Testing of Unbound Aggregates and Subgrade Soils at the University of Illinois

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1. Introduction

Over the past three decades, there has been an increasing tendency toward designing flexible pavements using mechanistic-empirical (M-E) principles. In mechanistic based design, pavement response variables such as the deformations, stresses and strains due to wheel loads are calculated. The development of pavement distresses is then predicted empirically using transfer functions relating response(s) to distress(es). In flexible pavements, granular base and subbase layers are essential components. Their functions are to reduce the traffic related stresses in the pavement layers and minimize rutting within the granular layer(s) and subgrade soil. Granular layers are of particular significance in low to medium ESAL (equivalent single axle load) applications where the asphalt concrete (AC) surface course is thin (less than 4 to 6 inches) or only a surface treatment is utilized.

Starting with the 1986 AASHTO Guide, resilient modulus is used to characterize subgrade soils and assign "layer coefficients" to granular base and subbase layers. With the routine use of resilient modulus as a primary input into the upcoming 2002 Design Guide, many state highway agencies are soon to face challenges in establishing the appropriate "resilient modulus" inputs for granular materials and subgrade soils. This document is intended to provide information on the different resilient modulus test procedures currently used in modulus testing of soils and granular materials at the University of Illinois Advanced Transportation Research and Engineering Laboratory in Rantoul, Illinois.

2. Modulus Testing

a. Background

Repeated load triaxial testing has received major emphasis recently as a means to evaluate in the laboratory modulus–deformation characteristics of granular materials and subgrade soils. Both resilient modulus and permanent deformation accumulation can be quantified based on the appropriate repeated load testing data. Resilient behavior is typically realized after the specimen is shaken down during the conditioning stage, which generates the permanent deformation data for the soil and aggregate sample tested. In a well designed pavement system the permanent strain accumulated per load cycle is very small compared to the total strain.

Test procedures have been proposed for repeated load testing by several agencies and groups (TRB Special Report 162, 1975). In 1982, AASHTO adopted a testing procedure (T274-82) for, "Resilient Modulus of Subgrade Soils." In the fall of 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 T 292-91; "Resilient Modulus Testing of Subgrade Soils and Untreated Base/Subbase Materials") and the method was first included in the 1991 AASHTO Interim Test Methods (Part E) publication.

A SHRP Testing Protocol (P46 -RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE MATERIALS AND SUBGRADE SOILS) has been developed. SHRP P46 was utilized in testing the various granular material and subgrade soil samples collected in support of the SHRP (FHWA) LTPP (Long Term Pavement Performance) program. A "round robin" type evaluation was conducted with the SHRP P46 Protocol. The results are very helpful in a priori M-E design activities. SHRP P46 was first approved as an AASHTO Interim Method of Test (AASHTO T 294-92 I; "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46"), then carried the designation T294-94 in the 1996 AASHTO specifications, and finally now carries the designation T 307-99 (2002).

No doubt the recent work done by Dick Barksdale in the NCHRP 10-28 project and the SHRP LTPP studies ("LTPP Materials Characterization: Resilient Modulus of Unbound Materials - LTPP Protocol P46 Laboratory Startup and Quality Control Procedures," FHWA-RD-96-176) helped greatly in preparing the current SHRP TP P46 and the AASHTO T307-99 (2002) test protocols, which are proposed for routine use in the upcoming 2002 Design Guide. It is also apparent that resilient testing procedures for soils and granular materials are still undergoing development and refinement. A series educational videotapes have been prepared by the Federal Highway Administration on "Laboratory Resilient Modulus Testing: Startup and Quality Control Procedure" and on "Laboratory Resilient Modulus Testing: Sample Preparation and Test Procedure," which can be found on http://www.tfhrc.gov/pavement/ltpp/rmodulus.htm.

b. Concepts

Generally constant confining pressure type triaxial test conditions are used for testing soils and granular materials. Cohesive soils can also be tested under unconfined compression conditions. The SHRP P46 and the AASHTO T 307-99 stipulate triaxial testing for both granular materials and cohesive soils.

Pneumatic and electro-hydraulic repeated loading equipment have been successfully utilized. The equipment must be capable of producing load pulse duration of approximately 25 to 150 msec. The load pulse is generally repeated 15 to 30 times a minute. In the P46 procedure, the load duration is 100 msec and the cycle duration is 1 sec (60 repetitions per minute). In the T 307 procedure, the load duration is between 100 msec and 1 sec and the cycle duration is from 1 to 3 sec (60 to 20 repetitions per minute). Specimen deformation over the entire length, or in some cases a portion, of the specimen is typically measured with either "externally" or "internally" mounted LVDTs. Total, resilient (rebound), and plastic (permanent) deformations are typically recorded. Using resilient strain and applied stress, the resilient modulus can be calculated as follows:

$$E_R \text{ (or } M_R) = \sigma_d / \varepsilon_r$$

where E_R (or M_R) = resilient modulus; σ_d = repeated deviator stress; and

ε_r = recoverable axial strain.

3. Test Procedures

Figure 1 shows the principal stresses applied in a triaxial test apparatus. The typical stress states applied on the specimen are according to the constant confining pressure (CCP) conditions with cell pressure not pulsed in the triaxial chamber. For nonstandard testing that involves stress path testing to simulate moving wheel loads, variable confining pressure (VCP) conditions must be considered to repeatedly pulse the confining pressure at the same time with the pulsed deviator stress.

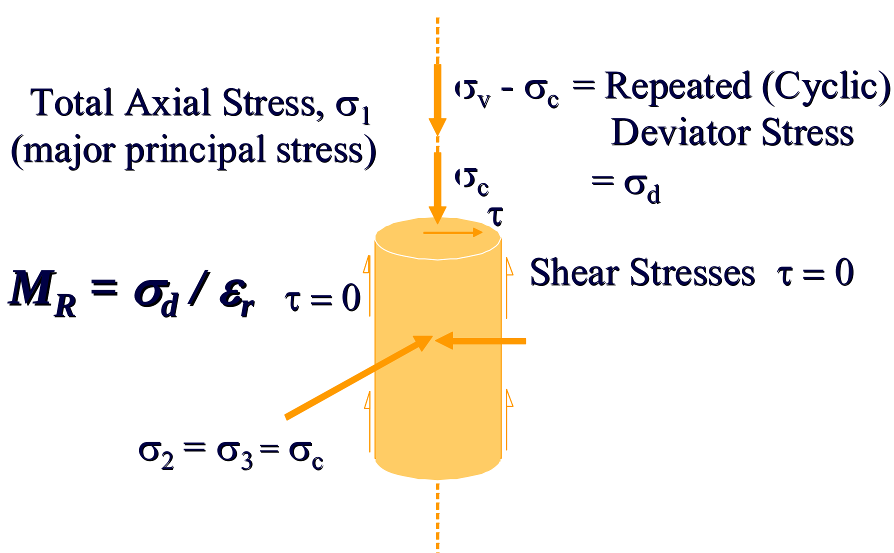

Figure 1. Stress States in A Triaxial Test Apparatus

a. Base/Subbase Materials

▪ Specimen Preparation

A cylindrical specimen, 6-in. or 152-mm in diameter by 12-in. or 254-mm high is prepared to fit in the confinement chamber for the repeated load triaxial testing, using a split aluminum compaction mold (see Figure 2). A nitrile membrane, 0.6-mm thick, is attached to the bottom platen with an o-ring and the platen is placed in the split mold. The aggregate mixed with required amount of water is placed in the mold in three lifts and each lift is rodded 25 times using a standard rod for concrete testing.

Figure 2. Split Mold Assemblies Used In Sample Preparation and Compaction

A pneumatic vibratory compactor is used. Specimen density is calculated by measuring the weight of material, and the compacted thickness of each lift, referenced to the top of the mold. Each lift is then scarified up to a depth of approximately 12-mm, and the next lift then placed, and compacted. After compaction, the final height and density of specimen are noted. The achieved densities are typically higher than the maximum

Proctor densities due to the increased compaction effort exerted by the vibratory compactor.

- ## AASHTO Test Procedure

When compaction is completed, a second membrane is placed on the specimen to provide vacuum and prevent air leakage in and out of the specimen. The load cell is then placed on top of the specimen with the specimen sitting in the upright position in the confining chamber of the triaxial setup. A confining pressure of 103.4 kPa is supplied through the chamber pressure supply line for initial conditioning. Generally, before connecting the chamber pressure, proper sealing of the plexiglas chamber wall should be accurately maintained with grease or liquid rubber latex. Figure 3 shows the triaxial test apparatus and the data acquisition system. Two external LVDTs are mounted on the triaxial chamber for measuring vertical displacements and averaging them for estimating the specimen vertical deformation during testing.

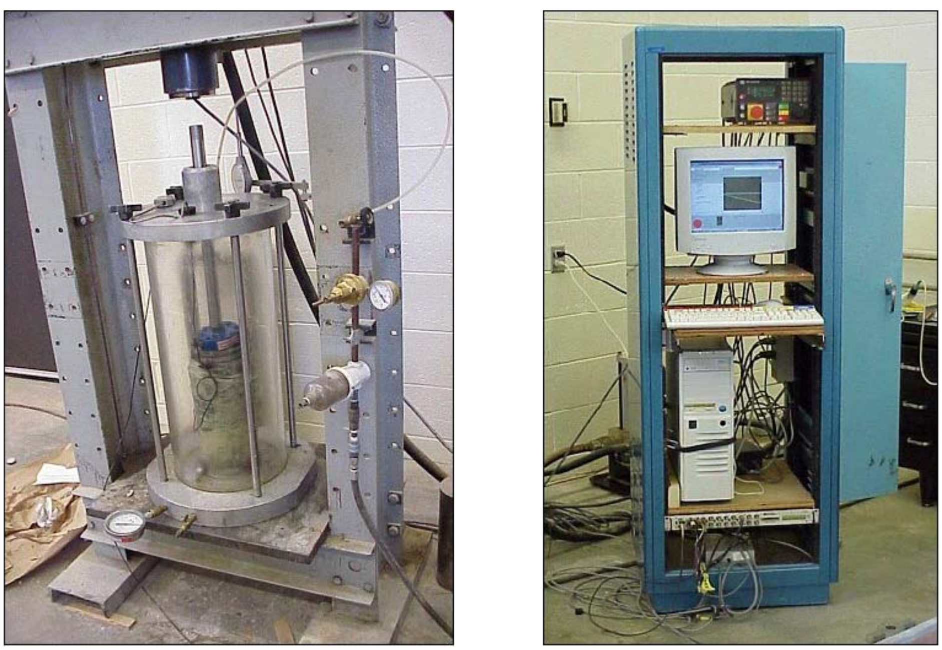

Figure 3. Triaxial Test Apparatus and Data Acquisition System

Conditioning Stage – Set the confining pressure to 103.4 kPa and apply a minimum of 500 repetitions of a load equivalent to a maximum axial stress of 103.4 kPa (stress ratio = 2), using a haversine-shaped load pulse. If the sample is still decreasing in height at the end of the conditioning period, stress cycling shall be continued up to 1000 repetitions prior to testing. If the total vertical permanent strain reaches 5% during conditioning, the conditioning process should be terminated and sample compaction shall be reviewed.

Resilient Modulus Testing – Apply 100 repetitions of the corresponding cyclic stress using a Haversine-shaped load pulse. Record the average recovered deformations for each LVDT separately for the last five cycles on the report form. Continue the test for the remaining load sequences shown in Table 1, recording the vertical recovered deformation.

Table 1. AASHTO Testing Sequences for Base/Subbase Materials

Sequence No.	Confining Pressure (kPa)	Max Axial Stress (kPa)	No. of Load Applications
0	103.4	103.4	500 ~ 1000
1	20.7	20.7	100
2	20.7	41.4	100
3	20.7	62.1	100
4	34.5	34.5	100
5	34.5	68.9	100
6	34.5	137.9	100
7	68.9	206.8	100
8	68.9	68.9	100
9	68.9	103.4	100
10	103.4	206.8	100
11	103.4	103.4	100
12	103.4	206.8	100
13	137.9	103.4	100
14	137.9	137.9	100
15	137.9	275.8	100

▪ University of Illinois Test Procedure

Cylindrical specimen, 6-in. or 152-mm in diameter by 12-in. or 254-mm high, is subjected to various triaxial stress states that are less than the failure stress states. A haversine load waveform is applied with load pulse duration of 0.1 seconds (10 Hz) and a rest period of 0.9 seconds.

Conditioning – The specimen is initially conditioned for 1000 load repetitions at a deviator stress of 310.5 kPa and a confining pressure of 103.4 kPa.

Resilient Modulus Testing – After conditioning, modulus testing is conducted at various stress states listed in Table 2. The deviator stresses range from 68.9 kPa to 414 kPa and confining pressures range from 34.5 kPa to 207 kPa.

Table 2 University of Illinois Testing Sequences for Base/Subbase Materials

Sequence No.	Confining Pressure (kPa)	Max Axial Stress (kPa)	No. of Load Applications
0	103.4	310.5	500 ~ 1000
1	34.5	69	100
2	34.5	103.4	100
3	69	138	100
4	69	207	100
5	103.4	207	100
6	103.4	310.5	100
7	207	310.5	100
8	207	414	100

One hundred load repetitions are applied at each sequence (stress state). If the difference between the modulus values at 50th and 100th load repetition is more than 5 percent, the sequence should be repeated. The main difference between the AASHTO procedure and the U of IL procedure is that a higher and more reasonable stress ratio of 4 [(310.5 +103.4)/103.4 = 4] is applied during conditioning than a ratio of 2 [(103.4+103.4)/103.4 = 2] of AASHTO procedure, which helps better the shake down of materials and represents more realistic under the wheel field stress conditions.

UI – FastCell (Anisotropic and Stress Path) Testing

The most recent addition to our laboratory equipment at University of Illinois is a new cyclic/repeated load triaxial testing device referred to as University of Illinois FastCell (UI-FastCell). This is a new innovative testing device having provisions for switching and pulsing of the major principal stresses both in the vertical and radial directions by the use of the two independently controlled stress channels. The UI-FastCell was custom-designed and manufactured mainly for determining in the laboratory the anisotropic and dynamic properties of unbound aggregates and subgrade soils. Since it is not possible to reorient the granular samples in the triaxial cell, applying and switching of the various stress states on the same specimen facilitates determining the inherent and load-induced anisotropy. The device is also suitable for simulating field stress conditions in the laboratory and for studying the effects of principle stress rotation due to moving wheel loads that involve a change in total shear stress direction.

The UI-FastCell uses a fluid/air interface to minimize compressibility effects when conducting tests in which the horizontal stress on a specimen must be cycled. This is useful for investigating anisotropic effects and the response to loading in which a 90° rotation of planes of principal stress is important. The cell also provides a capability for on-specimen displacement measurements, which eliminate problems associated with compliance of the machine used to load the specimen. When on-specimen vertical displacements are used as well, end effects are eliminated.

Figure 4 shows a picture of the UI-FastCell with the confinement cell lowered down on the specimen for the testing position. An air actuator applies the axial pressure and the confining pressures are cycled through a hydraulic fluid within the rubber membrane. The driving cylinders on the back of the confining cell (not shown here) include an air-fluid interface which provides "fast" application and switching of the dynamic loading in the confinement "cell." Figure 4 also presents a drawing of the cylindrical specimen, 150-mm in diameter by 150-mm high (approximately 6-in. in diameter by 6-in. high), under the independently applied vertical and radial stresses and the instrumentation consisting of LVDTs measuring axial and radial specimen deformations. Some of the unique capabilities are as follows:

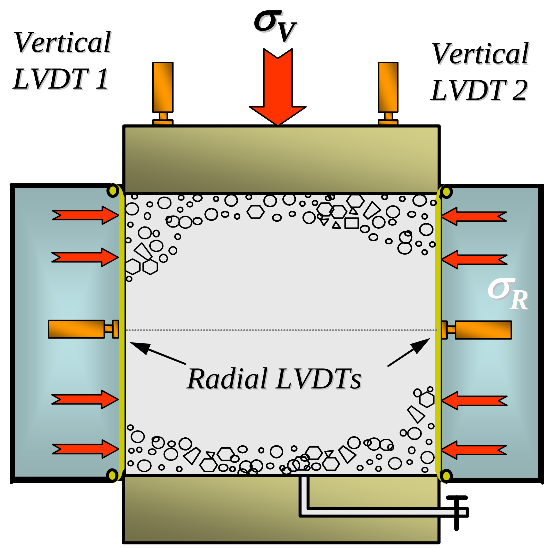

Figure 4. University of Illinois – FastCell (UI-FastCell)

(a) measurement of on sample vertical and radial displacements, and axial force and displacement external to cell;

(b) measurement of pore pressures in undrained and/or cyclic loading by the use of a transducer, which can be installed in the bottom plate;

(c) a bladder type horizontal confinement chamber with a built-in membrane which is inflated to apply variable confining pressures during vertical cyclic loading;

(d) ability to independently cycle either vertical or radial loading/confining pressures in phase or out of phase, in compression or extension type loading; and

(e) ability to reverse principal loading direction on the same specimen with applied radial pulse stresses exceeding the vertical ones.

The new UI-FastCell is a fundamental research tool as compared to the standard cyclic triaxial testing equipment. Using the UI-FastCell, the following important laboratory testing considerations can be conveniently addressed: (i) the aggregate specimen is anisotropically consolidated (K_0 condition in the field); (ii) various stress paths experienced under a rolling wheel load is adequately applied; (iii) anisotropic aggregate resilient moduli are conveniently obtained by individually pulsing either vertical or horizontal loading at a time; and (iv) the different orientations of the principal stresses are achieved by independently applying vertical and radial cyclic stresses – major principal stress direction is not limited to only 0 or 90 degrees with the horizontal.

- ## Anisotropic Testing

A new triaxial test procedure has been developed to determine cross-anisotropic material properties using UI-FastCell. Consideration has been given to adequately represent the extreme stress conditions that may exist in the base layer of a flexible pavement structure under a moving wheel load. Then considering these extreme compression and extension loading conditions, deviator stresses are pulsed either in the vertical or horizontal directions. If the tested specimen is made up of a material that is truly isotropic in behavior, the moduli determined from the two-extreme loading conditions should be similar in magnitude.

Different magnitude stress pulses are typically applied on granular layers under moving wheel loads. The wheel load not only acts on the pavement element directly underneath it, but also on other elements at some horizontal distance away from the centerline of wheel loading. The types and durations of the load pulses applied on a triaxial specimen in the laboratory should simulate the load pulses applied on a granular base layer in the field. The wheel load pulse was found to be close to a Haversine shape near the pavement surface and the pulse duration increased with depth.

Resilient Modulus Testing – The cylindrical specimens are compacted by the pneumatic vibratory compactor during the sample preparation stage. This compaction effort on the specimens is assumed to represent the initial conditions of the granular layers in the field just after pavement construction. Therefore, the specimens are not conditioned before the actual testing sequence. Following the standard AASHTO test procedure, the specimens are subjected to 15 triaxial stress states that are typically less than the failure stress states (AASHTO T307-99). A haversine load waveform is applied with a load pulse duration of 0.1-seconds, and a rest period of 0.9- seconds. After the 2-kPa (0.3-psi) hydrostatic seating stress is applied on the specimen, resilient modulus testing is conducted as noted in Table 1 in both the vertical (direction 1) and radial (direction 3) pulsing directions with the applied (pulsed) deviator stresses σ_{nd} (n = 1 or 3). The order of pulsing in each direction determined the test procedure followed for one specimen, i.e., either test procedure A or B, as shown in Table 3. Each sample is tested following the test procedures A and B at a total of 30 stress states to study the directional dependency of granular material stiffness with previous loading history.

Table 3. Anisotropic Resilient Modulus Test Procedures and Stress States

				Hydrostatic Stress, $\sigma_{hydrostatic}$ (kPa/psi)														
				21/3			35/5			69/10			103/15			138/20		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Test Procedure A	1	Vertical Pulsing	σ_{1d} (kPa/psi)	21/3	42/6	62/9	35/5	69/10	103/15	69/10	138/20	207/30	69/10	103/15	207/30	103/15	138/20	276/40
			σ_{3d} (kPa/psi)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	2	Radial Pulsing	σ_{1d} (kPa/psi)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
			σ_{3d} (kPa/psi)	21/3	42/6	62/9	35/5	69/10	103/15	69/10	138/20	207/30	69/10	103/15	207/30	103/15	138/20	276/40
Test Procedure B	1	Radial Pulsing	σ_{1d} (kPa/psi)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
			σ_{3d} (kPa/psi)	21/3	42/6	62/9	35/5	69/10	103/15	69/10	138/20	207/30	69/10	103/15	207/30	103/15	138/20	276/40
	2	Vertical Pulsing	σ_{1d} (kPa/psi)	21/3	42/6	62/9	35/5	69/10	103/15	69/10	138/20	207/30	69/10	103/15	207/30	103/15	138/20	276/40
			σ_{3d} (kPa/psi)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

The pulsed deviator stresses, σ_{nd}, range from 21 to 276 kPa (3 to 40 psi) in both axial and radial directions whereas the hydrostatic pressures range from 21 to 138 kPa (3 to 20 psi). The applied stress ratios, total stress in any direction to hydrostatic stress [(σ_{nd} + $\sigma_{hydrostatic}$)/ $\sigma_{hydrostatic}$], range from 1.66 to 4. One hundred load repetitions are applied at each stress state. Typically, the same vertical and radial recoverable deformations have to be measured between the 50th and 100th load repetitions.

- ### Stress Path Testing

To better characterize aggregate behavior it is important to properly simulate in the laboratory the actual loading conditions. The pavement in the field is usually loaded by moving wheel loads, which at any time impose varying magnitudes of normal and shear stresses in the aggregate layer as reflected by the rotation of the principal stresses. This type of loading can not be ideally simulated in the laboratory by the constant confining pressure (CCP) type repeated load triaxial tests, which have been commonly used in the U.S. since late 1960s and recognized as the standard procedure (AASHTO T307-99). It is only possible to apply one constant stress path ($m = \Delta q/\Delta p = 3$; see Figure 5) in the CCP tests. The variable confining pressure (VCP) type repeated load triaxial tests, on the other hand, offer the capability to apply a wide combination of stress paths by pulsing both cell pressure and deviatoric stress (see Figure 5). Such stress path loading tests better simulate actual field conditions since in the pavement structure the confining stresses acting on the material are cyclic in nature.

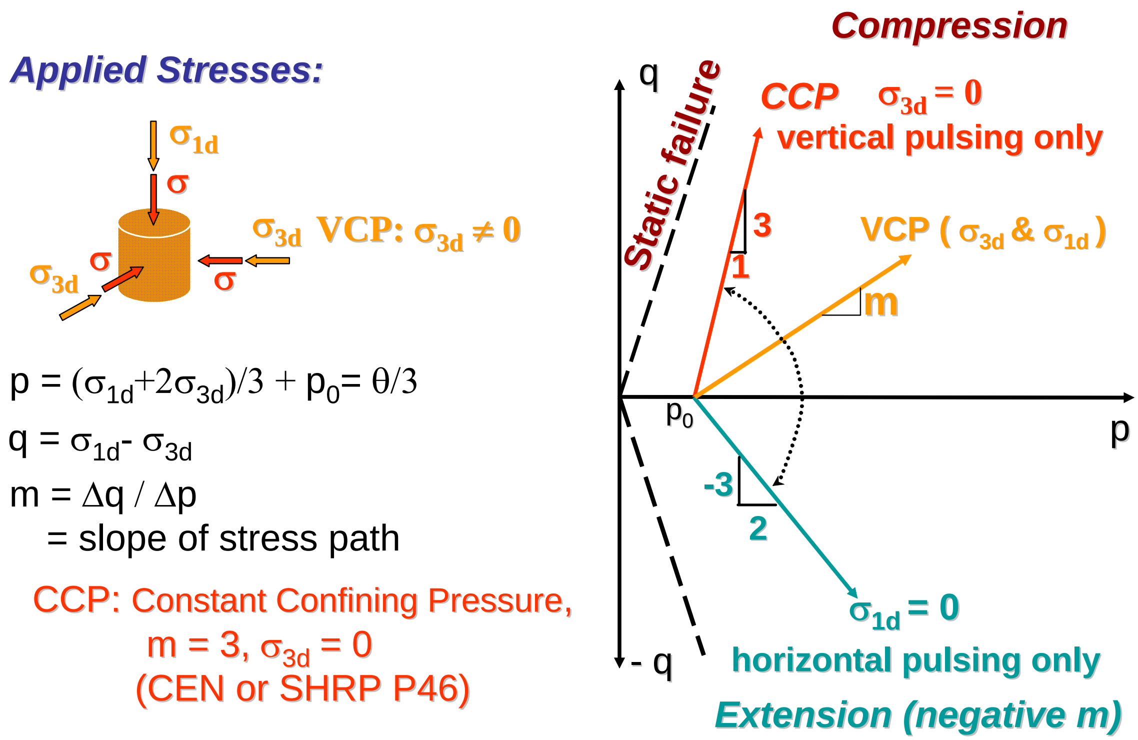

Figure 5. Stress Paths That Can Be Studied by UI-FastCell

Stress path test can be performed by switching stress states from Constant Confining Pressure (CCP) to Variable Confining Pressure (VCP), depending on the stress path slope that is subject to be studied. The VCP tests require pulsing of the stresses in both vertical and horizontal directions. For example, in order to test a specimen with a stress path slope of 1.5 (3/2), horizontal dynamic stresses should be one forth of the vertical dynamic stresses in magnitude.

b. Subgrade Soils

Both laboratory compacted and undisturbed subgrade soil samples can be used to conduct triaxial modulus test. Compacted sample preparation is described here.

- ## Specimen Preparation

University of Illinois

If the sample is damp when received from the field, it is air dried and passed through a No. 4 sieve to break up aggregations. This procedure facilitates the distribution of water through the soil during mixing. The prepared soils are mixed with the required amount of water to bring the moisture content to the target value. Soil samples (typically 2 in. diameter by 4 in. high) are mechanically compacted by a full-face impact hammer (such as a Proctor hammer) in three lifts to the target density. To ensure bonding between layers, the top of the compacted layer is scarified before the next layer is compacted. The soil sample is then placed in the loading frame between end caps. The loading shaft is brought to contact the upper cap. Once the loading shaft is seated, the two external axial displacement transducers are set up, and the soil sample is ready for testing.

AASHTO

Use 71-mm or 86-mm diameter specimens for tests in undisturbed cohesive specimens of Type II materials. If the maximum particle size exceeds 25 percent of the largest mold diameter available, these particles need to be scalped. Length for all specimens shall be at least 2 times the diameter. The mass of the moisture content specimen shall be at least 200g for samples with a maximum particle size smaller than the 4.75 mm (No. 4) sieve and at least 500 g for samples with a maximum particle size greater than the 4.75 mm (No. 4) sieve. The following process is same as that for base/subbase materials. Please refer to AASHTO T307-99 Appendix B.

- ## Procedure

AASHTO

The procedure for subgrade soils shall be similar to that for base/subbase (Type I) materials except the stress states (see AASHTO T307-99 page 10).

Table 4. AASHTO Testing Sequences for Subgrade Materials

Sequence No.	Confining Pressure (kPa)	Max Axial Stress (kPa)	No. of Load Applications
0	41.4	27.6	500 ~ 1000
1	41.4	13.8	100
2	41.4	27.6	100
3	41.4	41.4	100
4	41.4	55.2	100
5	41.4	68.9	100
6	27.6	13.8	100
7	27.6	27.6	100
8	27.6	41.4	100
9	27.6	55.2	100
10	27.6	68.9	100
11	13.8	13.8	100
12	13.8	24.8	100
13	13.8	37.3	100
14	13.8	49.7	100
15	13.8	62.0	100

University of Illinois

A UTM-5P pneumatic testing system is used to apply repeated and static loads to soil specimens. Soil specimen response is recorded from attached load and axial displacement transducers, and stored in binary files in a personal computer. Resilient modulus tests are conducted to establish the variation of resilient modulus with the applied deviator stress. A haversine load pulse with load duration of 0.1 seconds and cycle duration of 1 second is used and no confining pressure is added. The unconfined conditions are applied only for the sake of the weakest soil and the worst case loading conditions simulated in the laboratory. The soil specimen is first conditioned by applying 200 load pulses at a stress level of 6 psi. Following conditioning, the specimen is subjected to stress levels of 2, 4, 6, 8, 10, 12, 14, and 16 psi. Each stress level is applied 100 times and resilient modulus calculated based on the last 50 cycles. Figure 5 shows the resilient modulus equipment setup for testing the 2 in. in diameter by 4 in. high soil specimens.

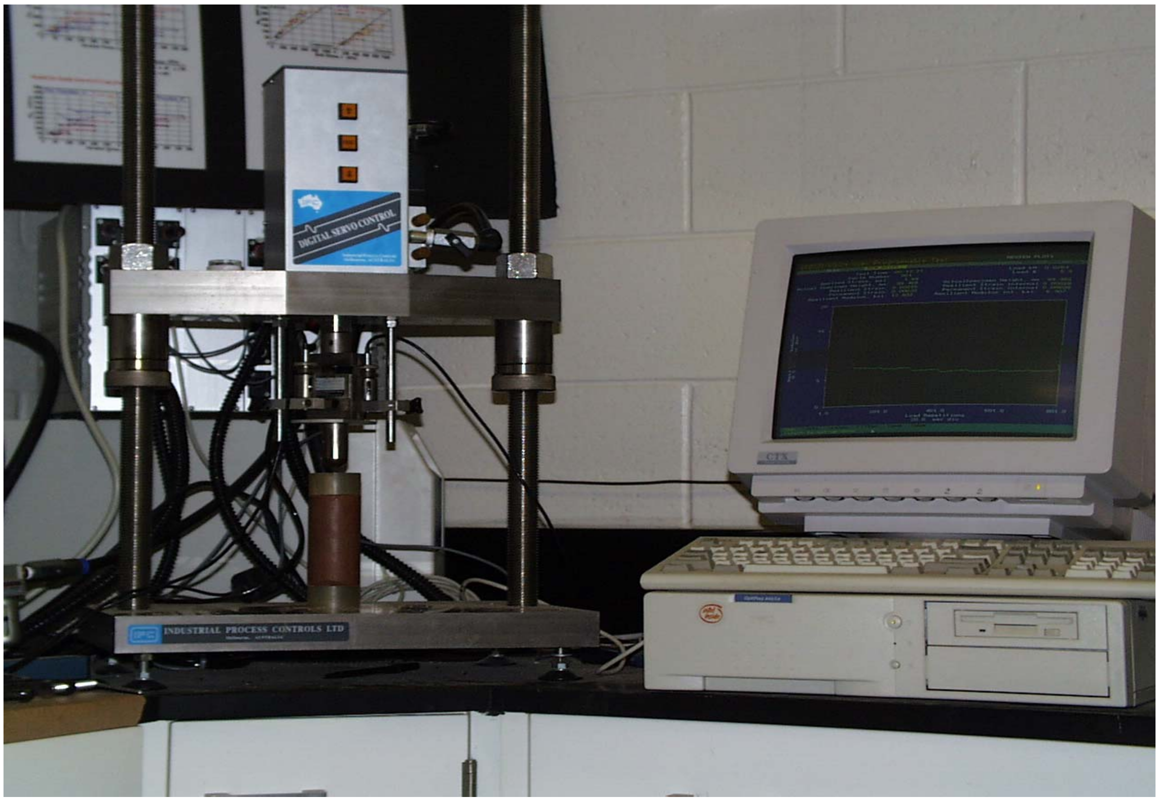

Figure 5. Repeated Load Triaxial Testing of Subgrade Soils at the University of Illinois

4. References

AASHTO T307-99, "Determining the Resilient Modulus of Soils and Aggregate Materials", Part 2B, 22nd Edition, AASHTO, 2002.

TRB-SP-162, "Test Procedures for Characterizing Dynamic Stress-Strain Properties of Pavement Materials," Special Report 162, Transportation Research Board, 1975.