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Unbound material characterisation with Nottingham asphalt tester

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Unbound material characterisation with Nottingham asphalt tester

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The resilient modulus (M_R) of unbound materials is a required input in most of the mechanistic-based pavement analysis and design process and has a significant effect on the projected pavement performance in the mechanistic–empirical pavement design guide programme or AASHTOWare DARwin. The Iowa Department of Transportation (DOT) recently acquired a servo-hydraulic dynamic loading materials test system known as the Nottingham asphalt tester (NAT). The Iowa DOT NAT is a hybrid servo-hydraulic machine designed for testing not only hot-mix asphalt performance properties but also unbound materials' MR (although this has not been verified so far). The primary objectives of this research are to update and verify the capacity of the Iowa DOT hybrid NAT for testing unbound material's MR through a detailed laboratory testing programme and regression analyses using non-linear stress-dependent models.

1. Background and introduction

After the release of the mechanistic–empirical pavement design guide (MEPDG) (NCHRP, 2004a) in the USA, several states have developed strategic and phased plans with the intention of implementing the MEPDG for routine analysis and design. An important implementation task is to verify whether the agency is prepared in terms of material characterisation facilities to provide the design inputs required to run the MEPDG software. This is considered an important step towards achieving long-lived, sustainable pavements that perform well (Gopalakrishnan, 2011).

The resilient modulus (M_R) properties of unbound materials are required by the MEPDG (NCHRP, 2004a) as the material inputs for pavement design. Three different levels of inputs, depending on the desired level of accuracy, are available for resilient modulus of unbound materials in the MEPDG. Level 1 analysis requires coefficient (K_1, K_2 and K_3) values of non-linear resilient modulus determined using the M_R data obtained from laboratory testing through statistical analysis. The two laboratory test protocols commonly used in the USA for M_R testing are the National Cooperative Highway Research Program (NCHRP) 1–28A test protocol (NCHRP, 2004b) and the American Association of State Highway and Transportation Officials (AASHTO) T307 (AASHTO, 1999) procedure. The input parameters for level 2 analysis include the M_R values obtained from empirical correlations with other unbound material properties such as California bearing ratio (CBR), R-value, AASHTO layer coefficient, dynamic cone penetrometer (DCP) and so on. Level 3 analysis requires the typical M_R values of local soil based on agency experience.

Proper characterisation of unbound materials is important since the moduli of these materials may be highly influenced by the stress state (non-linear) and in situ moisture content. As a general rule, coarse-grained materials have higher moduli as the state of the confining stress is increased. In contrast clayey materials tend to have a reduced modulus as the deviator stress component is increased. Thus, while both categories of unbound materials are stress dependent (non-linear), each behaves differently under the changes of stress states.

While it is expected that resilient modulus testing is to be completed for level 1 design by state agencies implementing the MEPDG, many agencies, including the Iowa Department of

Transportation (DOT) were not fully equipped to complete resilient modulus lab testing. Therefore, M_R values were determined indirectly by Iowa DOT based on empirical correlations for level 2 designs. However, with more and more agencies adopting the mechanistic-empirical design concept in their pavement designs, Iowa DOT began implementing the resilient modulus testing protocol in consideration of the benefits that can be derived.

In 2003, the Iowa DOT was equipped with a servo-hydraulic dynamic loading materials test system known as the Nottingham asphalt tester (NAT). The NAT originally was developed at the University of Nottingham (Cooper and Brown, 1995) and has been widely used throughout the UK for hot-mix asphalt (HMA) stiffness, rutting and fatigue testing (Edwards *et al.*, 2005). The Iowa DOT NAT, developed from the original NAT with the support of the UK-based manufacturer, is a hybrid servo-hydraulic machine designed for testing not only HMA performance properties but also unbound materials' resilient modulus. It can perform a frequency sweep test, which the original NAT could not. Iowa DOT has so far utilised this system only for testing HMA properties and not for testing unbound materials' resilient modulus, since the capacity of this system for testing the unbound material resilient modulus has not been verified. Also, little information is available about the M_R properties of unbound materials in Iowa.

This research was initiated to recommend Iowa unbound material properties design inputs for MEPDG implementation, as well as to verify the capacity of an Iowa DOT hybrid NAT for testing unbound materials' resilient modulus. A detailed laboratory testing programme using common Iowa unbound materials was designed and carried out in accordance with the AASHTO T307 resilient modulus test protocol. The programme included laboratory tests to characterise basic physical properties of the unbound materials, specimen preparation and repeated load triaxial tests in the Iowa DOT hybrid NAT to determine the resilient modulus of typical Iowa unbound materials. The procedure and the results of data analysis are discussed in the present paper, highlighting the important findings regarding the non-linear stress-dependent behaviours of tested Iowa unbound materials and the accuracy of the Iowa DOT hybrid NAT for testing unbound materials' resilient modulus.

2. Resilient modulus of unbound materials

2.1 Laboratory testing

Resilient modulus values for base/sub-base aggregate and subgrade soil are determined from repeated load triaxial tests on prepared representative samples. The repeated load triaxial test consists of applying a cyclic load on a cylindrical specimen under constant confining pressure (σ_3 or σ_c) and measuring the axial recoverable strain (ε_r). The resilient modulus determined from the repeated load triaxial test is defined as the ratio of the repeated axial cyclic (resilient) stress to the recoverable (resilient) axial strain

$$1. \quad M_R = \frac{\sigma_{cyclic}}{\varepsilon_r}$$

where M_R is the resilient modulus, σ_{cyclic} (or σ_d) is the cyclic (deviator) stress and ε_r is the resilient (recoverable) strain in the vertical direction. The typical repeated load triaxial test system consists of a loading frame with a crosshead-mounted hydraulic actuator. A load cell is attached to the actuator to measure the applied load. The soil sample is housed in a triaxial cell where confining pressure is applied. As the actuator applies the repeated load, sample deformation is measured by a set of linear variable differential transducers (LVDTs). A data acquisitions system records all data during testing.

AASHTO has provided standard test procedures for determination of resilient modulus using the repeated load triaxial test, which include AASHTO T 292 (AASHTO, 1991a), AASHTO T 294 (AASHTO, 1994) and AASHTO T 307 (AASHTO, 1999) (previously AASHTO TP46). The comparisons of these test procedures are discussed by Ping *et al.* (2003) and Kim and Siddiki (2005). The AASHTO T 307 improved with time and is one of the current protocols for determination of resilient modulus of soils and aggregate materials. Detailed background and discussion on AASHTO T 307 are presented by Groeger *et al.* (2003).

NCHRP Project 1–28 A (NCHRP, 2004b) was conducted to harmonise existing AASHTO methods with those developed in NCHRP Project 1–28. The final product of NCHRP Project 1–28 A (NCHRP, 2004b) is *Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design*. The test procedures of AASHTO T 307 (AASHTO, 1999) and NCHRP 1–28A (NCHRP, 2004b) are similar except for a few differences, including material classification methods, load cell and LVDT location, and loading test sequence. In particular, AASHTO T 307 (AASHTO, 1999) requires the use of a load cell and deformation devices (LVDTs) mounted outside the triaxial chamber, whereas NCHRP 1–28A requires the use of a load cell and clamp-mounted deformation devices inside the triaxial chamber. The MEPDG recommends that M_R be obtained from repeated triaxial testing using either AASHTO T 307 (AASHTO, 1999) or NCHPR 1–28A (NCHRP, 2004b) test protocols.

2.2 Resilient modulus models

For mechanistic–empirical design, resilient moduli at different stress conditions are estimated using a generalised constitutive model from laboratory-measured M_R data. Many researchers have proposed predictive models to capture the resilient behaviour of unbound materials. Among the proposed models, simple resilient modulus models, such as the K–θ (Hicks and Monismith, 1971), Uzan (1985) and the universal models (Uzan *et al.*, 1992), consider the effects of stress dependency for modelling the non-linear behaviour of base/sub-base aggregates. These resilient modulus models are as follows.

K_{GB}–θ model (Hicks and Monismith, 1971)

2. $$M_R = K_{GB}\theta^n$$

Uzan model (Uzan, 1985)

3. $$M_R = K_1 P_a (\theta/P_a)^{K_2} (\sigma_d/P_a)^{K_3}$$

Universal model (Uzan *et al.*, 1992)

4. $$M_R = K_1 P_a (\theta/P_a)^{K_2} (\tau_{oct}/P_a)^{K_3}$$

where $\sigma = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ = bulk stress, $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress, τ_{oct} = octahedral shear stress $= \sqrt{2/3} \times \sigma_d$ in triaxial conditions, P_a is the atmospheric pressure or unit reference pressure (101·3 kPa or 14·7 psi) used in the models to make the stresses non-dimensional, and K_{GB}, n and K_1 to K_3 are multiple regression constants obtained from repeated load triaxial test data on granular materials.

Figure 1 illustrates stress-dependent behaviour of base/sub-base aggregates. Typically, base and sub-base aggregate moduli increase in proportion to the increasing stress levels thus exhibiting stress-hardening type behaviour (see Figure 1). The simpler K–θ model often adequately captures the overall stress dependency (bulk stress effects) of unbound materials' (base/sub-base aggregate and subgrade soil) behaviour under compression-type field loading conditions. The Uzan (1985) model considers additionally the effects of deviator stresses on base/sub-base aggregate and handles very well the modulus increase with increasing deviator stresses (stress-hardening) even for extension-type field loading conditions. A more recent universal model (Uzan *et al.*, 1992) also accounts for the stress dependency of the resilient behaviour as power functions of the three-dimensional (3D) stress states.

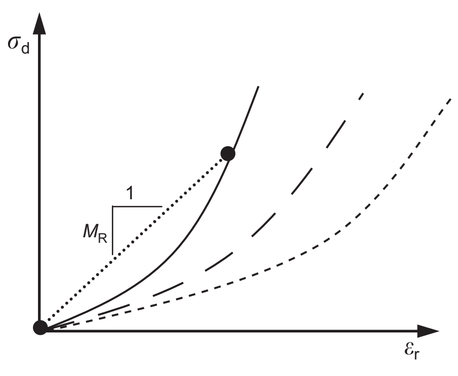

Figure 1. Stress hardening behaviour of base/sub-base aggregates

The resilient modulus of fine-grained subgrade soils is also dependent upon the stress state as shown in Figure 2. Typically, soil modulus decreases in proportion to the increasing stress levels thus exhibiting stress-softening type behaviour. As a result, the most important parameter affecting the resilient modulus becomes the vertical deviator stress on top of the subgrade due to the applied wheel load. The bilinear or arithmetic model (Thompson and Robnett, 1979) given in Equation 5 is the most commonly used resilient modulus model for subgrade soils expressed by the modulus–deviator stress relationship. As indicated by Thompson and Elliot (1985), the value of the resilient modulus at the break-point in the bilinear curve, M_{Ri} or E_{Ri}, can be used to classify fine-grained soils as being soft, medium or stiff.

Bilinear model (Thompson and Robnett, 1979)

5. $$\begin{cases} M_R = M_{Ri} + K_1(\sigma_d - \sigma_{di}) & \text{for} \quad \sigma_d \le \sigma_{di} \\ M_R = M_{Ri} + K_2(\sigma_d - \sigma_{di}) & \text{for} \quad \sigma_d > \sigma_{di} \end{cases}$$

where K_1 and K_2 are slopes, M_{Ri} or E_{Ri} are break-point resilient modulus and σ_{di} is break-point deviator stress.

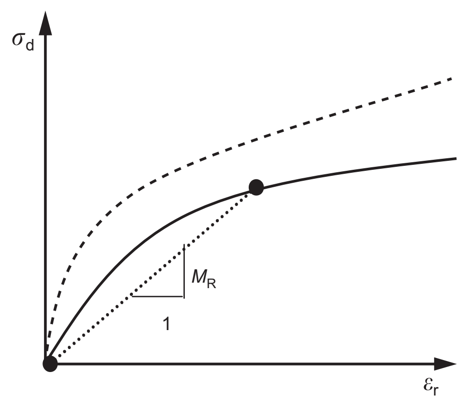

Figure 2. Stress dependency behaviour of fine-grained subgrade soils

In the MEPDG, resilient modulus for unbound granular materials and subgrade is predicted using a similar model to Equation 4, as shown below in Equation 6

MEPDG model (NCHRP, 2004a)

$$M_R = K_1 P_a (\theta / P_a)^{K_2} (\tau_{oct} / P_a + 1)^{K_3} \quad (6)$$

Coefficient K_1 is proportional to resilient modulus. Thus, the values for K_1 should be positive since M_R can never be negative. Increasing the bulk stress, θ, should produce a stiffening or hardening of the material, which results in a higher M_R. Therefore, the exponent K_2, of the bulk stress term for the above constitutive equation should also be positive. Coefficient K_3 is the exponent of the octahedral shear stress term. The values for K_3 should be negative since increasing the shear stress will produce a softening of the material (i.e. a lower M_R).

3. Laboratory resilient modulus test programme with Iowa DOT hybrid NAT

A laboratory testing programme was designed to verify the capacity of the Iowa DOT hybrid NAT for resilient modulus testing of Iowa unbound materials. The laboratory testing programme included the selection of common Iowa unbound materials, the characterisation of basic physical properties of selected materials and the specimen preparation and repeated load triaxial tests in accordance with the AASHTO T 307 resilient modulus test protocol. The AASHTO T 307 was chosen over NCHRP 1–28A protocol for resilient modulus testing based on the recommendations of Iowa DOT.

3.1 Iowa DOT hybrid NAT

Iowa DOT has been utilising NAT to measure HMA dynamic modulus and assess resistance to rutting under repeated loading. Kim and Coree (2006) with support from Iowa DOT developed the HMA moisture sensitivity testing protocol using Iowa DOT NAT. The Iowa DOT has recently attempted to update this system with the support of a UK-based manufacturer for testing unbound pavement geomaterials.

Figure 3 shows pictures of the Iowa DOT hybrid NAT. The system utilises a sophisticated control and data acquisition system with 16-bit digital servo-control to digitally generate control waveforms so that materials are tested under conditions that are simulative of those applied by static or moving vehicles. The main user interface is a user-friendly Windows software written in LabView that allows user-designed test routines, which can include multiple wave types and methods of data acquisition. Cooper Research Technology Ltd provided the updated software of the resilient modulus test for this research. Temperature-controlled cabinets can cycle temperature in a range of −10℃ to +60℃ with ±0·2℃. The significant amendment to the hardware system for unbound materials is two triaxial cells for 100 mm (3·9 in.) and 150 mm (5·9 in.) specimens which are not used for HMA materials testing.

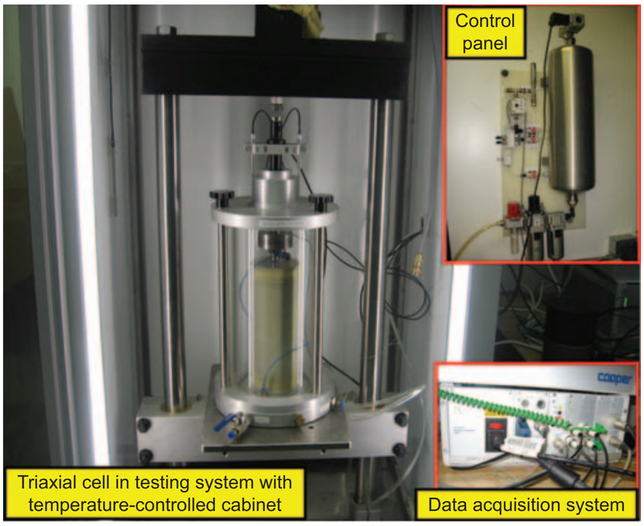

Figure 3. Iowa DOT hybrid NAT

3.2 Testing materials

As a first step, a total of three soil types commonly found and used in Iowa were sampled and tested for this study. The three soil types were obtained from a new construction site near US-20 highway in Calhoun County, Iowa (STA. 706 to STA. 712, project number NHSX-20-3(102)-3H-13). The engineering properties of these soil samples are shown in Table 1.

Following Iowa DOT specifications (Iowa DOT, 2008), the collected soils were categorised as select, suitable soil or class 10, and unsuitable soil. The select soil meets the criteria for subgrade treatments. A select soil sample can be classified as an A-6(4) soil and SC in accordance with the AASHTO soil classification system (AASHTO, 1991b) and the unified soil classification system (USCS) (ASTM, 2006), respectively. The suitable soil (class 10) is the excavated soil including all normal earth materials such as silt, clay, sand and gravel and is suitable for the construction of embankments. A suitable soil sample can be classified as an A-6(8) soil and CL. The unsuitable soil can be used in the work only as specified in Iowa DOT specifications or should be removed. An unsuitable soil sample can be classified as an A-7-6(16) soil and CH. In addition to these three types of soil materials, one type of typical base/sub-base aggregate material in Iowa was also tested to determine resilient modulus.

3.3 Specimen preparation

The unbound materials could be categorised as subgrade soil (type 2) or base/sub-base aggregate (type 1) to fabricate

Property	Select[a]	Suitable[b] (Class 10)	Unsuitable[c]
Classification			
AASHTO (group index)	A-6 (4)	A-6 (8)	A-7-6 (16)
USCS group symbol	SC	CL	CH
USCS group name	Clayey sand	Sandy, lean clay	Sandy, fat clay
Grain size distribution			
Gravel (> 2 mm): %	34·6	28·6	34·6
Sand (0·06–2 mm): %	22·4	19·4	7·0
Silt and clay (< 0·06 mm): %	43·0	51·9	58·4
Atterberg limits			
Liquid limit (LL): %	34·8	39·3	50·5
Plasticity limit (PL): %	15·6	16·0	16·3
Plasticity index (PI): %	19·1	23·3	34·2
Proctor test			
Optimum moisture content (OMC): %	15·7	17·7	20·4
Maximum dry unit weight ($\gamma_{d\ max}$): kg/m^3(pcf)	1772 (110·6)	1691 (105·7)	1616 (100·9)

[a]Select cohesive soil: 45% ⩾ % silt and clay, 10% < PI, A-6 or A-7-6 soils of glacial origin, maximum dry unit weight (AASHTO T 99) ⩾ 1762 kg/m^3.
[b]Suitable soil: 30% > PI, maximum dry unit weight (AASHTO T 99) ⩾ 1522 kg/m^3.
[c]Unsuitable soil: soil not meeting select and suitable requirements.

Table 1. Engineering properties of soils

samples and apply loading test sequence in accordance with AASHTO T 307. Subgrade soil samples are prepared in 71 mm (2·8 in.) dia. mould (minimum size) with five-lift static compaction. Since the Iowa DOT hybrid NAT has a triaxial cell of 100 mm (3·9 in.) dia. for subgrade soil, specially designed mould apparatuses, as shown in Figure 4, were fabricated and used to prepare soil specimens by static compaction with five layers of equal thickness. For each soil type, compacted soil specimens were prepared at three different moisture content combinations, namely: OMC, OMC−4 on the dry side, and OMC+4 on the wet side. After a soil specimen was compacted with specified moisture content, it was placed in a membrane and mounted on the base of the triaxial cell. Porous stones were placed at the top and bottom of the specimen. The triaxial cell was sealed and mounted on the base of the dynamic materials test system frame. All connections

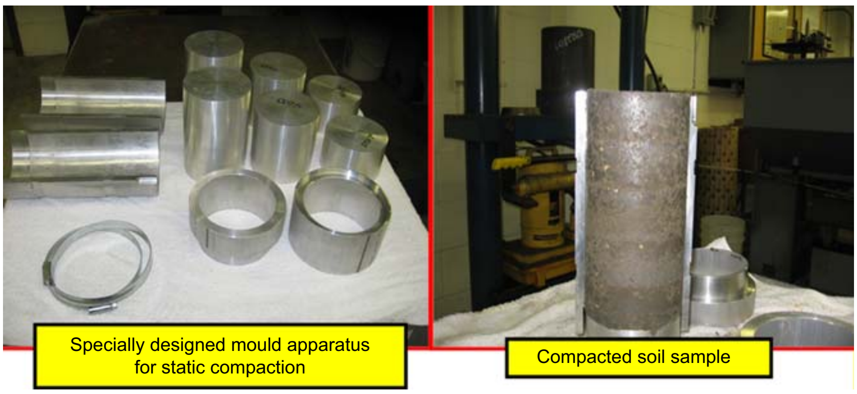

Figure 4. Subgrade soil sample preparation for resilient modulus test

were tightened and checked. Cell pressure, LVTDs, load cell, and all other required set-up equipment were connected and checked.

The base/sub-base aggregate sample was prepared in a 150 mm (5·9 in.) dia. mould with vibratory compaction. Compacted aggregate specimens with 10% moisture content were prepared. The membrane was fitted inside the mould by applying a vacuum. The required amount of aggregate and water were mixed and compacted by vibratory compaction with five layers of equal thickness. The vacuum was maintained throughout the compaction procedure. After compaction, the membrane was sealed to the top and bottom platens with rubber 'O' rings and checked. The triaxial cell was sealed and mounted on the base of the dynamic materials test system frame. All connections were tightened and checked. Cell pressure, LVTDs, load cell and all other required set-up equipment were connected and checked. Figure 5 shows base/sub-base aggregate sample preparation for the resilient modulus test.

3.4 Specimen testing

The software that controls the dynamic materials test system was programmed to apply repeated loads according to the test sequences specified by AASHTO T 307 based on the material type. The soil specimen was conditioned by applying 500–1000 repetitions of a specified cyclic load at a certain confining pressure. Conditioning eliminates the effects of specimen disturbance from compaction and specimen preparation procedures and minimises the imperfect contacts between end platens and the specimen. The specimen is then subjected to different deviator stress and confining stress sequences as per AASHTO T 307 test procedure. The stress sequence is selected to cover the expected in-service range that a subgrade (soil) or base/sub-base (aggregate) material would experience due to traffic loading. After the repeated load triaxial test was completed, compressive loading with a specific confining pressure (27·6 kPa for subgrade soil and 34·5 kPa for base/sub-base aggregate) in accordance with AASHTO T 307 (referred to as a quick shear test) was applied on the test specimens. The applied loads and measured displacements were continuously monitored during the test to ensure that the applied loads were close to the specified loads. If there were significant differences between the applied and the specified loads, then the test was stopped and the test sample was discharged.

4. Resilient modulus test results of Iowa unbound materials

Resilient modulus test results include the mean resilient modulus values, standard deviation (SD), and coefficient of variation (CoV) for the 15 test sequences conducted according to AASHTO T 307. The mean resilient modulus values, SD and CoV are obtained from the last five load cycles of each test sequence. The CoV values for soil testing results range between

Figure 5. Base/sub-base aggregate sample preparation for resilient modulus test

0·04% and 2·5% and the CoV values for aggregate testing results range between 0·24% and 1·3%, which indicates fairly consistent test results during each test sequence.

The resilient modulus of soil is dependent on stress condition such as bulk stress, deviator stress and confining stress. The effects of stress condition on resilient modulus values of select soil are illustrated in Figure 6. A positive slope value in the linear equation indicates an increase in resilient modulus with the increase of stress and a negative slope value indicates a decrease in resilient modulus with the increase of stress. Figure 6(a) indicates that the resilient modulus of soils increases with increasing bulk stress. This result is consistent with the K–θ model result displayed in Figure 1 showing typical behaviour of unbound material under repeated loads. The effects of deviator stress on resilient modulus are illustrated in Figure 6(b) and the effects of confining stress on resilient modulus are illustrated in Figure 6(c). As shown in Figures 6(b) and 6(c), in general, the resilient modulus increases with the increase in confining stress and decrease in deviator stresses (stress-softening behaviour). In particular, the stress-softening behaviour of tested soil is consistent with the trends displayed in Figure 2(b). These results reflect a typical stress-dependent behaviour of soil under compression-type field loading conditions. Moreover, the select soil specimens with lower moisture contents exhibited relatively higher resilient modulus values compared to the other specimens.

The resilient modulus of base/sub-base aggregate material is also dependent on stress condition. The effects of stress condition on aggregate resilient modulus values are illustrated in Figure 7. Similar to resilient modulus of soil, resilient modulus of aggregate increases with increasing overall stress (bulk stress) and confining stress but at a higher slope (see Figures 7(a) and 7(b)). This result is also consistent with the K–θ model result displayed in Figure 1 showing typical behaviour of unbound material under repeated loads. However, the resilient modulus of aggregate increases with the increase in deviator stress (stress-hardening behaviour) as shown in Figure 7(c), while the resilient modulus of soils decreases with the increase in deviator stress (stress-softening behaviour) as shown in Figure 6(c). This stress-hardening behaviour of tested aggregate is consistent with the Uzan model behaviour displayed in Figure 1.

The average resilient modulus values and the shear strength of tested unbound material specimens are presented in Table 2 to illustrate the effects of unbound material types and moisture contents on the resilient modulus values. As seen in Table 2, the M_R values range from 21 to 82 MPa (2905 to 11 865 psi) for select soils, from 51 to 78 MPa (2765 to 11 249 psi) for suitable soils, and from 24 to 65 MPa (3495 to 9483 psi) for unsuitable soils under different moisture content conditions.

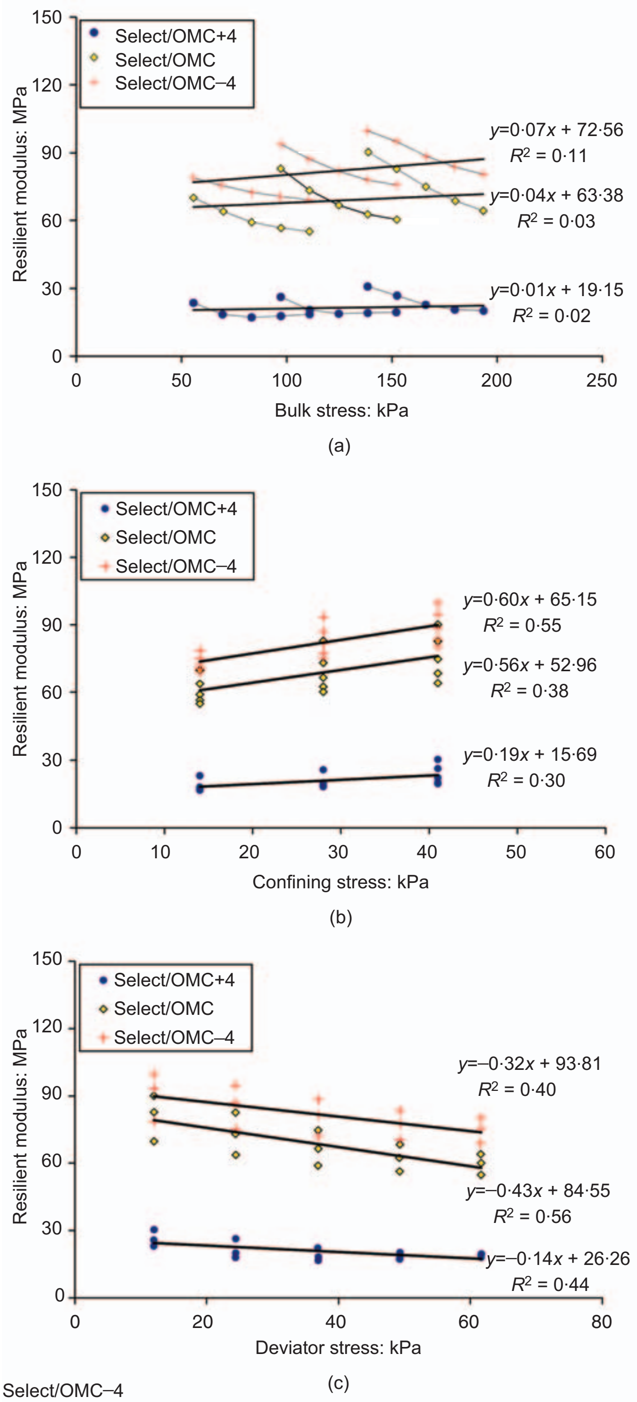

Figure 6. Resilient modulus test results of Iowa select soils: (a) resilient modulus plotted against bulk stress; (b) resilient modulus plotted against confining stress; (c) resilient modulus plotted against deviator stress

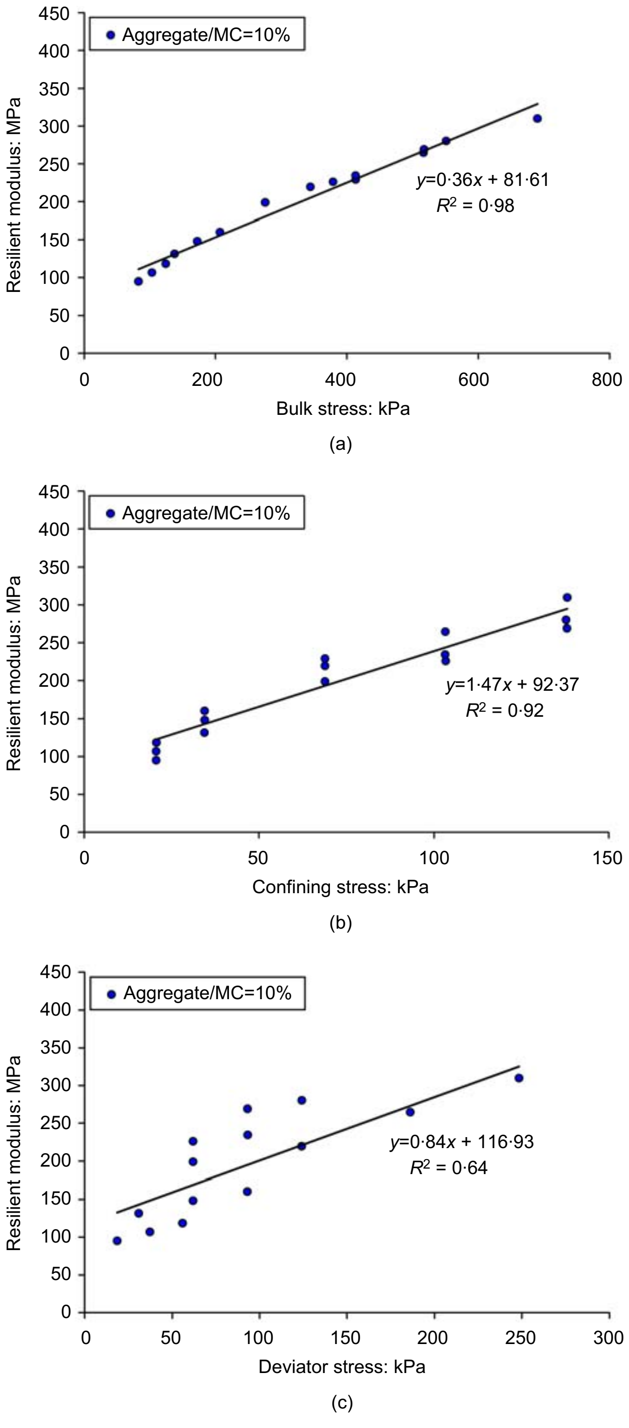

Figure 7. Resilient modulus test results of Iowa base/sub-base aggregate: (a) resilient modulus plotted against bulk stress; (b) resilient modulus plotted against confining stress; (c) resilient modulus plotted against deviator stress

For the same type of soil, specimens with lower moisture contents exhibit higher resilient modulus values compared to those with relatively higher moisture contents. The effect of increased soil moisture content on reducing the resilient modulus is significant. For all the investigated soils, the resilient modulus of soil compacted at OMC−4 were higher compared to those compacted to OMC, as expected. Similarly, resilient modulus of soil specimens compacted at OMC+4 were relatively lower compared to soils compacted to OMC. The soil compacted at moisture content less than the optimum exhibited hardening and showed higher values of resilient modulus with the increase of the overall stress. Similar to observations made from resilient modulus test results, the maximum shear strength values of the select soils and the soils with low moisture content (OMC−4) are higher than those of the others. The average M_R and maximum shear strength values of the tested aggregate specimen are 199 MPa (28 928 psi) and 338 kPa (49 psi).

5. Regression analyses of laboratory resilient modulus data

Regression analyses with commonly used stress-dependent models were carried out for each of the unbound materials to examine if the resilient modulus test results can capture the non-linear behaviour of unbound materials. The MEPDG and bilinear models (Thompson and Robnett, 1979) were used for test results of each soil type with three different moisture contents. The MEPDG (NCHRP, 2004a) and Uzan (1985) models were used for the base/sub-base aggregate test results. The results of regression analyses for subgrade soil and base/sub-base aggregate are presented in Tables 3 and 4, respectively.

The magnitude of K_1 in the MEPDG model for tested materials is always greater than zero since the resilient modulus should always be greater than zero. The values of K_2 in the MEPDG model for tested materials are also greater than zero since the resilient modulus of unbound materials increases with the increase in the bulk stress (confinement). The values of K_3 in the MEPDG model are smaller than zero (i.e. negative), since increasing the shear stress will produce a softening of the unbound materials. The multiple correlation coefficient, R^2, of the MEPDG model for tested materials exceeded 0·90, except for the select soil with OMC+4. The MEPDG recommends that the test results and equipment should be checked for possible errors and/or test specimen disturbance if the R^2 for a particular test specimen is less than 0·90 (NCHRP, 2004a). The higher values of R^2 for the results of most tested samples indicate the good accuracy of test results obtained from Iowa DOT hybrid NAT.

The stress-softening behaviour of most subgrade soil tested could be captured through the negative values of K_1 and K_2 in bilinear models. Only select soil with OMC+4 had a positive

Sample I.D.	Average M_R: MPa	Shear strength: kPa
Select/OMC−4	82	N/A[a]
Select/OMC	69	222
Select/OMC+4	21	88
Suitable/OMC−4	78	N/A
Suitable/OMC	51	203
Suitable/OMC+4	20	88
Unsuitable/ OMC−4	65	279
Unsuitable/OMC	56	211
Unsuitable/ OMC+4	24	107
Aggregate/ MC = 10%	199	338

aNot available.

Table 2. Average resilient modulus and quick shear test results of unbound materials

value of K_2 in bilinear models with a relatively lower R^2 value of 0·78 in the MEPDG model. The values of break-point deviator stress (σ_{di}) for tested soil with OMC ranged from 41 kPa to 47 kPa, which is fairly consistent with about 41·3 kPa reported by Thompson and Robnett (1979). The K_1, K_2 and K_3 values of 1032, 0·58 and −0·03, respectively, in the Uzan model for tested aggregate were close to 869, 0·65 and −0·04 of average K_1, K_2 and K_3 values for base materials obtained from laboratory test results of 125 long-term pavement performance (LTPP) test sections (von Quintus and Killingsworth, 1998). All of these results indicate that Iowa DOT hybrid NAT can provide reasonable test results with high accuracy.

6. Summary and conclusion

This research was mainly conducted to verify the capacity of the Iowa DOT hybrid NAT for testing unbound materials' resilient modulus, which has not been conducted before. A detailed laboratory testing programme using common Iowa unbound materials was designed and carried out in accordance with the AASHTO T 307 resilient modulus test protocol. The programme included the selection of common Iowa unbound materials, the characterisation of basic physical properties of selected materials, and the specimen preparation and repeated load triaxial tests in the Iowa DOT hybrid NAT to determine the resilient modulus of typical Iowa unbound materials. Non-linear, stress-dependent behaviours of tested unbound materials were discussed and regression analyses with commonly used stress-dependent models were carried out to examine if the resilient modulus test results from the Iowa DOT hybrid NAT can capture the resilient behaviour of unbound materials. Based on the results of this research, the following conclusions were drawn.

- The Iowa DOT hybrid NAT can be applied not only to HMA performance testing but also to unbound materials' resilient modulus (M_R) in accordance with the AASHTO T 307.
- The results of the repeated load triaxial test on the investigated Iowa unbound materials provide typical resilient modulus values for MEPDG level 1 analysis, which has not been available before.
- Typical representative M_R values of Iowa subgrade soil are about 69 MPa for select, 51 MPa for suitable (class 10) and 56 MPa for unsuitable soils. The typical representative M_R value of Iowa base/sub-base aggregate is about 199 MPa. However, it should be noted that these values can significantly vary under different stress and moisture conditions.

	MEPDG model				Bilinear model				
Sample I.D.	K_1	K_2	K_3	R^2	σ_{di}(kPa)	M_{Ri}(kPa)	K_1	K_2	R^2
Select/OMC−4	1003·22	0·28	−1.52	0·99	43	78 385	−396·04	−187·42	0·41
Select/OMC	922·05	0·30	−2.10	0·98	41	64 301	−569·10	−221·84	0·58
Select/OMC+4	284·69	0·32	−2.22	0·78	38	18 482	−294·34	17·11	0·58
Suitable/OMC−4	927·55	0·24	−1.33	0·99	43	75 510	−297·66	−231·09	0·43
Suitable/OMC	618·37	0·25	−1.48	0·97	47	48 228	−220·17	−161·87	0·45
Suitable/OMC+4	293·92	0·25	−2.66	0·94	41	17 515	−268·52	−58·51	0·77
Unsuitable/OMC−4	792·77	0·16	−1.35	0·98	124	42 464	−267·73	−260·00	0·68
Unsuitable/OMC	671·84	0·23	−1.40	0·98	46	53 300	−229·15	−175·01	0·46
Unsuitable/OMC+4	364·08	0·33	−2.85	0·97	49	21 167	−238·20	−169·99	0·66

Table 3. Summary of resilient model coefficients for Iowa subgrade soils

	MEPDG model				Uzan model			
Sample I.D.	K_1	K_2	K_3	R^2	K_1	K_2	K_3	R^2
Aggregate/MC = 10%	1080·79	0·59	−0·10	0·997	1032·29	0·58	−0·03	0·997

Table 4. Summary of resilient model coefficients for Iowa base/sub-base aggregate

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