A COMPREHENSIVE SYSTEM FOR CHARACTERISING GRANULAR MATERIALS: PROVIDING MATERIAL INPUT FOR PAVEMENT DESIGN

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ABSTRACT

The new 2002 AASHTO Guide for Pavement Design advocates the use of the resilient modulus parameter for the characterization of granular materials used as base and sub-base layers in flexible pavements. The multitude of factors that affects the resilient behaviour of granular material makes the determination of the resilient modulus at different loading and physical conditions a critical factor for the pavement design process. This calibration task requires the availability of a robust system capable of producing the needed results in a timely and effective fashion. The current paper reports on recent research activities at the National Research Council, which aim at providing tools that can be utilised to carry out the calibration process. The objective of the research program is to establish database of resilient moduli for the different types of granular materials used in the Canadian Provinces. The research program combines both laboratory testing and numerical techniques to develop the required database. The paper presents an overview of the characterization system together with typical results obtained.

Application of the new system to quantify the effect of compaction density, a major construction factor affecting the behaviour of granular material, on the resilient modulus is illustrated. Preliminary results obtained from repeated load tests and discrete element modeling (DEM) confirm the adequacy of the developed tools to produce the sought database.

INTRODUCTION

Characterization of pavement materials is a key requirement for the pavement design process. The characterization task involves obtaining material properties that identify the material response to external stimuli of traffic loading and environmental conditions. In its 2002 design guide, the American Association of State Highway and Transportation Officials (AASHTO) advocates the use of the resilient modulus parameter for describing granular material behaviour. The resilient modulus, M_r, determined from repeated triaxial tests, is defined as the ratio of the applied deviator stress, (s_d) to the recoverable resilient strain (e_r):

$$M_r = \frac{s_d}{e_r} \quad \text{[1]}$$

Several methods, such as laboratory testing, non-destructive pavement evaluation techniques and empirical methods, were proposed to obtain this property. Although only laboratory techniques provide a means for directly measuring the M_r parameter, the process usually involves elaborate and extensive testing at various stress levels and physical conditions to completely map the range of the M_r parameter for any material under consideration. To be able to adopt the 2002 design guide for use in Canada, calibration of the Guide material models to reflect Canadian conditions need to be carried out. The fact that the resilient modulus is influenced by many factors such as the state of stress, density and moisture content, and material type makes the calibration activity even more critical. This paper reports on current research activities at the National Research Council, which aim at providing tools that can be utilised to carry out the calibration process. The objective of the research program is to establish database of resilient moduli for the different types of granular materials used in the Canadian Provinces. The research program combines both laboratory testing and numerical tools to develop the required database. The following sections present a brief description of both investigative tools with some typical results.

LABORATORY CHARACTERIZATION SYSTEM

This section describes the NRC Resilient Modulus Test system and the protocols followed to prepare test specimens. The section also illustrates how the acquired test data is analyzed.

Resilient modulus testing

The resilient modulus is a mechanistic parameter used to describe the material response to applied load. Resilient modulus testing is usually carried out using a triaxial cell set-up. The sample is placed inside the triaxial chamber and is then subjected to a repeated axial deviator stress pulse of a fixed magnitude, duration and frequency simulating the action of a commercial vehicle. During application of the deviator stress, the specimen is also subjected to an all-round static pressure simulating the confinement condition in the field. The parameters that are measured during the test include the total axial deformation, the deviator stress and the confining pressure. Segregation of the total axial strain into its resilient (recoverable) and permanent components is required prior to the computation of the resilient modulus parameter. The resilient modulus is then calculated as the ratio of the peak cyclic deviator stress to the recoverable measured axial strain.

Figure 1 shows a photograph of the recently developed NRC resilient modulus test system (RMT System). This system consists of (A) a triaxial pressure chamber, used to house the test specimen and maintain the confining pressure; (B) an MTS 810 loading frame, used to apply the deviator load; (C) an assembly of axial and radial deformation measuring sensors, contained within the triaxial chamber; (D) a load cell placed on top of the test specimen for measuring the axial repetitive load; (E) a pressure manifold and regulator for applying the confining pressure; and (F) an MTS data acquisition system, to collect the load and deformation signals generated during the test. Complete description of the system can be found in NRC internal report (IRC/RMT System manual).

Sample preparation

Material to be tested is initially air dried and thoroughly mixed. A mechanical sample splitter is used, as per AASHTO designation T248 – 95, to reduce the sample to the desired weight needed for specimen preparation. The material is spread over a tray and oven dried at 110^0C, for 24 hours. Cylindrical specimens, 150 mm in diameter by 300 mm high, are then prepared for testing in the RMT System.

Sample preparation follows the procedure outlined in the NRC/RMT System manual. A rubber membrane is placed inside a 300mm-split compaction mould. The granular material, mixed with the required amount of water, is placed in the mould in eight lifts. Each lift is rodded several times using a standard rod and then compacted using a vibrator to produce a compacted lift thickness of 37.5mm. Special aluminum cylinders are manufactured and used during compaction to ensure that each compacted lift attains the target thickness. This procedure is followed to ensure uniform density within the test specimen.

Sample set-up and test procedure

The deviator load is controlled by an MTS TestStar-IIm digital controller (see Figure 1). This system is equipped with Multi-Purpose TestWare (MPT) software, which is capable of providing various test protocols. The MPT software also has a built-in module for data acquisition. Prior to starting the resilient modulus test, the system is warmed up using a sine wave pulse.

The prepared test specimen is placed inside the triaxial chamber. An assembly of two linear variable differential transducers (LVDT) is secured around the test specimen to monitoring axial deformation. Both LVDTs are mounted internally, inside the triaxial cell, onto the sample. A load cell used for measuring the deviator load is mounted internally on the top of the test specimen. The loading ram of the MTS frame is lowered to ensure that there is no eccentricity between the loading rod and the load cell. After this check is performed, the loading rod is raised again an adequate distance to enable the assembly of the remaining parts of the triaxial chamber. Lead wires from the load cell, pressure transducer and LVDTs are connected to the MTS data acquisition system. A confining pressure of a specified magnitude is applied to the test specimen and the system is checked for leakage.

Resilient modulus testing is carried out following a modified AASHTO procedure. The loading sequence adapted from AASHTO T 292 – 91 is shown in Table 1. The test protocol involves subjecting the sample, initially, to a conditioning deviator stress of 52kPa under a confining pressure of 138kPa. Conditioning is carried out for 500 loading cycles. Each cycle consisted of applying the repetitive stress for a period of 0.1 second, followed by a rest period of 0.9 second. This loading scheme is intended to simulate the action of a commercial vehicle moving at street speed. A typical stress pulse is shown in Figure 2. Upon completion of the conditioning stage, the remaining load sequence shown in Table 1 is applied. Fifty load repetitions are applied at each load level and the corresponding axial deformation is recorded. Figure 3 displays the average axial deformation pulse recorded by the two LVDTs for a typical loading cycle.

As shown in Figure 3, the total axial deformation recorded for each loading cycle can be divided into two parts: a resilient (or recoverable) deformation component, F1-G1, and a permanent deformation component, G1-H1. Using information from Figures 2 and 3, the resilient modulus for each loading cycle can be computed as illustrated below.

From Figure 2, the peak deviator stress can be computed as:

$$s_d = \frac{(B - A)}{a} \quad \text{.......} \quad [2]$$

where,

$B - A$ = axial deviator load, kN.
a = cross sectional area of test sample, m^2.

From Figure 3, the recoverable strain can be computed as:

$$e_r = \frac{(F1 - G1)}{H} \quad \text{.......} \quad [3]$$

where,

$F1 - G1$ = axial recoverable deformation, mm.
H = average sample height, mm.

Using the procedure described above, a Microsoft Excel macro was developed to automate the computation of the resilient modulus parameter for each loading cycle. The average M_r value of the last five cycles, for each loading sequence of Table 1, is obtained as the representative value under the prescribed test conditions.

NUMERICAL INVESTIGATIVE TOOL

The discrete element method

The discrete element method (DEM) is a special numerical technique for investigating the mechanical behaviour of granular materials. It has been gaining popularity during the last two decades mainly because it allows simulating the discontinuous and discrete paths of load transfer behaviour directly linked to the material microstructure. Moreover, it permits monitoring particle movement in terms of displacements and rotations through the simulation process. In fact, DEM treats materials as an assemblage of discrete, distinct, particles behaving independently while interacting with each other at contacts.

The flexibility of the DEM technique enables adoption of different loading configurations, particle size distributions, and physical properties of the particles. The technique provides a wealth of information that no other methods can offer which made it a very attractive and powerful tool for studying granular materials assemblies.

DEM was first applied by Cundall (1971) to investigate the behaviour of rock masses and then adapted by Cundall and strack (1978 and 1979) for studying the behaviour of granular materials. They analysed the response of soils by idealizing grains by 2-D circular elements (discs). As computer computational capabilities evolved, the method became very attractive and has been used in a variety of fields such as fluid mechanics and earthquake engineering and was applied to study many practical engineering problems (slope stability and wave propagation for example).

In the DEM program, each particle is defined by two sets of properties. The first set includes particle radius, mass and moment of inertia while the second set defines particle contact properties. Modeling contact involves a combination of spring-dashpot element in the normal direction and spring-dashpot-slider element in the tangential direction (see Figure 4). Tangential forces are bound by a maximum (Coulomb friction) as shown in equation 4:

$$F_s\,(\max) = \mu\, F_n \quad [4]$$

Where F_s and F_n are the tangential and normal forces, respectively, and μ is the coefficient of friction between the particles at contact.

The stiffnesses of the particles and their velocities at the time of collision determine the overlap between them. The change in overlap can be used along with the force-displacement law to determine interparticle forces. The contact forces can be used to determine the motion of particles by using Newton's second law of motion to first calculate accelerations and then by integration to determine velocities and displacements.

In the current study, the DEM technique is used to simulate the resilient modulus test.

Simulation of the resilient modulus test

Discrete element method simulation of the resilient modulus test involves two tasks: sample preparation and loading. Sample preparation involves two stages, compaction and confinement. During the compaction stage, particles are randomly generated (see Figure 5) and then compacted by moving lateral rigid boundaries inwards. Once the desired degree of compaction is achieved, the velocity of lateral boundaries are set to zero and iterations are continued until particle velocities converged to zero (equilibrium state).

During the confinement stage the compacted sample is subjected to a confining pressure, equals to that used in resilient modulus testing, by using the boundary particles of the sample (see Figure 6). The configuration of the flexible boundary (made of these boundary particles) is updated at regular intervals to include any internal particle moving between two external (boundary) particles. Lateral rigid boundaries used during compaction are moved outwards and they do not have any role in the confinement and loading stages.

During the loading stage, sample prepared through compaction and confinement, is subjected to a deviator repetitive stress similar to the one used in laboratory testing (see Figure 2).

Calculation of the resilient modulus follows the same procedure described earlier for laboratory-tested specimen.

APPLICATION: EFFECT OF COMPACTION

The above described system (laboratory/analytical) was utilised to examine the effect of compaction density on the resilient modulus of a typical granular material. Using the modified Proctor method, the density–moisture relationship for the selected material was obtained. Specimens representing two compaction densities of 89 and 92 % of maximum Proctor density were prepared. Repeated load tests on the two specimens were performed using a combination of 50kPa confining pressure and 70kPa deviator stress.

DEM simulations for the two test specimens were also carried out. The material physical properties used in these simulations are shown in Tables 2 and 3, respectively. Results obtained from repeated load tests and the DEM simulations are displayed in Table 4.

Examination of the results shown in Table 4 reveals the following findings:

- Both investigative techniques suggest an increase in the resilient modulus with increased compaction density. For the investigated range of density, 89% to 92%, the modulus increased by 55% and 31% using laboratory and DEM results, respectively.

- Results obtained from the DEM simulation are within 10% of those determined from laboratory tests. This finding substantiates the ability of the DEM technique to adequately model the resilient modulus test.

CONCLUSION

This paper describes a comprehensive system for characterizing granular material behaviour. The system combines both laboratory testing and numerical techniques to obtain the resilient characteristics of the material. Application of the system to examine the impact of compaction density on the resilient modulus of a typical granular material is illustrated.

The system described in this paper is presented here as a potential tool for generating resilient moduli database for base and subbase materials used in flexible pavements. The availability of such a system is anticipated to smooth the implementation of the AASHTO 2002 Design Guide in Canada by providing the vehicle that can be used to obtain the required material models.

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Figure 1: IRC resilient modulus test system

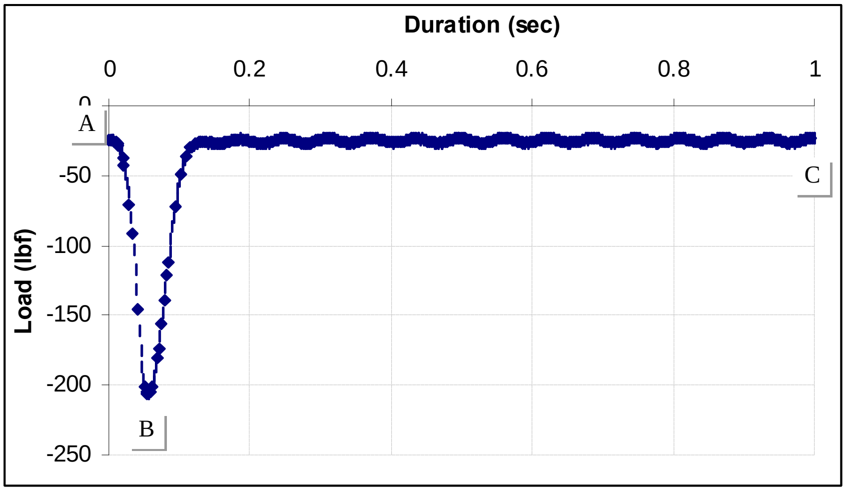

Figure 2: Typical deviator stress pulse

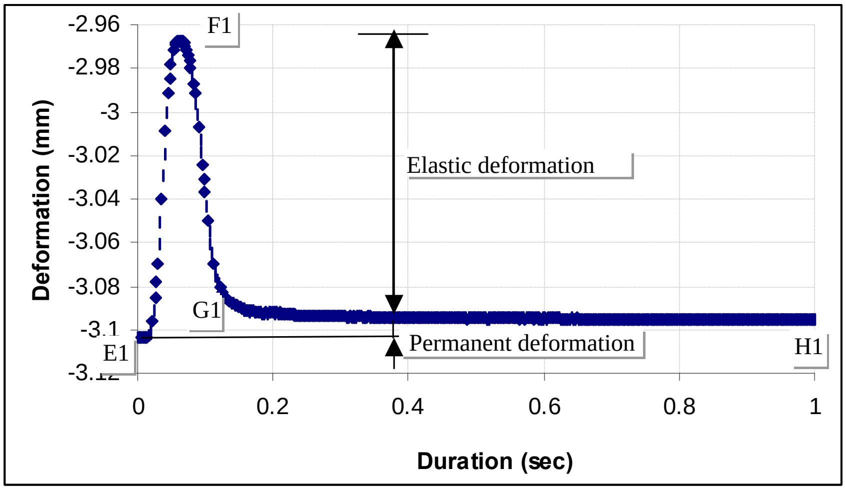

Figure 3: Axial deformation pulse

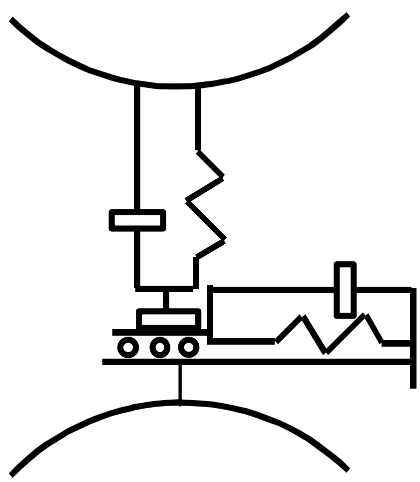

Figure 4: Modeling particle-to-particle contact

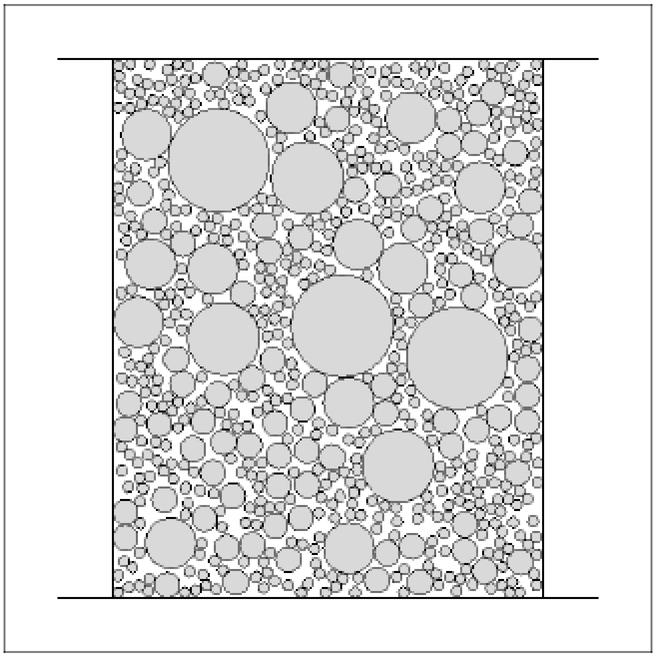

Figure 5: Typical randomly generated sample

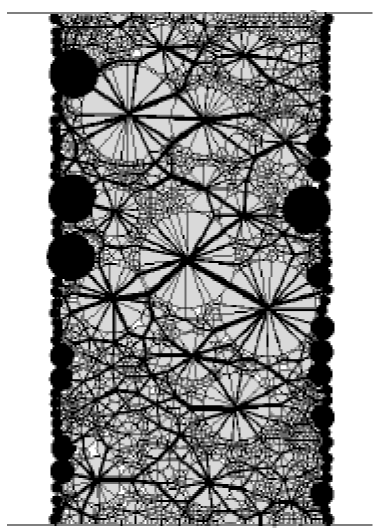

Figure 6: Interparticle forces after confinement

Table 1: Resilient modulus testing sequence implemented in laboratory investigation

Deviator force (N)	Contact force (N)	Cyclic force (N)	σ_d (kPa)	σ_3 (kPa)	Load sequence	Number of repetitions
919	92	827	52	138	SPC-CON	500
848	85	763	48	35	LS1	50
919	92	827	52	35	LS2	50
1219	122	1097	69	35	LS3	50
884	88	796	50	69	LS4N	50
1219	122	1097	69	69	LS4	50
1467	147	1320	83	69	LS5	50
1820	182	1638	103	69	LS6	50
1219	122	1097	69	103	LS7	50
1467	147	1320	83	103	LS8	50
1820	182	1638	103	103	LS9	50
1467	147	1320	83	138	LS10	50
1820	182	1638	103	138	LS11	50
2440	244	2196	138	138	LS12	50
2757	276	2481	156	138	LS13	50

Table 2: Particle size distributions used in DEM simulation

Particle Size(mm)	Percentage (%)
	Gradation A
25.4	
19.0	3.0
13.2	8.0
9.5	15.0
4.75	74.0

Table 3: Particle properties used in DEM simulation

Normal Stiffness (kPa)	10^5
Shear Stiffness (kPa)	10^5
Density (g/cm^3)	2.63
Friction	0.5

Table 4: Resilient moduli results

Density (%)	Laboratory resilient moduli (MPa)	Numerical resilient moduli (MPa)	Discrepancy between lab and model (%)
89	242	265	9.5
92	376	347	7.7