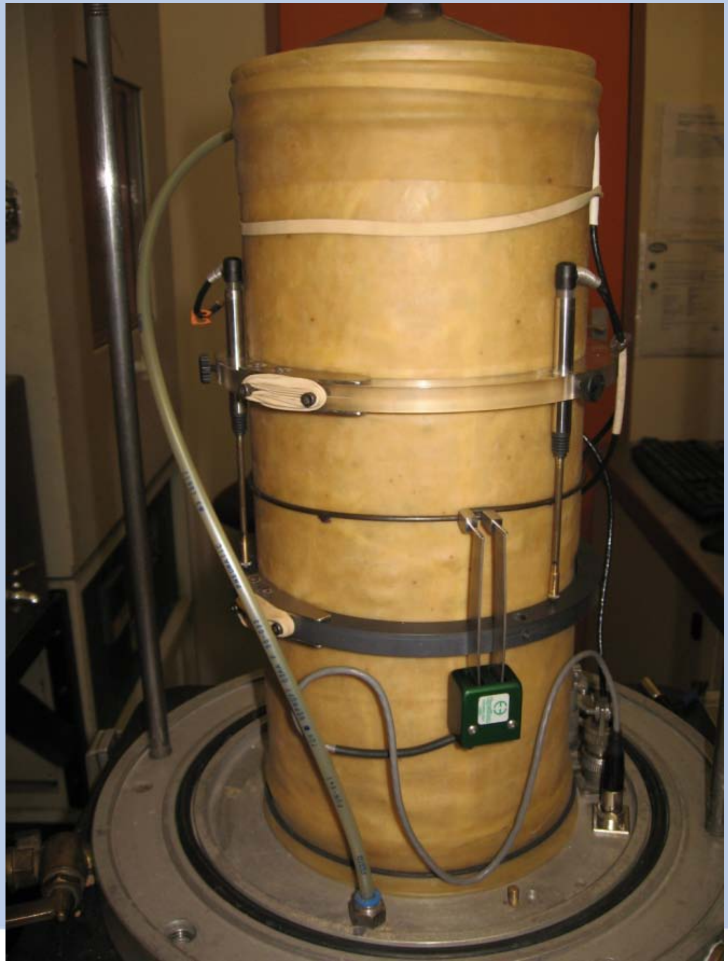


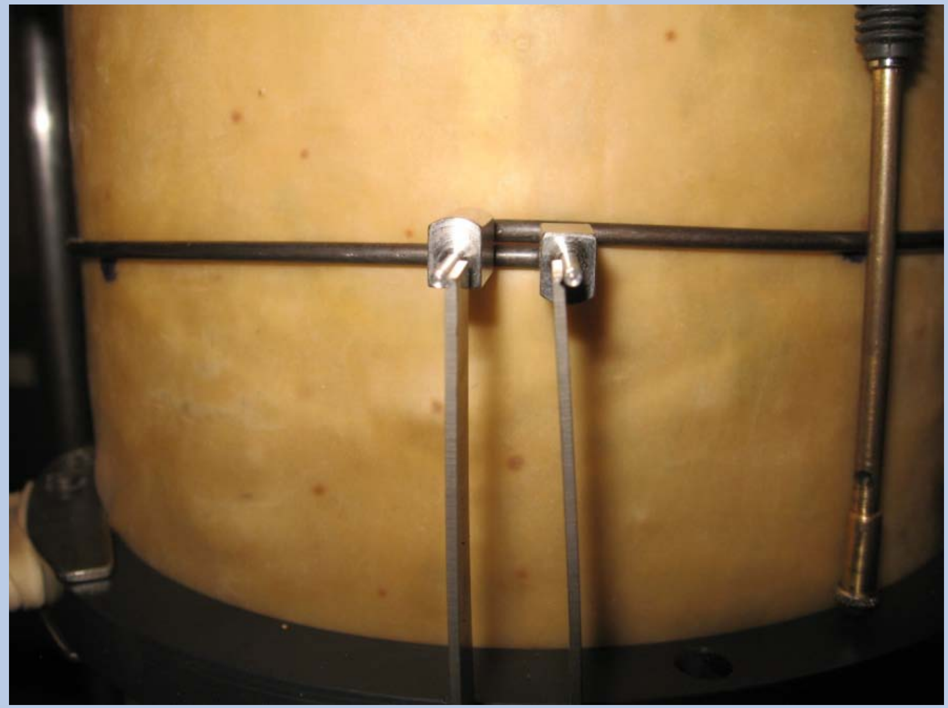
Triaxial machine for resilient modulus testing (R595k)

Lab equipment refurbished to support project

Triaxial Testing machine for resilient modulus testing

Circumferential deformation

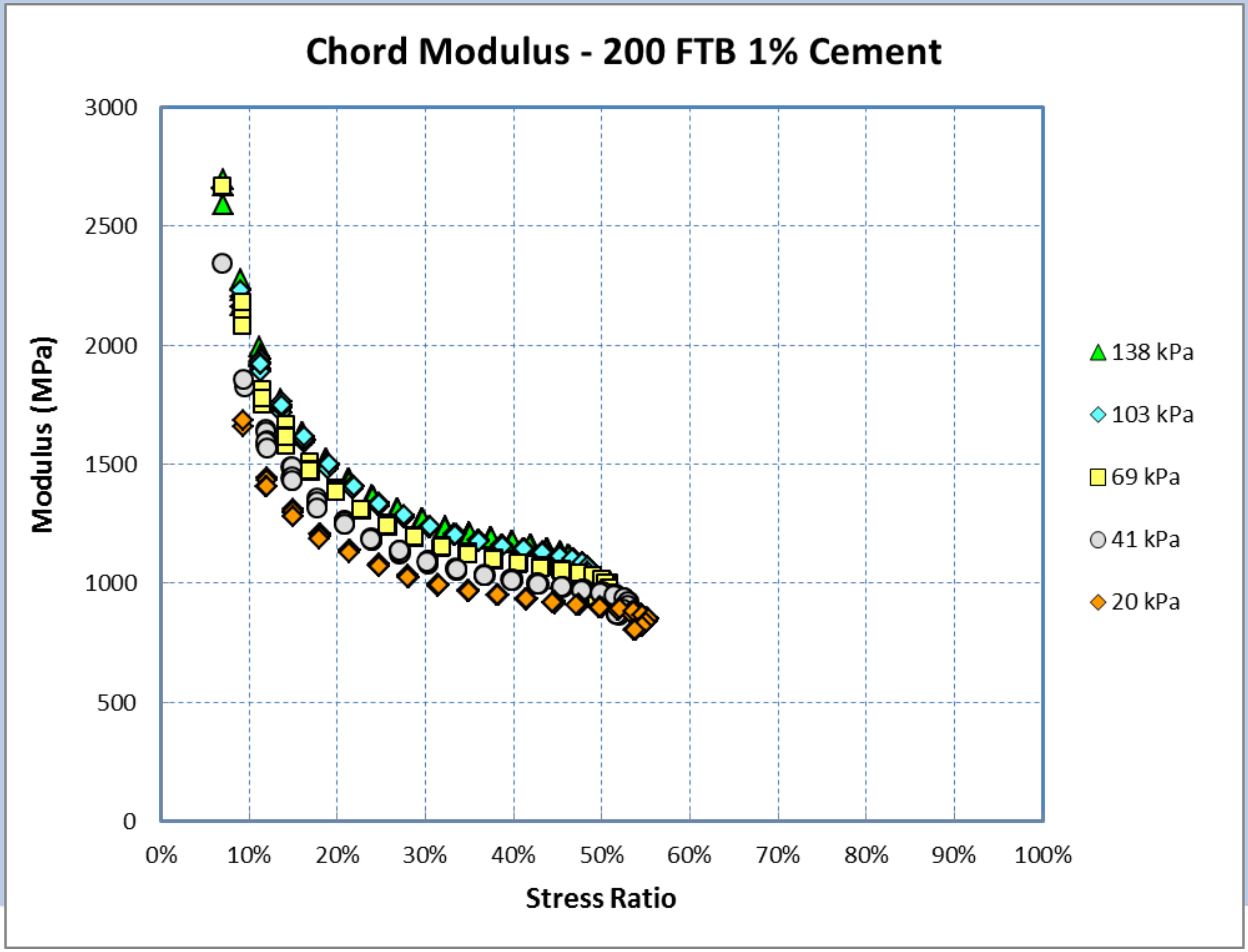




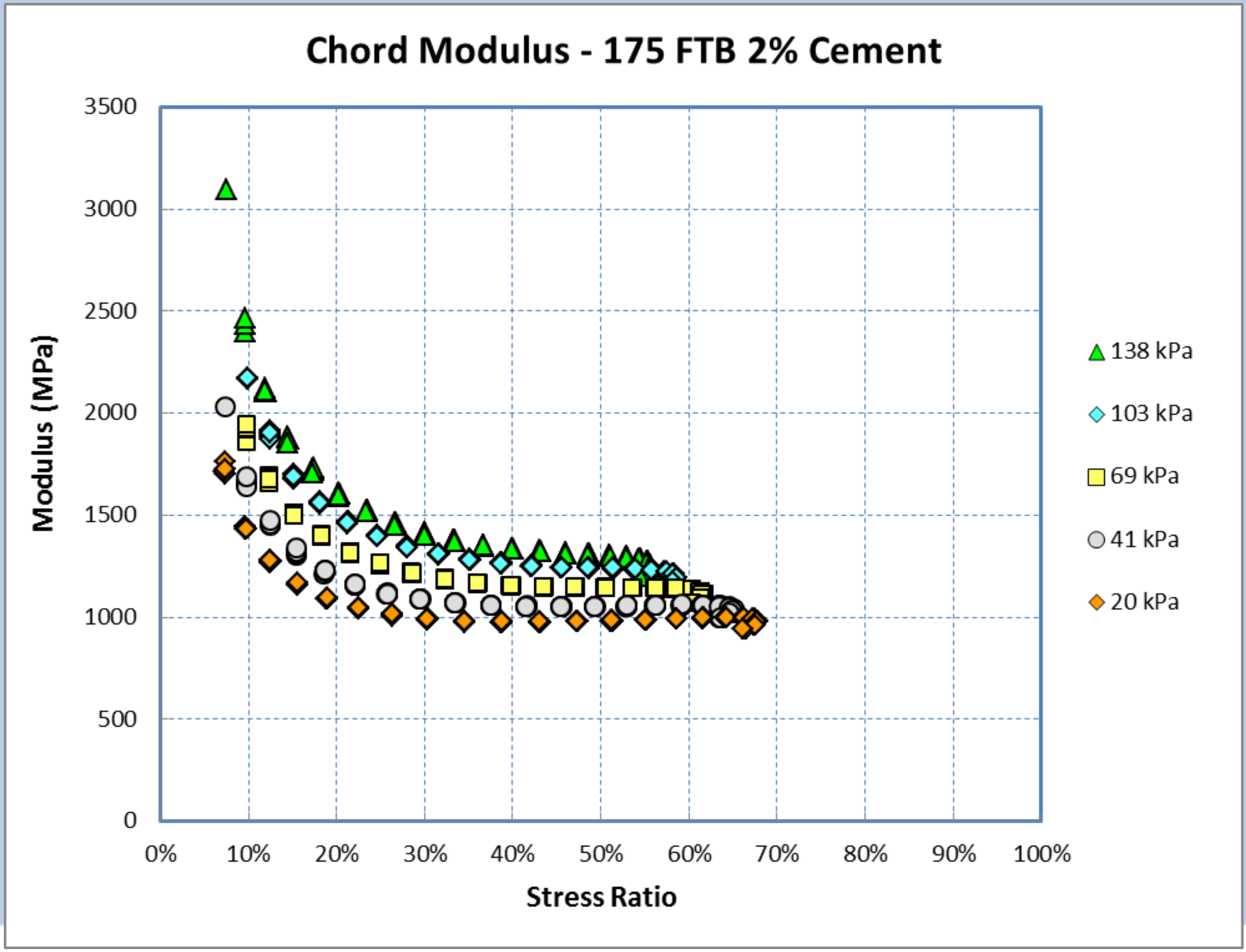
Lab Equipment Refurbished to Support Project

Strain-at-Break for stabilized materials

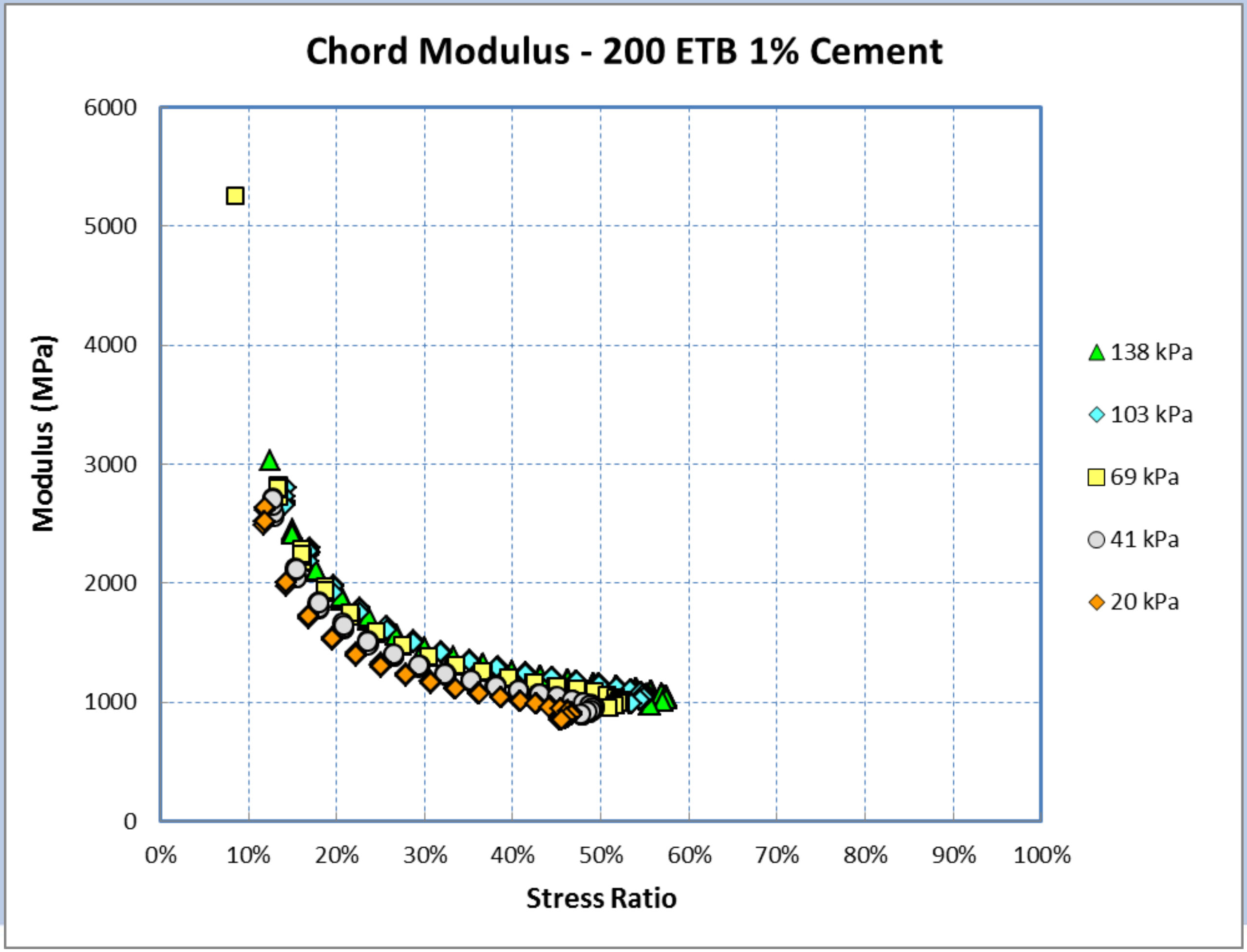
Modeling of Resilient Modulus



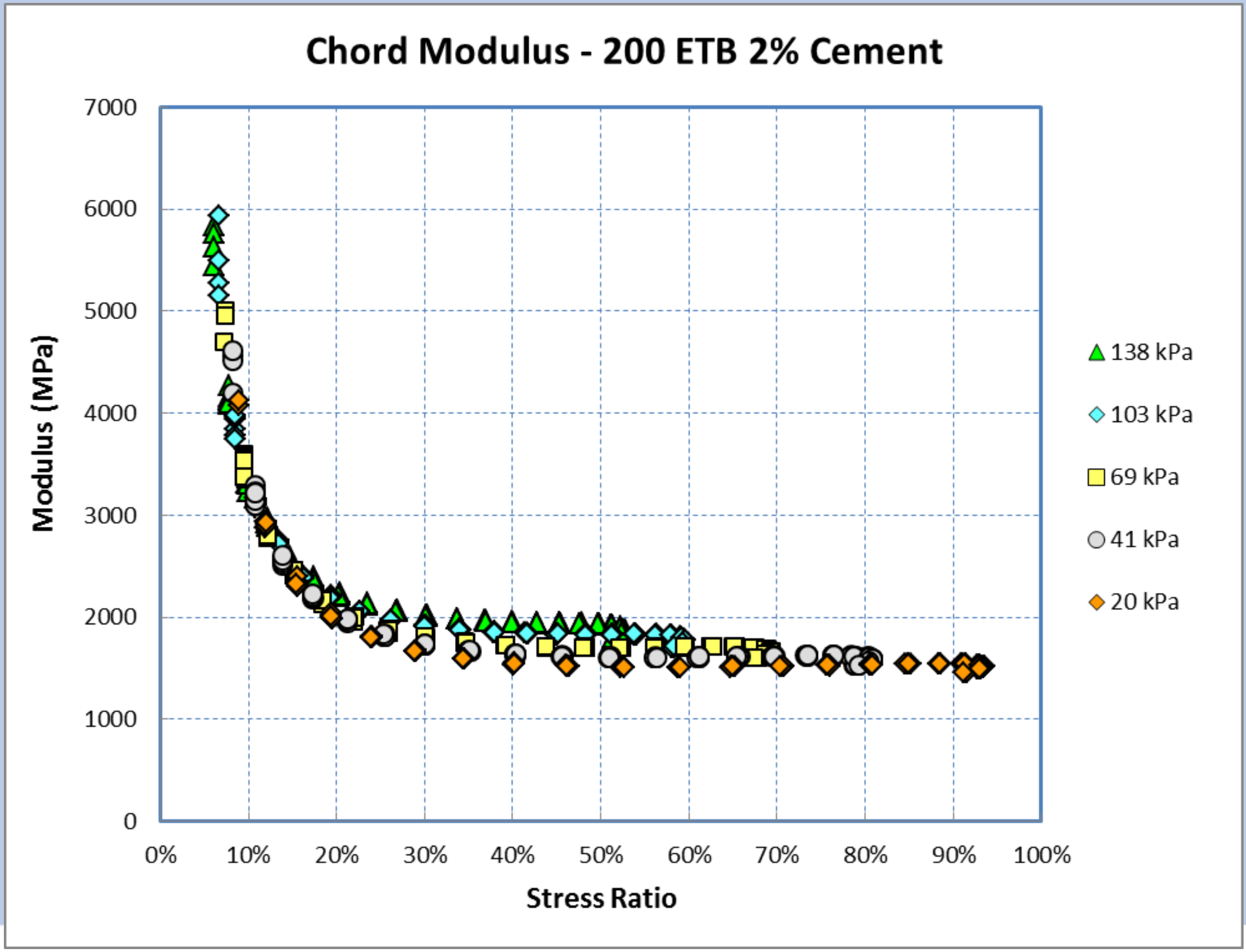
Modeling of Resilient Modulus



Modeling of Resilient Modulus



Modeling of Resilient Modulus



Modeling of Resilient Modulus

	Independent variable	Equation
1	σ_d Deviator stress	$\boldsymbol{M_r = k_1\left(\frac{\sigma_d}{p_a}\right)^{k_2}}$
2	σ_3 Confining stress	$\boldsymbol{M_r = k_1\left(\frac{\sigma_3}{p_a}\right)^{k_2}}$
3	σ_{sum} (sum of the Principle stresses)	$\boldsymbol{M_r = k_1\left(\frac{\sigma_{sum}}{p_a}\right)^{k_2}}$
4	σ_{sum}, σ_d	$\boldsymbol{M_r = k_1\left(\frac{\sigma_{sum}}{p_a}\right)^{k_2}\left(\frac{\sigma_d}{p_a}\right)^{k_3}}$
5	σ_3, σ_d	$\boldsymbol{M_r = k_1\left(\frac{\sigma_3}{p_a}+1\right)^{k_2}\left(\frac{\sigma_d}{p_a}+1\right)^{k_3}}$
6	σ_d, τ_{oct}	$\boldsymbol{M_r = k_1\left(\frac{\sigma_{sum}}{p_a}+1\right)^{k_2}\left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3}}$
7	σ_{sum}, σ_d	$\boldsymbol{M_r = k_1\left(\frac{\sigma_{sum}}{p_a}+1\right)^{k_2}\left(\frac{\sigma_d}{p_a}+1\right)^{k_3}}$
8	Volumetric density, degree of saturation, deviator stress, stress ratio	$M_c = p_a 10^{K_0} VD^{K_{VD}} S^{K_S}\left(\frac{\sigma_3}{p_a}\right)^{K_{conf}}\left(\frac{\sigma_1}{\sigma_1^y}\right)^{K_{SR}} = p_a k_0 VD^{K_{VD}} S^{K_S}\left(\frac{\sigma_3}{p_a}\right)^{K_{conf}}\left(\frac{\sigma_1}{\sigma_1^y}\right)^{K_{SR}}$

Selected formulation

$$M_r = P_a K_0 VD^{K_{VD}} S^{K_S}\left(\frac{\sigma_3}{P_a}\right)^{K_{conf}}\left(\frac{\sigma_1}{\sigma_1^y}\right)^{K_{SR}}$$

K_{vd} : influence of volumetric density

K_{conf}: influence of confining pressure

K_{SR}: influence of stress ratio

CSIR SRP Funded R&D

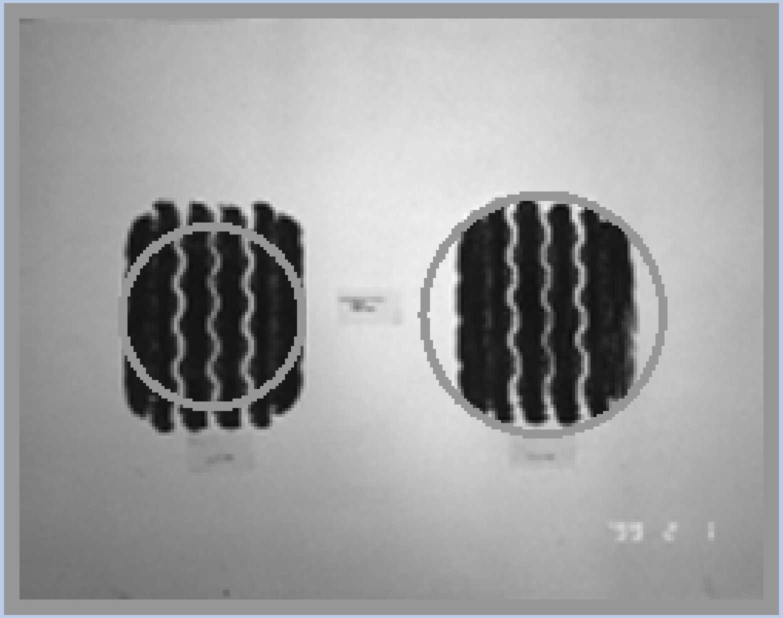
1. *To review need for new numerical models for pavement analysis based on multi-layer linear elastic (MLLE) and Finite Element Method (FEM)*
2. *To develop new computer algorithms for numerical analysis to be used in MLLE/FEM*
3. *To develop algorithms for measured contact stresses to be used as input data on MLLE/FEM*

SANRAL

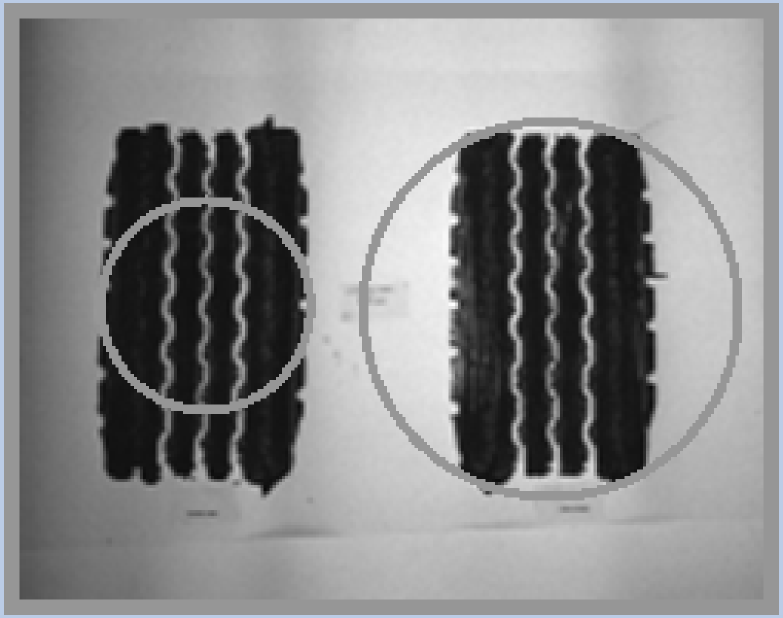
1. *Validation and implementation of the algorithms developed under SRP on MLLE package (GAMES).*
2. *Validation and implementation of the algorithms developed under SRP on FEM package (FEMPA).*
3. *Development of software for back-calculation analysis based on static and dynamic loads.*
4. *Data base and software viewer of contact stresses using CSIR Stress-in-Motion technology*

Improved pavement analysis models (MLLE)

1. <u>Loading</u>
   - *Non-circular contact stress*



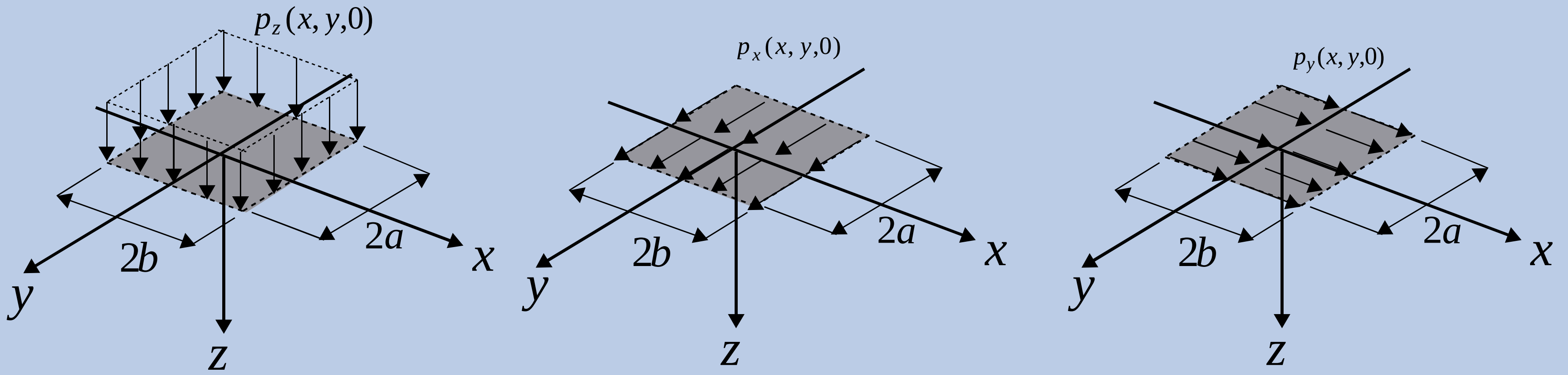
HVS DUAL TYRE FOOTPRINT @ 30 kN & 420 kPa inflation pressure



HVS DUAL TYRE FOOTPRINT @ 70 kN & 420 kPa inflation pressure

1. Loading

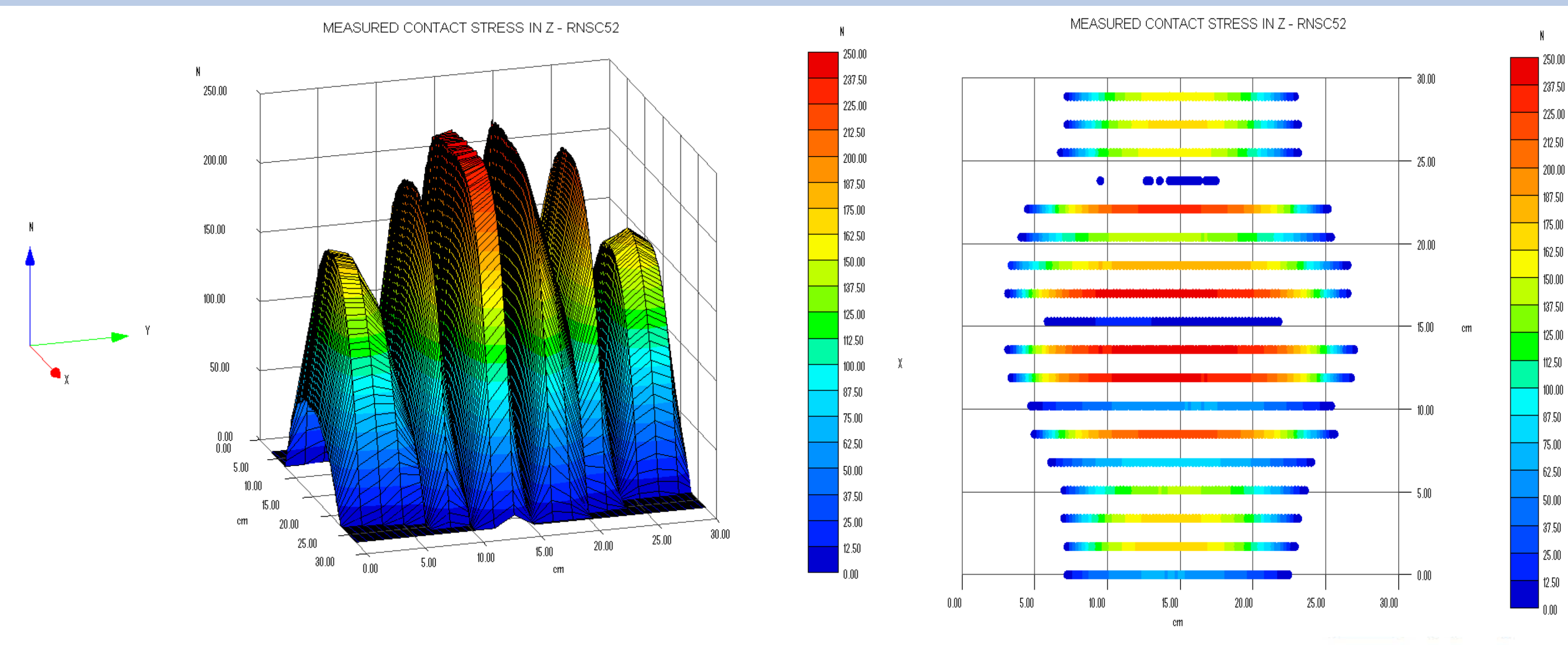
- *Non-circular contact stress*



Improved pavement analysis models (MLLE)

1. Loading

I. Non-uniform measured contact stresses (Ref. SIM)



2. Pavement Materials

- *Cross-anisotropic material behaviour*

Isotropic material

E *: constant elastic modulus*

ν *: constant Poisson's ratio*

G *: shear modulus*

$$G = \frac{E}{2(1+\nu)}$$

Cross-anisotropic material

E_v *: vertical elastic modulus*

E_h *: horizontal elastic modulus*

G_{vh} *: shear modulus*

ν_v *: vertical elastic modulus*

ν_h *: horizontal elastic modulus*

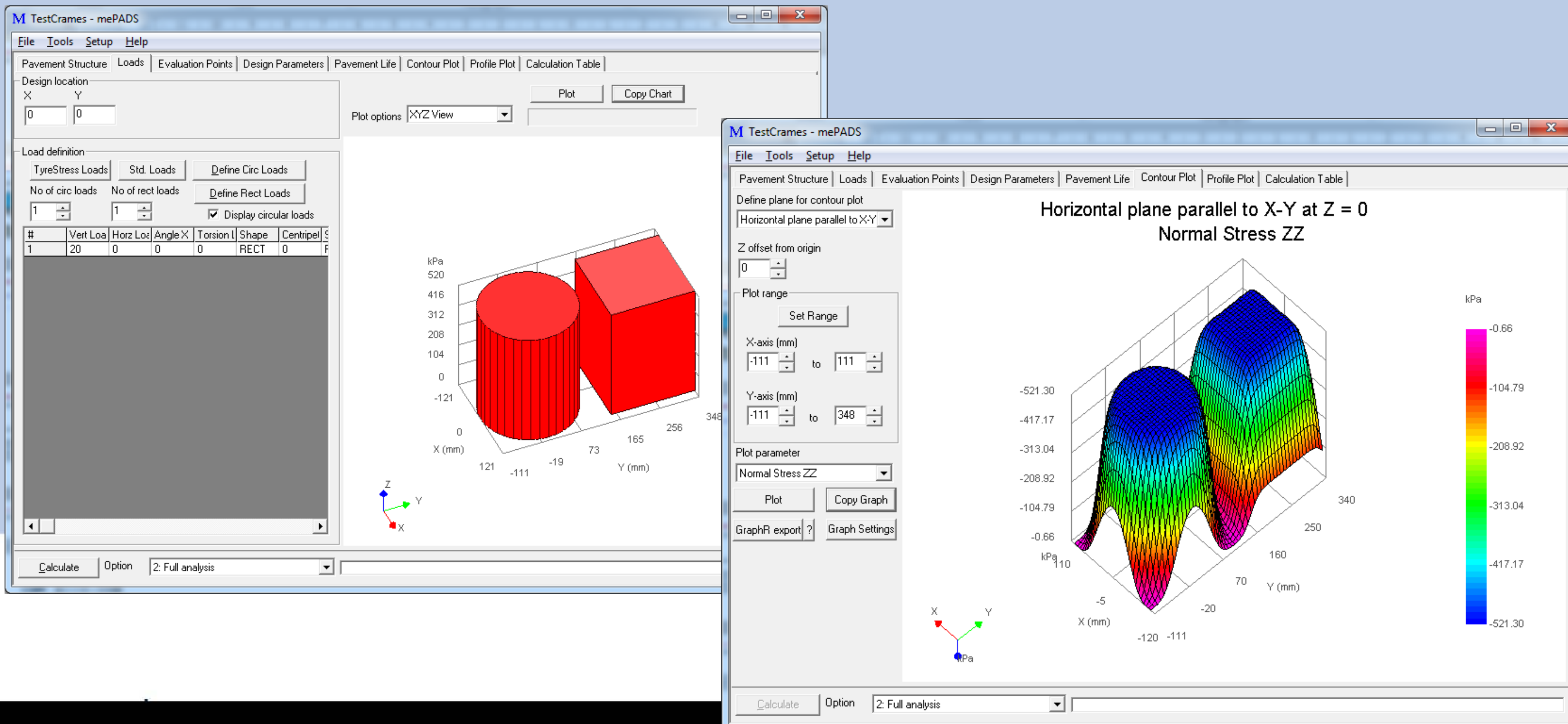
3. Pavement Geometry

- *Layer interface condition (de-bonding (slip) v. bonding)*

Improved pavement analysis models (MLLE)

4. Software development

- *Incorporating loading characteristics, pavement structure and material properties*

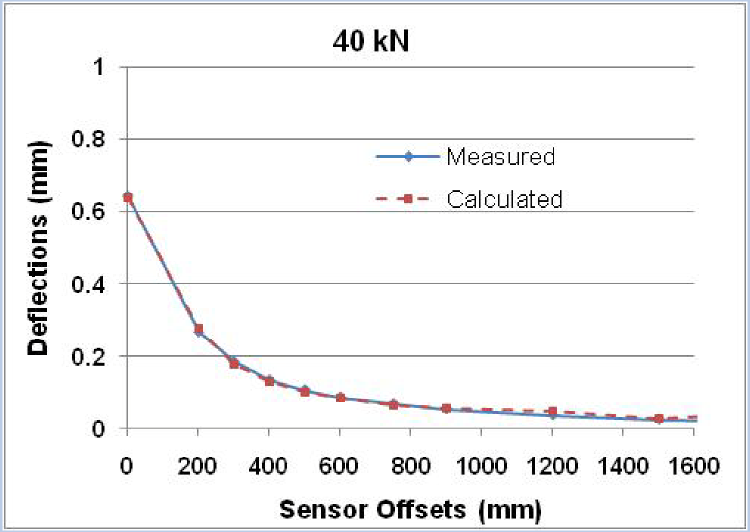


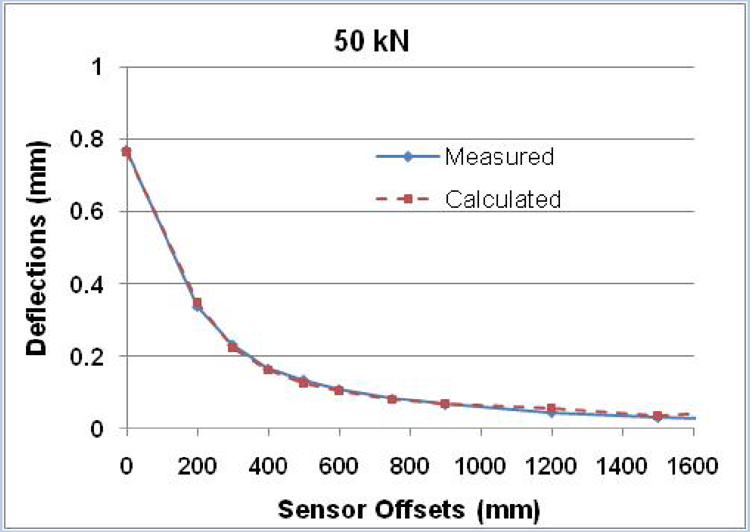
1. Field Testing

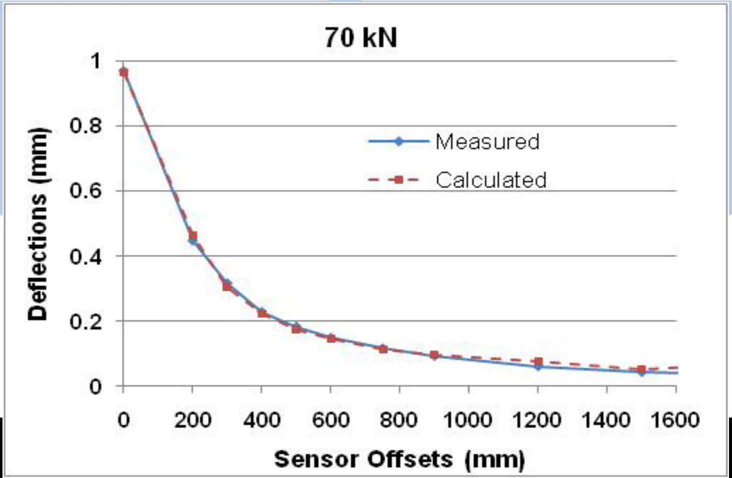
- *Surface and Multi-depth deflections*

1. Field Testing

- *FWD surface measured vs predicted deflections*



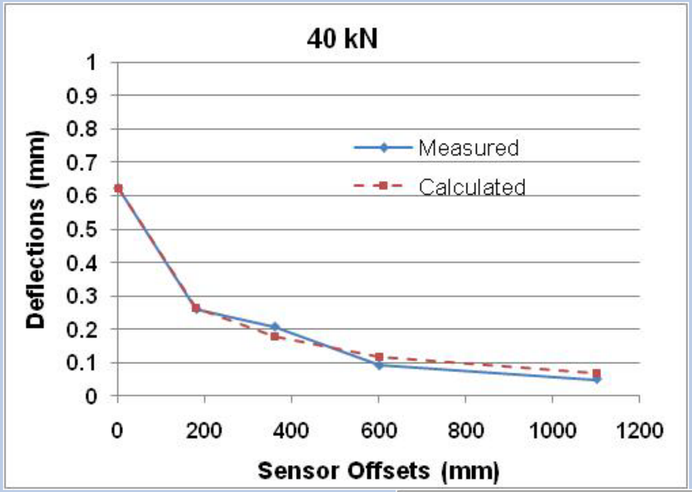


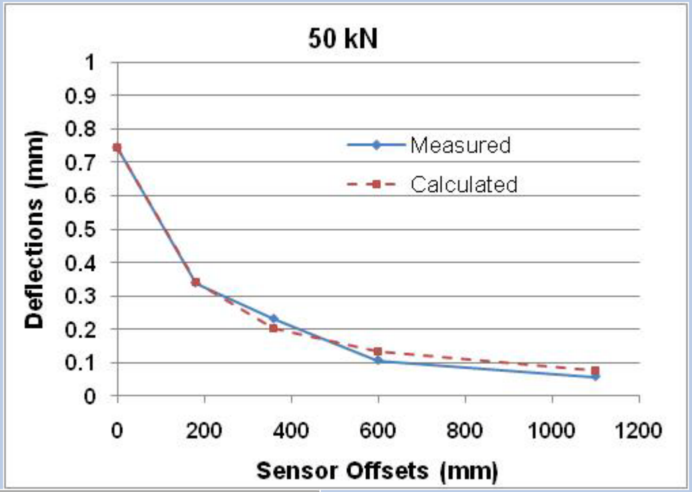


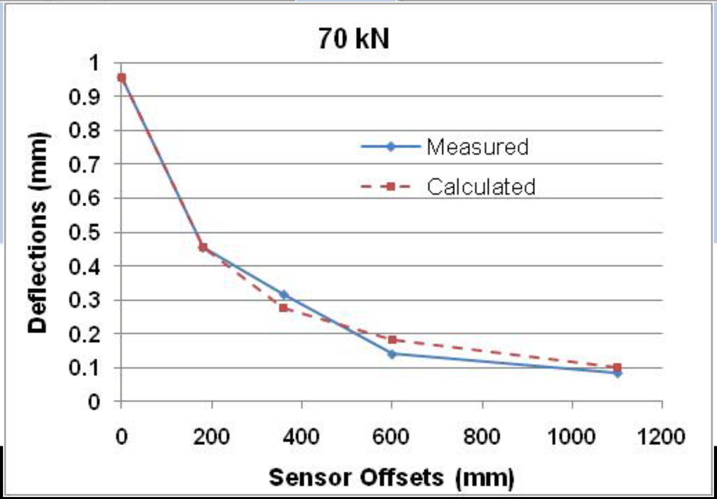
CSIR

1. Field Testing

- *MDD measured vs predicted deflections*







OUTCOMES
&
ACHIEVEMENTS

ACHIEVEMENT TO DATE and FUNDING

1. ***<u>Involvement of industry</u> in determination of research needs and research direction***
   - ***Linking of research work with industry needs***
2. ***Testing of standard South African asphalt mixes***
   - ***Extra mixes funded by SABITA are currently being tested***
3. ***Testing of unbound and stabilized materials***
4. ***Leveraging funding (CSIR: R20.9m (2008/12), SANRAL: R28.5m + additional R6.4m submitted for approval (2012/13), SABITA: R2.4m (2011/13)***
5. ***Numerous experimental, field and laboratory testing***
6. ***Multiple research reports, conference and journal publications***

POTENTIAL FOR IMPACT

Impact is envisaged on:

I. ***More efficient and cost-effective roads servicing the functional needs of users;***

II. ***Training and dissemination of the new gained knowledge to all entities working in the field of pavement engineering and technology – such as consulting, construction and road departments and agencies;***

III. ***Possible export of the design method to SADC, Sub-Saharan Africa and beyond.***

THANK YOU!

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Mr Robert Leyland
Ms Amrita Maharaj
Mr Willy Diederiks
Mr Colin Fisher
Mr Julius Komba
Mr Tso Nkgapele
Mr Zweli Mthembu
Ms Ellen Laubscher
Ms Rianie Castelyn
Mr Dave Ventura
Mr Georges Mturi
Ms Kele Makamu
Ms Keneilwe Mogonedi
Ms Magriet von Wissell
Ms Santa Conrad
Mr Thomas Thekiso
Mr Alan Crawford
Mr Alfred Nkuna
Mr David Mohatli
Mr David Molebalo
Mr Kenneth Baloyi
Mr Khayalami Mahlangu
Mr (Ngwako) Victor Maake
Mr Nnditsheni Mpofu
Mr Richard Mathibela
Ms Natasha Lotter