EVALUATION OF TEST METHODS FOR ESTIMATING RESILIENT MODULUS OF PAVEMENT GEOMATERIALS

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ABSTRACT

Resilient modulus is a key parameter required for the mechanistic empirical pavement design procedures currently being adopted around the world including the recently developed NCHRP 1-37A design guide in the United States and the current South African Pavement Design Method (SAPDM). The determination of the resilient modulus requires sophisticated equipment and skilled personnel for laboratory and field testing. These requirements have contributed immensely to the proliferation of different resilient modulus test procedures. Commonly used resilient modulus laboratory test methods for pavement geomaterials such as subgrade soils and unbound granular materials have evolved from the American Association of State Highway and Transportation Officials (AASHTO) and the Strategic Highway Research Program (SHRP) test protocols. This paper presents an overview on the state-of-the-art test procedures for determining resilient modulus of pavement geomaterials. Differences between current test procedures, and some potential challenges with the adoption of a universal test procedure are discussed. Common resilient modulus models used for characterising pavement geomaterials in flexible pavement design are also presented.

INTRODUCTION

Over the past 20 years, a great deal of practical research has been undertaken to improve or provide more appropriate test procedures and methods as well as response models to evaluate the resilient modulus of pavement geomaterials, i.e., fine-grained subgrade soils and unbound aggregate materials. All of this research has been enhanced by the increasing tendency toward designing flexible pavements using mechanistic-empirical design concepts in which pavement response variables such as stresses, strains and displacements are related to pavement distress using various transfer functions. The resilient modulus is a key input property for pavement geomaterials in the mechanistic-empirical pavement design approach. The recently developed National Cooperative Highway Research Program (NCHRP) flexible pavement design guide in the United States, and the current South African Pavement Design Methods (SAPDM) require repeated load triaxial testing in the laboratory to determine the resilient modulus for characterizing geomaterials (NCHRP, 2004; SANRAL, 2008). The determination of the resilient modulus of these pavement materials is expected to be done on a routine basis to support the implementation of multilayered pavement structural analysis and design.

Traditionally, resilient modulus used for the elastic stiffness of pavement materials is defined as the ratio of the repeatedly applied wheel load stress to the recoverable strain determined after shakedown of the material. Resilient modulus determination requires a fundamental understanding of the test procedures, and a review of the underlying concepts surrounding these procedures. This paper intends to advance the basic knowledge and understanding of the state of the practice on test procedures and methods used for evaluating the resilient modulus of pavement geomaterials. Information on different resilient modulus test procedures and loading conditions currently used worldwide are presented together with some of the resilient modulus models used in flexible pavement analysis and design of geomaterials. A brief discussion is provided on possible challenges of implementing resilient modulus test procedures by national or provincial agencies, the industry and research institutions.

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RESILIENT MODULUS TESTING CONCEPTS

Resilient modulus definition

The concept of resilient modulus (M_R) was initially introduced by Seed et al. (1962) for characterizing the elastic response of subgrade soils in flexible pavements. Due to its reliability in both measurement and application, resilient modulus response of unbound granular materials was used in the American Association of State Highway and Transportation Officials (AASHTO) design guide for pavement structures (AASHTO, 1986).

The ASHTO T307 repeated load triaxial compression test is currently the most commonly used method to measure the resilient (elastic) deformation characteristics of geomaterials in the laboratory (AASHTO, 2005). Under the repeated application of dynamic loads, the recoverable strains are used to evaluate the resilient properties of pavement geomaterials. Figure 1 indicates typical strains recorded under a repeated load test for pavement geomaterials. It can be seen that both elastic and plastic deformations occur at the initial stage of load application. As the number of load applications increases, the amount of plastic deformation decreases until a stage where the deformation is practically all recoverable. At that stage, the resilient modulus is obtained based on the recoverable axial strain under the applied dynamic load. The resilient modulus is defined by

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

in which σ_d is the dynamic deviator stress and ε_r is the resilient (recoverable) axial strain.

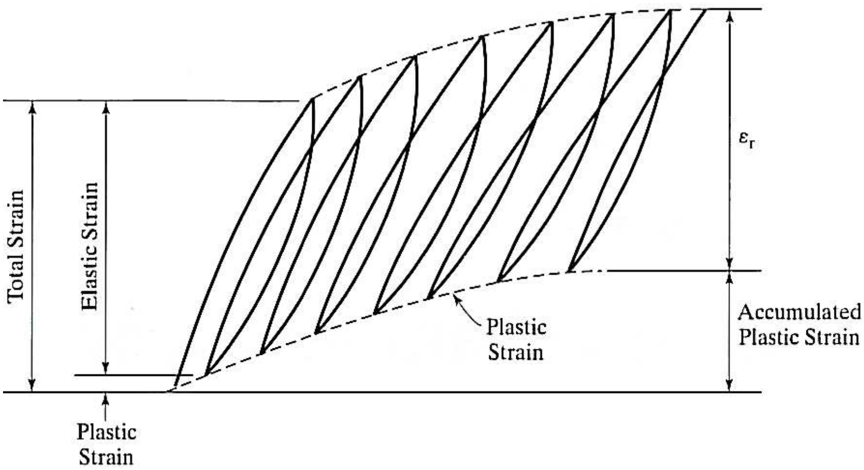

Figure 1. Strains of geomaterial specimen under repeated load test (Huang, 2004)

Stress states for resilient modulus testing

The principles of cyclic triaxial testing used in classical geotechnical engineering practice have been extended to the field of pavement engineering to perform resilient modulus tests simulating highway or airport types of loading. The major difference is that in the resilient modulus test, transient loads that are well below the failure stresses for that material are usually applied on the sample of the pavement material.

The typical stress states applied on the specimen for the direct measurement of principal stresses and strains is the cylindrical triaxial test. Figure 2 illustrates typical stress components used in repeated loading test for determining the resilient modulus of pavement geomaterials. The total axial stress (σ_1), consists of dynamic deviator (σ_d) stress and static confining stress or confining pressure (σ_3). The confining pressure is made of only a static stress component ($\sigma_2 = \sigma_3$) and a zero dynamic stress component in the horizontal direction. Both the deviator stress and confining pressure have substantial influence on the resilient behavior of geomaterial layers in the pavement. Note that the shear stress (τ) on the plane of the sample during testing is zero.

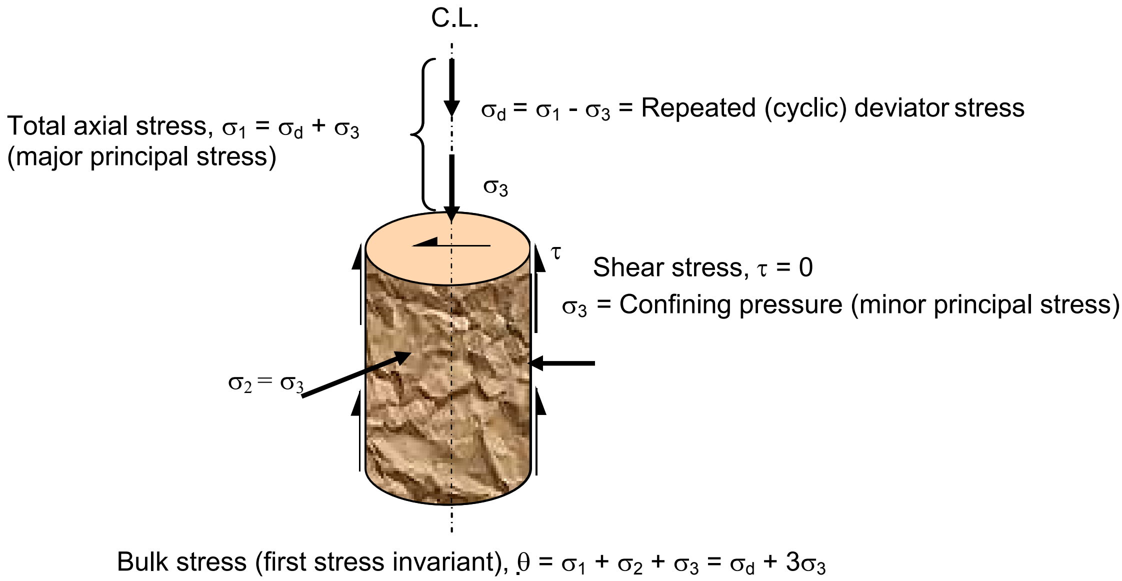

Figure 2. Concept of stress states for resilient modulus testing

Resilient modulus testing

Resilient modulus testing is performed at different confining pressure and deviatoric stress states in an attempt to simulate typical highway loadings of different vehicles at different depths in the pavement structure. During testing, cylindrical specimens are subjected to different repeated/pulsed stress states under different constant all-around confining pressures to simulate the lateral stress caused by the overburden pressure and dynamically applied wheel loadings. In the AASHTO T307 procedure, a haversine load pulse with 0.1-second loading and 0.9-second rest period is generally applied on the specimen for 100 load cycles with a minimum of 500 load cycles conditioning stage. Thus, the total duration for one load cycle is 1 second (60 load applications per minute). For subgrade materials, the NCHRP Project 1-28A report, "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design," specifies 0.2 -second haversine load pulse and 0.8-second rest period (NCHRP 1-28A, 2004). The total resilient axial deformation response of the specimen and the applied deviator stress are measured and used to calculate the resilient modulus.

To avoid failure of test samples at the beginning of a testing program, some agencies and researchers have recommended that the load applications should start at the highest confining pressure with the corresponding axial stress at the lowest level. This would ensure that stress states at which the material is least likely to fail are chosen first, followed by stress states at which the samples are most likely to fail. This approach is usually adopted for fine-grained soils. An alternative approach is to determine the shear strength (Mohr circles) of the material using static tests at a range of confining pressures prior to repeated load testing and use this as a basis for defining the stress regimes to be used for dynamic testing.

RESILIENT MODULUS AND PAVEMENT DESIGN

The theory of elasticity is usually used for flexible pavement design. This theory assumes that all materials in the pavement are homogeneous, isotropic, and linearly elastic. With these assumptions, only two material properties, i.e., Poisson's ratio and the modulus of elasticity would be necessary to calculate stresses, strains, and deflections in the pavement layers. The Poisson's ratio is usually assumed or obtained through the use of correlations, and the resilient modulus is used as the modulus of elasticity based on the recoverable strain under repeated loads. In the mechanistic-empirical flexible pavement design, a resilient modulus value determined in the laboratory is preferred, although field measurement through backcalculation procedures from Falling Weight Deflectometer (FWD) data is acceptable.

Since 1986, AASHTO has incorporated the resilient modulus of pavement layer materials into their design and analysis process. As mentioned earlier, both the NCHRP and SAPDM design guides, and other mechanistic based flexible pavement analysis and design approaches use the resilient modulus to characterize the unbound layers in the pavement system (NCHRP, 2004; SANRAL, 2008). In these design guides, the resilient modulus values of geomaterials determined from laboratory are mainly used for new, reconstruction and rehabilitated pavement analysis, whereas resilient modulus values obtained from FWD backcalculation could be used for the analysis of reconstruction and rehabilitated pavements.

The resilient behavior of geomaterials in flexible pavements is affected by several factors including the magnitude of stress levels, stress history, number of load applications and conditioning sequence. Other geomaterial properties such as liquid limit, plasticity index, particle size distribution, specific gravity, water content, density and organic carbon contents have also been linked to the resilient modulus of soils (Bejarano & Thompson 1999). The applied stresses, compacted density and the specimen moisture content significantly influence the resilient behavior of fine-grained soils. However, several authors have shown that the resilient response of geomaterials can be reasonably characterized by using stress dependent models which express the modulus solely as nonlinear power functions of the applied stress states (Hicks & Monismith, 1971; Thompson & Elliot, 1985; Uzan, 1985; Witczak & Uzan, 1992).

Granular materials under repeated load generally display stress-hardening while fine-grained cohesive soils show stress softening under repeated loads (Bejarano & Thompson 1999). Thus, the resilient modulus of granular materials generally increases with increase in stress whereas the resilient modulus of fine-grained cohesive soils decreases with increasing stress.

Several stress-dependent constitutive models are available to establish the stress sensitive relationship between the resilient modulus value and the various stress states.
For Level 1 input of material parameters in the AASHTO 2002 design guide, the following relationship describes the stress dependency of both fine-grained soils and unbound materials for mechanistic analysis and design (NCHRP 1-37A, 2004).

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \tag{2}$$

where,

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$;

σ_1 = major principal stress;

$\sigma_2 = \sigma_3$ for triaxial test on cylindrical specimen;

σ_3 = minor principal stress or confining stress in the triaxial cell;

τ_{oct} = octahedral shear stress;

$$= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$

$= \frac{\sqrt{2}}{3}(\sigma_1 - \sigma_3)$ for cylindrical specimen in triaxial tests;

P_a = normalizing stress atmospheric pressure = 101.3 kPa;

k_1, k_2, k_3 = model parameters obtained from regression analyses.

The model parameters k_1, k_2, and k_3 are obtained using non linear regression techniques to fit resilient modulus test data generated in the laboratory and are related to the material properties.

Mohammad et al. (1994) also reported that to some extent, the values of these model parameters depend on the measurement system and the testing procedure.

In this constitutive equation, the coefficient representing model parameter k_1 is proportional to the resilient modulus. The value of k_2 of the bulk stress term should be positive since the resilient modulus can never be negative. Also, increasing bulk stress should produce stiffening of the material, which results in a higher resilient modulus. However, parameter k_3, which is the exponent of the octahedral stress, should be negative since increasing the shear stress decreases the resilient modulus values or produces softening of the materials.

The resilient modulus can also be estimated from other material strength properties including the commonly used California Bearing Ratio (CBR) and Hveem Resistance (R) value. The use of CBR and R values are more or less empirical, and should only be used within the limits of the test conditions on which they are based. Equations 3 and 4 represent resilient modulus-CBR, and resilient modulus-resistance value correlations recommended in the NCHRP 1-37A design guide for flexible pavement analysis and design.

$$M_R\ (MPa) = 17.6\, CBR^{0.64} \tag{3}$$

$$M_R\ (MPa) = 8.0 + 3.8\, R \tag{4}$$

DEVELOPMENT OF RESILIENT MODULUS TESTING PROCEDURES

During the past decades, research groups and agencies in different countries have proposed test methods and procedures for repeated load testing to help in establishing appropriate resilient modulus test procedures for pavement design. This development contributed considerably to the use of resilient modulus in some pavement design guides. The 1986 AASHTO pavement design guide used the resilient modulus to characterize subgrade soils and to assign layer coefficients to granular base and subbase layers. In 1982, AASHTO adopted a resilient modulus testing procedure AASHTO T274-82 "Resilient Modulus of subgrade soils" but in 1989, the AASHTO materials committee withdrew AASHTO T274-82 from their standard tests. In 1991, AASHTO approved an interim method of resilient modulus testing (AASHTO T292-1991, "Resilient modulus testing of subgrade soils and untreated/subbase materials."). This test method was included in the 1991 AASHTO interim testing methods Part II and was modified to AASHTO T294-1992 (Puppala, 2008). Following this, the SHRP testing protocol (P46, "Resilient modulus of unbound granular base/subbase materials and subgrade soil) based on AASHTO T294-1992 was developed.

Later, the SHRP protocol P46 was also modified and developed into AASHTO standard, which was adopted as AASHTO T307-99. In the United States, AASHTO T307-99 is currently the standard test adopted by AASHTO for determining resilient modulus of pavement geomaterials in the laboratory. There are several other test methods and procedures developed, or being developed throughout the world to determine resilient properties of pavement geomaterials. For example, the University of Stellenbosch in South Africa has proposed a test procedure for testing granular materials (Ebels & Jenkins, 2007). Also, the NCHRP has proposed new procedures for testing unbound materials (NCHRP 1-28A Witczak, 2004) which are essentially the same as AASHTO T307-99 but specifies internal axial strain measurement and a different set of stresses for testing. Other methods include the European standard (CEN, 2004), and the Australian method "Determination of permanent deformation and resilient modulus characteristics of unbound granular materials under drained conditions" (Vuong & Brimble, 2000). Individual researchers have also made use of revised or proposed test procedures for determining resilient modulus of geomaterials (Andrei et al., 2004). It is worth to mention that resilient modulus test device is commercially available, and the size of the specimen required is reasonable for field representation and laboratory preparation although the testing equipment could be expensive.

Table 1 summarizes the main differences between the various resilient modulus test procedures. The characteristic differences between the test procedures show the emergence of different resilient modulus test procedures during the past decade. As part of the revision of the current mechanistic-empirical pavement design practice in South Africa the CSIR Built Environment through Strategic Research Project is developing test protocols for pavement materials characterization including geomaterials.

Table 1: Summary of different M_R test protocol requirements

Property	EN 13286-7 (2004)	AASHTO T307-99 (2005)	NCHRP I-28A (2004)	CSIR Transportek (2002)	University of Stellenbosch (2007)	University of Illinois (1998)	Australia AG:PT/053 (2007)
Material types	Max aggregate size < 0.2 sample diameter	1. (Max size < 70% < 2.0 mm < 20% < 0.075, PI < 10%) 2. all others	1. (Max size > 9.5; > 25.4 scalped) 2. (Max size < 9.5; < 10% < 0.075) 3. (Max size < 9.5; > 10% < 0.075) 4. Thin wall undisturbed	No details – Borrow pit or test pit Max size 37.5 mm	Unbound and bound granular materials Max size 19 mm duplicate specimens	Unbound aggregates and subgrade soils Max size 25 mm	Max size 19 mm – oversize discarded (not more than 5%)
Specimen preparation	Vibro-compression (1 layer) Vibratory hammer (6 – 7 lifts)	1. Vibratory hammer (6 lifts) 2. Static (5 lifts) or pneumatic kneading (5 lifts)	Type 1: Impact (Proctor) / vibratory hammer (or rotary) Type 2: vibratory Type 3: Impact/ kneading	Vibratory table 3-lifts in split mould	Not finalized	Standard pneumatic concrete vibratory compactor 3-lifts in split mould	Standard and modified Proctor methods at (5 or 8 lifts)
Specimen compaction state	Moisture content and density reps of field conditions 6 specimens (OMC – 4, 2,1% and 100, 97, 95% density)	In situ wet density and moisture content or standard and modified Proctor	Desired density and moisture content	2 levels of density (95-98% & 102-105% Mod) and moisture content (Sr 45, 75%)	Specified moisture content and density	Optimum moisture content and max dry density	Optimum moisture content and max dry density
Height : diameter	2 ± 2% Diam > 5 times max particle size; (160 x 320 mm)	2.0 70 mm diam (subgrade); Min diam = 5 times max size (base /subbase)	2.0 70 mm diam (fine-grained), 100 – 150 mm diam (coarse-grained)	2.0 150mm diam x 300 - 305 mm high	2.0 150 mm diam x 300 m high	2.0 50mm diam (subgrade soils); 150mm diam (base/subbase)	2.0 100 diam x 200 mm high for fine and coarse-grained
Response measurement	Load cell Internal 3 axial LVDTs measuring centre 100 mm of sample at 120°, attached to membrane	Load cell external 2 external axial LVDTs	Load cell internal 2 Internal axial LVDTs	Load cell On sample full length	Load cell On specimen LVDTs over middle third	Load cell internal; 2 external axial LVDTs	Load cell external or internal 2 axial LVDTs

Table 1 (contd): Summary of different M_R test protocol requirements

Property	EN 13286-7 (2004)	AASHTO T307 (2005)	NCHRP I-28A (2004)	CSIR Transportek (2002)	University of Stellenbosch (2007)	University of Illinois (1998)	Australia AG:PT/053 (2007)
Confining pressure	Variable and Constant (vacuum option) up to 600 kPa	Constant up to 140 kPa	Constant up to 140 kPa	Constant up to 200 kPa	Constant up to 200 kPa	Constant up to 140 kPa	Constant up to 500 kPa
Chamber medium	Water, air or silicon oil	Air	Air	Air	Air or water	Air	Silicon oil or water covering sample, together with air for pressure
Specimen conditioning	70 kPa confining, and axial deviator stress of 200 - 340 kPa; 20 000 reps	103.4 kPa confining, and axial deviator stress of 103.4 kPa; 500 - 1000 reps	27.6 -103.5 kPa confining for subgrade, base /subbase at 1000 reps; axial deviator stress of 50.8 - 227.7 kPa	200 kPa confining and axial deviator stress of 0.45xσ_d at failure; 500 - 1000 reps	200 kPa confining and 20 kPa axial deviator stress, 5000 reps	103.4 kPa confining at deviator stress of 310.5 kPa; 1000 reps	50 kPa confining and axial deviator stress of 100kPa ; 1000 reps
Load type	Frequency of axial load (0.2 -10Hz)	Haversine, 0.1s load and 0.9s rest (hydraulic); 0.9 to 3s rest (pneumatic)	Haversine, 0.1s load, 0.9s rest period (base /subbase); 0.2s load, 0.8s (subgrade)	Haversine, 0.2s load and 0.8s rest period	Haversine, 0.5s load, 0.5s rest period	Haversine, 0.1s load, 0.9s rest period	3s vertical force wave with load of 1s and rise and fall of 0.3s
Test sequence	100 reps at 29 stress states; confining of 20 - 150 kPa and axial deviator stress of either 30 - 475 kPa or 20 - 300 kPa	100 reps at 15, stress states confining of 20.7-138 kPa and max axial deviator stress of 20.7 - 276 kPa	100 reps at 30 stress states (Type 1); 20 stress states (Type 2) and 16 stress states (Type 3); confining of 20.7 to 138 kPa and deviator of 20.7 to 993 kPa cyclic	100 reps at 14 stress states; confining of 20 - 200 kPa and axial deviator stress of 0.08 to 0.81 times the failure stress	100 reps at 15 stress states; confining of 20 - 200 (coarse) 140 (fine) kPa and axial deviator stress of 0.1 - 0.9 times the failure stress	100 reps at 8 stress states; confining of 34.5 - 207 kPa and axial deviator stress of 69 - 414 kPa	At least 50 reps at 66 stress states; confining of 20 -150 kPa and axial deviator stress of 100 - 600 kPa
Results	Average of last 10 cycles use to computed M_R	Average of last 5 cycles use to computed M_R	Average of last 5 cycles use to computed M_R	Average of all load cycles use to compute M_R	Average of all load cycles use to compute M_R	Average of last 50 cycles use to computed M_R	Average of last 6 cycles use to computed M_R

Implementation of resilient modulus test procedure

The purpose of laboratory testing is to subject a sample to loads representative of field conditions. The equipment selected for test procedures must have capabilities of applying the necessary loading conditions on specimens and should have loading systems that are capable of measuring the magnitude of the applied loads as well as recording accurate responses of the materials tested. The testing devices must also be simple enough for road agencies and researchers to use routinely and quickly to acquire the necessary material parameters with acceptable confidence.

The implementation of resilient modulus test procedures by road agencies and researchers needs adequate capital and human resources. The laboratories should be well equipped and have the capacity to conduct reproducible and appropriate resilient modulus testing that closely simulates field loading conditions. The testing system should consist of a loading frame, triaxial cell, control and data acquisition system as well as an integrated software package and personal computer that allow automatic control of the applied stresses on test specimen. Other integral accessories such as load cells and linear variable displacement transducers (LVDTs), for measuring load and specimen deformation should also be included in the budget for resilient modulus testing. The loading frame for resilient modulus testing should limit external deflections and vibrations, which could influence the accuracy of measurements of the geomaterial properties.

A successful and comprehensive implementation of resilient modulus testing would need a total commitment to equipment and the accompanying substantial training investments. A comprehensive training program is needed for the technicians on both the testing program and use of the testing equipment for effective resilient modulus testing.

SUMMARY AND CONCLUSIONS

Improved or new test procedures are needed to better estimate resilient properties of pavement geomaterials. A broader impact of appropriate resilient modulus test procedures will be establishing an accurate database to meet the requirements of implementation of various mechanistic-empirical pavement design guides including NCHRP 1-37A design guide and SAPDM. An adequate characterization of resilient modulus is necessary in the pavement layer analysis, since it is a very important variable in predicting the resilient stress, strains, and deflections in a flexible pavement. Resilient modulus models for pavement geomaterials can properly be modeled based on sound resilient modulus data obtained from good laboratory practices.

The state of the practice of resilient modulus testing in southern Africa can be advanced through the adoption of harmonized repeated load triaxial testing procedures. Successful resilient modulus testing is highly dependent on factors such as implementation of intensive training programs for technicians, use of simple but correct equipment, and the organization of quality control and calibration measures such that sample preparation, verification of the testing equipment, reliable software and evaluation of the proficiency of the technicians for laboratory or field testing is of the highest quality. Generally, laboratory participation in a round robin or similar testing exercise is recommended to ensure consistency in resilient modulus test results. Also, there is a need to organize training programs or workshops for road agencies and laboratories to demonstrate resilient modulus testing for pavement geomaterials. With the ongoing developments of the mechanistic design process in South Africa, a standard resilient modulus test protocol is urgently needed for all local testing.

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