Characterizing Resilient Behavior of Naturally Occurring Bituminous Sands for Road Construction

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Abstract: Oil sand is a generic name given to natural deposits of bituminous sand materials that are mined for crude oil production. These materials are currently used as subgrade materials of temporary and permanent roads in oil sand fields for operating large capacity haul trucks and shovels. This paper focuses on determining in laboratory the resilient behavior of three oil sand materials with bitumen contents of 8.5%, 13.3% and 14.5% by weight. The resilient modulus (M_R) properties were obtained using a newly established repeated load triaxial test procedure. From the test results, nonlinear M_R models were successfully developed in the forms of K-theta, Witczak-Uzan, and the Mechanistic Empirical Pavement Design Guide (MEPDG) models to properly characterize temperature and stress dependent resilient behavior. The modified K-theta model predicted the overall M_R dependency on applied stress states and temperature quite satisfactorily for all the three oil sands when compared to the modified Witczak-Uzan and MEPDG models. The M_R results presented and the models developed can be practically used to estimate the field stiffness behavior of oil sands as subgrade materials.

Keywords: Bituminous Sands, Resilient Modulus, Repeated Load Triaxial Tests, Bitumen Contents, Temperature, Load Pulse Duration.

Introduction

Oil sands are natural deposits of bituminous sand materials that are rich in bitumen content to the extent that oil can be extracted from these deposits. The largest and most thoroughly studied deposits are located in Canada, United States and Venezuela. The Alberta Province in Canada has the world's largest deposit of oil sands. Oil sand surface mining involves excavation to remove the overburden and providing access to the mineral sands below it using haul trucks and shovels. In situ, these

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deposits are predominantly quartz sand surrounded by a thin film of water and fines, with bitumen filling the pore spaces between the sand grains. The quartz sand, silt and clay, i.e., inorganic materials of the oil sand composition constitutes about 80% by weight, with bitumen and water constituting about 15% and 5%, respectively (National Energy Board, 2004). Oil sands are generally unconsolidated and easily crumble in the hand, and must be properly characterized to be accepted as road construction material.

The presence of high bitumen content in the oil sand composition makes these naturally occurring sands low load-bearing materials for haul trucks, shovels and other mining equipment. Over the years, research studies on oil sands have traditionally focused on obtaining laboratory stress-strain test data (Dusseault and Morgenstern 1978; Agar et al. 1987; Samieh and Wong 1997, 1998). Based on the data collected in these studies, confining pressure, peak stress or strain, friction angle and cohesion have been primarily used for modeling the strength and elastic behavior of oil sands. Recent field studies indicated that oil sand ground stiffness could be defined as a function of ground deformation due to equipment loading (Joseph 2002). To properly characterize the stiffness behavior of oil sands, it is also important to take into account its actual time and temperature dependent behavior as part of the resilient modulus characterization under dynamic, repeatedly applied wheel loading conditions.

The repeated load triaxial compression test is currently the most commonly used method to measure the resilient (elastic) deformation characteristics of geomaterials, i.e., fine-grained subgrade soils and unbound aggregates, in the laboratory. Under the repeated application of dynamic loads, the recoverable strains are used to evaluate the resilient properties of pavement foundation geomaterials. Traditionally, resilient modulus used for the elastic stiffness of pavement materials is defined as the repeatedly applied wheel load stress divided by the recoverable strain determined after shakedown of the material. Resilient modulus (M_R) can also be obtained through empirical correlations with other material strength properties including the commonly used California Bearing Ratio (CBR) and Hveem Resistance (R) value.

Field plate load tests conducted on oil sand materials have indicated that oil sands exhibit stress-softening type deformation behavior, that is, resilient modulus decreases with increasing deviator stress (Joseph 2005). Joseph (2005) reports that oil sand is currently used as subgrade materials for the construction of temporary and permanent roads in oil sand fields for hauling activities. Joseph (2005) observed that deformation and stiffness problems during summer were more prevalent in pavements with high-grade oil sand subgrade compared to low-grade oil sand subgrade materials. The low-grade oil sands performed significantly better as subgrade materials than high-grade oil sands (Joseph 2005). In comparison to highways, limited research has been devoted to the design and construction of roads in oil sands mining field. No research study is currently undertaken to characterize the resilient behavior of oil sand materials.

Resilient modulus models commonly developed from laboratory M_R data, such as the K-theta model by Hicks and Monismith (1971), Uzan model (1985), Witczak-Uzan universal model (Uzan et al. 1992), the National Cooperative Highway Research Program (NCHRP) Mechanistic Empirical Pavement Design Guide (MEPDG) model (NCHRP 1-37A 2004), and Thompson and Robnett (1979) bilinear/arithmetic model properly consider the effects of stress dependency for modeling the nonlinear behavior of geomaterials. These models are used to estimate the resilient modulus as a function of stress state, and handle very well the modulus increase/decrease with increasing applied stresses in these geomaterials.

This paper mainly focuses on characterizing the resilient behavior of three types of oil sand materials with bitumen contents 8.5%, 13.3% and 14.5% by weight from a newly established repeated load triaxial test procedure, which was also implemented recently for permanent deformation testing of the same oil sand materials (Anochie-Boateng et al. 2008). Resilient deformation properties obtained from the new test procedure were used to determine M_R properties at two haversine type load pulse durations (or loading frequencies) of 0.1 and 0.5 seconds, and temperatures of 20^oC and 30^oC. The well known K-theta, Witczak-Uzan, and MEPDG nonlinear M_R models were modified by including temperature as independent variable to obtain model parameters to describe resilient behavior of the three oil sands. The performances of M_R models developed for each oil sand are further investigated to determine which model would better predict field behavior of oil sand materials.

Sample Preparation and Resilient Modulus Testing

The three types of oil sand materials used in this study were obtained from Suncor Energy, Inc. and Syncrude Canada Ltd. oil sand mines in Canada. The selection of these samples was mainly based on their field loading behavior under construction and mining equipment, and the on-going research on these materials. Suncor Energy, Inc. provided two oil sand materials (SE samples) whereas Syncrude Canada Ltd. provided one oil sand material (AU sample). The oil sand materials were initially tested for bitumen contents using AASHTO T 308 test procedure. The bitumen contents were found to be 8.5%, 13.3% and 14.5% for the SE samples and the AU sample, respectively. Accordingly, the SE samples were designated as SE-09 and SE-14, and the AU was designated as AU-14. All the three oil sand samples were uniformly graded fine to medium sands with the smallest to largest size particles ranging from 0.6 mm to 2.36 mm and the fines contents, i.e., passing No. 200 sieve or 0.075 mm, ranging from 7% to 15%.

The oil sand specimens were prepared using an Industrial Process Controls (IPC, Australia) Servopac gyratory compactor. The specimens were compacted at different density levels depending on the applied number of gyrations at the approximate density states in the field using the gyratory compactor. Specimen sizes of 150-mm diameter by 150-mm high were prepared at room temperature of approximately 21°C for the resilient modulus testing. Recent research studies have investigated and established a close agreement between modulus results obtained from samples at diameter to height ratios of 1:1 and 1:2 (Edil 2000, Seyhan 2002). Especially, when determining resilient modulus from the vertical specimen response, i.e., standard definition, changing specimen height did not make a difference in the modulus values computed (Edil 2000, Seyhan 2002). Moreover, a very low level of end friction could be attained in a triaxial set up with a 1:1 sample size ratio by placing a smooth plastic coated paper between the polished platen and specimen (Adu-Osei 2000), which proved to minimize specimen end effects in modulus testing. The typical bulk densities achieved in gyratory compactors for SE-09 and SE-14 were 2,000 kg/m^3 at 100 gyrations and 2,050 kg/m^3 at 40 gyrations, respectively. The density achieved for AU-14 was 2,050 kg/m^3 at 25 gyrations. These achieved densities obtained for the cylindrical specimens 150 mm in diameter by 150 mm high prepared were very close to field density values reported by Joseph (2005). Following compaction, specimens were placed in 0.6-mm thick latex membrane, and conditioned at the desired temperatures for a minimum of 6 hours in a temperature chamber for testing. Fig. 1 shows the AU-14 sample in loose and gyratory compacted states.

(a) AU-14 Oil sand sample in natural state; (b) Gyratory compacted AU-14 specimens

Fig. 1. Naturally occurring and compacted states of oil sand sample

The AASHTO T 307 is currently the standard test procedure performed using repeated load triaxial test setups to determine the resilient properties of subgrade soils and unbound aggregate materials. The AASHTO T 307 test procedure primarily applies stress states on the specimens to simulate highway loading conditions in the laboratory. During testing, cylindrical specimens are subjected to 15 different repeated/pulsed stress states under different constant all-around confining pressures to simulate lateral stress caused by the overburden pressure and dynamically applied wheel loadings. The maximum total vertical stress in the AASHTO T 307 test procedure is limited to 110 kPa and 414 kPa for subgrade soils and unbound aggregate materials, respectively. Yet these vertical stresses are not large enough to simulate higher field stresses such as those that would occur under large capacity off-road mining equipment. Joseph (2005) noted from field studies that a Caterpillar 797B off-road haul truck could produce vertical stresses of about 800 kPa with confining pressures ranging between 250 and 300 kPa, i.e., a vertical stress to confining stress ratio of about 3.20. Joseph (2005) also observed that the P&H 4100 BOSS shovels generated a static ground loading of up to 220 kPa, and could induce a ground confinement of about 70 kPa. Properly simulating such field loading conditions in laboratory testing and developing prediction models for the oil sand stiffness behavior would help better understand use of oil sand materials for road construction.

A newly established repeated load triaxial test procedure used in this study to obtain resilient properties of the three oil sand materials is described in more detail in a companion paper for permanent deformation behavior (Anochie-Boateng et al. 2008). This test procedure is based on the field loading characteristics of haul trucks and mining equipment for oil sands, and considers higher total vertical stresses ranging from 82.8 kPa to as high as 552 kPa. In comparison to the AASHTO T 307 procedure, the test procedure also required a much higher number of load applications applied to accumulate permanent deformations in the specimen. Conducting these tests separately would be very time-consuming and costly. Note that permanent deformation test is basically destructive, that is why one stress ratio could be applied to one specimen at a time. As a result, in our testing program, the same load pulse durations were used to evaluate both the modulus and permanent deformation properties. Table 1 lists the applied stress states with the total vertical stress (σ_1) to confining stress (σ_3) stress ratios used to obtain the M_R properties of the oil sand materials. Nine applied stress states listed in Table 1 were repeated at two temperatures, 20^o Celsius and 30^o Celsius, and two load pulse durations of 0.1 and 0.5 seconds with 0.9- and 0.5-second rest periods, respectively. A total of 36 tests were performed for each type of oil sand material, i.e., SE-09, SE-14, and AU-14, with bitumen contents of 8.5%, 13.3% and 14.5%, respectively, to record resilient properties of the samples. The resilient modulus test data were collected at 100 load cycles. The stress states applied were recorded, and the resulting recoverable axial strain responses of the specimen were measured. The average recoverable axial strain and the applied deviator stress of the last 5 cycles were used to compute the resilient moduli of the oil sand materials (see Eq. 1).

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

where, σ_d is the dynamic deviator stress and ε_r is the resilient (recoverable) axial strain. The resilient modulus results are presented and analyzed in the next section.

Table 1. Applied Stress States in the Oil Sand Repeated Load Test Procedure

Specimen Number	Stress State (kPa)			Stress Ratio σ_1/σ_3
	Confining Stress (σ_3)	Deviator Stress (σ_d)	Total Vertical Stress (σ_1)	
1	41.4	41.4	82.8	2.00
2	41.4	138.0	179.4	4.33
3[a]	41.4	276.0	317.4	7.67
4	138.0	41.4	179.4	1.30
5	138.0	138.0	276.0	2.00
6	138.0	276.0	414.0	3.00
7	276.0	41.4	317.4	1.15
8	276.0	138.0	414.0	1.50
9	276.0	276.0	552.0	2.00

[a]: Specimens did not survive this high stress ratio

Analyses and Discussion of Test Results

It is well known that resilient modulus obtained from repeated/cyclic load test better simulates behavior of road materials compared to modulus obtained from static load test. Previous studies on oil sand deformation properties highlighted the effect of confining pressure on the elastic modulus obtained from mainly static testing (Li and Chalaturnyk 2005, Joseph 2005). Therefore, confining pressure was the only parameter used to model the elastic behavior of oil sands. Note that resilient modulus is the preferred elastic property to model material behavior for road construction under realistic dynamic loading which also accounts for the accumulation of permanent deformations. The test results obtained from this study show that the resilient modulus increases with increasing applied confining pressures for the three oil sand materials, i.e., SE-09, SE-14 and AU-14 samples. The effect of applied stress states, load pulse duration and temperature on resilient behavior of oil sands were also analyzed. These additional factors were not studied before to model the resilient behavior of oil sands for road construction.

At each stress state, the resilient modulus was calculated using the applied deviator stress and the corresponding recoverable strain. The resilient modulus values computed from the 96th to 100th load cycles were averaged for each specimen at every stress state. Tables 2 to 4 show the applied stresses and M_R values computed for the three oil sand samples at temperatures of 20°C and at 30°C. Resilient moduli for all the three samples were higher at 20°C than at 30°C. This trend is common to bituminous materials, which become stiffer at low temperatures than at high temperatures. At the load pulse duration of 0.1 seconds, the average M_R of SE-09 sample at 20°C was about 28% higher than the M_R at 30°C, and at 0.5 seconds, the M_R of SE-09 sample at 20°C was about 31% higher than the M_R at 30°C. For the SE-14 sample, M_R at 0.1 seconds was about 26% higher at 20°C than the M_R at 30°C, and at 0.5 seconds, the M_R at 20°C was about 32% higher than the M_R at 30°C. The AU-14 sample had the lowest differences in M_R between 20°C and 30°C. At 0.1 seconds, the modulus was about 15% higher at 20°C than the M_R at 30°C, and at 0.5 seconds, the M_R at 20°C was about 16% higher than the M_R at 30°C.

The analyses showed that there was virtually no difference between the resilient moduli obtained with 0.1-second and 0.5-second load pulse durations for all the samples tested at the two temperatures. The differences between the resilient moduli at the two load durations for the SE-09 sample were about 0.5% and 2.7% at 20°C and 30°C, respectively, whereas those of the SE-14 samples were nearly 0% at 20°C and 2% at 30°C. The AU-14 sample had the highest percentage differences of 4.7% and 5% at 20°C and 30°C, respectively. This trend is in agreement with other studies that reported the loading frequency or load pulse duration has little to no effect on the modulus or stiffness properties of granular materials (Boyce 1976; Sousa and Monismith 1987).

The SE-09 sample had the highest M_R, and the AU-14 had the lowest. The SE-14 also had higher M_R values than AU-14, although at some stress states the moduli of the two samples were comparable. Thus, the low grade oil sand material was stiffer than the high grade oil sands. As expected, the resilient moduli of the oil sand materials tested increases with increasing confining stress levels for all the three oil sand materials. On the other hand, Anochie-Boateng et al. (2008) reported that permanent deformations of the three oil sand materials generally decrease with increasing confining stresses. As they are linked to each other, both resilient modulus and permanent deformation results can be used as performance indicators of the oil sand behavior in the field. Direct shear tests conducted recently in the laboratory on the three oil sand samples indicated that, the SE-09 sample has an average friction angle of 36.2 degrees for the two test temperatures, 20^{o}C and 30^{o}C, whereas the SE-14 and AU-14 samples have 33.2 degrees and 30.6 degrees, respectively (Anochie-Boateng and Tutumluer 2009). Accordingly, the SE-09 sample is expected to be stiffer and exhibit greater potential to resist permanent deformation in oil sand mining roads than the SE-14 and AU-14 samples. This may explain why the low grade oil sands are the preferred subgrade materials for haul roads in mining fields (Joseph 2005), and this study provides typical data for characterizing oil sand behavior that can be used with higher confidence in road construction.

Based on the average M_R values obtained at the two load pulse durations (0.1 and 0.5 seconds), further analyses were performed to characterize the stress dependency of the resilient behavior of the three oil sand samples at the two test temperatures. Figs. 2 to 4 show graphically the variations of resilient moduli of SE-09, SE-14 and AU-14 samples with the applied deviator stresses at each of the three confining pressure levels and the two test temperatures. At one constant confining pressure, an increase in deviator stress resulted in little or no change in the resilient modulus values for all the three oil sands materials. Only the AU-14 sample especially, at the confining stress of 41.4 kPa shows a clear decrease in resilient modulus with increasing deviator stress. These common trends support the general findings from the field that oil sand can be considered a stress softening material (Joseph 2002).

Table 2. Resilient Modulus Test Results for SE-09 Oil Sand Sample (Suncor, 8.5% Bitumen Content)

Test Temperature = 20^{o}C						Test Temperature = 30^{o}C					
Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds			Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds		
σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)
40.4	42.5	98.1	39.8	44.7	97.4	40.4	42.5	70.9	40.4	43.6	65.9
40.4	135.9	104.3	40.4	141.9	105.9	40.4	136.4	65.5	40.4	141.9	72.2
138.8	42.0	200.6	139.3	43.6	183.0	138.2	42.5	160.4	138.2	43.6	151.5
138.8	135.3	206.3	139.3	143.0	193.6	138.2	135.9	173.5	138.8	141.4	158.0
138.2	250.8	194.2	138.8	278.4	209.0	138.8	248.6	167.8	138.8	279.0	170.5
279.1	42.0	290.4	278.0	44.2	283.8	278.6	42.5	240.8	278.0	44.7	216.9
278.6	140.8	274.4	278.6	135.9	302.1	278.0	142.5	221.2	278.0	137.0	222.4
278.0	229.2	292.1	278.0	272.8	285.2	277.5	227.0	232.8	278.6	271.7	234.3

Table 3. Resilient Modulus Test Results for SE-14 Oil Sand Sample (Suncor, 13.3% Bitumen Content)

Test Temperature = 20^{o}C						Test Temperature = 30^{o}C					
Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds			Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds		
σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)
40.4	43.1	70.9	40.4	44.7	86.1	40.4	43.1	61.9	40.4	43.6	62.4
40.9	134.8	91.2	40.4	141.9	94.8	40.4	136.4	60.0	40.9	140.8	64.0
138.2	42.5	175.0	138.2	43.6	177.9	138.2	43.1	136.3	138.2	43.6	127.4
138.8	134.8	153.1	138.2	141.9	176.3	138.2	137.0	131.2	138.8	141.4	131.9
138.8	247.5	176.0	138.8	277.9	165.4	138.2	247.5	131.9	138.2	278.4	128.0
278.6	41.4	241.0	278.0	44.7	251.7	278.0	42.5	219.6	278.0	44.2	199.0
278.0	135.9	260.1	278.6	141.4	247.6	278.0	135.9	202.8	278.0	141.4	201.0
277.5	223.7	262.6	278.0	272.8	249.6	278.0	224.3	215.2	278.6	272.3	205.2

Table 4. Resilient Modulus Test Results for AU-14 Oil Sand Sample (Syncrude, 14.5% Bitumen Content)

Test Temperature = 20^{o}C						Test Temperature = 30^{o}C					
Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds			Load Pulse Duration = 0.1 seconds			Load Pulse Duration = 0.5 seconds		
σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)	σ_3 (kPa)	σ_d (kPa)	M_R (MPa)
40.4	42.5	82.8	40.4	44.2	69.7	40.9	42.0	67.0	40.4	43.6	60.9
40.4	136.4	50.3	40.9	140.8	49.1	40.4	136.4	47.1	40.4	141.9	45.1
138.8	40.9	166.8	138.8	43.6	165.6	138.2	42.2	132.1	138.2	44.2	129.8
138.8	135.3	161.1	138.8	141.9	158.9	138.2	135.3	135.1	138.8	141.9	124.6
138.2	240.8	157.8	138.5	278.4	149.3	138.2	243.6	130.2	138.8	279.0	121.2
278.6	30.4	209.8	278.6	43.6	196.1	278.0	43.1	192.6	278.0	44.2	188.1
278.6	133.1	197.9	278.6	140.8	194.3	278.6	135.3	180.7	278.0	141.9	176.8
278.6	222.1	195.5	278.6	272.8	195.0	277.5	222.6	189.5	278.0	272.8	178.5

Resilient Modulus Model Development

The resilient response data obtained from the newly established repeated load triaxial tests were used to develop model parameters for the three oil sand materials tested. Figs. 2 to 4 show that only for the high stress regimes of the repeated load tests, the stress softening and deviator stress dependent bilinear model (Thompson and Robnett 1979) could be considered. Therefore, the bilinear model would not give complete behavior including those at lower stress states. Instead, the resilient responses of the oil sand samples were characterized by determining the regression model parameters of modified K-theta, the Witczak-Uzan and the MEPDG models which now include temperature as a variable as given in Eqs. (2), (3) and (4). The nonlinear model parameters k_1, k_2, k_3 and k_4 were determined by expressing the M_R models in logarithmic relationships to transform the power functions into linear expressions having separate terms. Multiple regression analyses were performed on the data sets to determine the model parameters, which were used to develop the M_R prediction models for the three oil sand materials.

Model 1: $$\log M_R = \log k_1 + k_2 \log \theta + k_3 \log T \tag{2}$$

Model 2: $$\log M_R = \log (k_1 \cdot P_a) + k_2 \log\left(\frac{\theta}{P_a}\right) + k_3 \log\left(\frac{\tau_{oct}}{P_a}\right) + k_4 \log T \tag{3}$$

Model 3: $$\log M_R = \log (k_1 \cdot P_a) + k_2 \log\left(\frac{\theta}{P_a}\right) + k_3 \log\left(\frac{\tau_{oct}}{P_a} + 1\right) + k_4 \log T \tag{4}$$

where, M_R = resilient modulus;

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 (14.7 psi); and

k_1, k_2, k_3 k_4 = model parameters obtained from regression analyses.

All the resilient modulus test results generated for each oil sand sample at the two test temperatures were used for developing resilient modulus models. To properly model resilient modulus of the oil sand there is also a need to include temperature in the material characterization. Note from the test results that the resilient moduli of the three oil sand samples were mainly influenced by the applied stresses and temperature. Accordingly, the resilient modulus results were combined to create individual databases to model the three oil sand materials. Table 5 lists the resilient modulus models developed for each oil sand material and the overall summary of model parameters (k_i) obtained from multiple regression analyses of the different nonlinear M_R models selected for the study.

Strong correlations were obtained for the three models as observed in the regression coefficient (R^2) and low root mean square error (RMSE) values for all the three models. However, relatively low R^2 values ($R^2 < 0.9$) were observed for AU-14 oil sand sample in model 1. The R^2 values improved when models 2 and 3 were used in the analyses. This improvement is accounted for by the inclusion of octahedral stress term in these models. The overall R^2 values were comparatively higher in model 2 than models 1 and 3

The overall objective was to establish a basic understanding as well as to develop practical predictive equations to estimate resilient stiffness behavior of oil sand materials in the field. The regression model analyses results presented in Table 5 showed no significant differences among the model parameters for the three oil sand samples. Moreover, a close examination of the test results at the different test conditions, and the physical properties of the three oil sands such as particle size distribution and density with the assumption of similar bitumen rheological properties suggested that the individual databases could be combined for further analyses. Therefore, it was reasonable to combine the test data to develop a generalized model for oil sand materials. A total of 288 resilient modulus data sets (96 for each sample) were used to develop the models.

The SAS software package was used to perform nonlinear multiple regression analyses to establish the resilient modulus characterization models for the oil sand materials using the modified K- theta, the Witczak-Uzan and MEPDG resilient modulus models. Table 6 lists the generalized resilient modulus models studied using the models 1, 2 and 3, and gives the model parameters obtained from stepwise multiple regression analyses for the resilient modulus results. The high coefficient of correlation (R^2) values obtained for all the models indicate strong correlations between resilient modulus and the applied stress states, and temperature for all the oil sand samples tested.

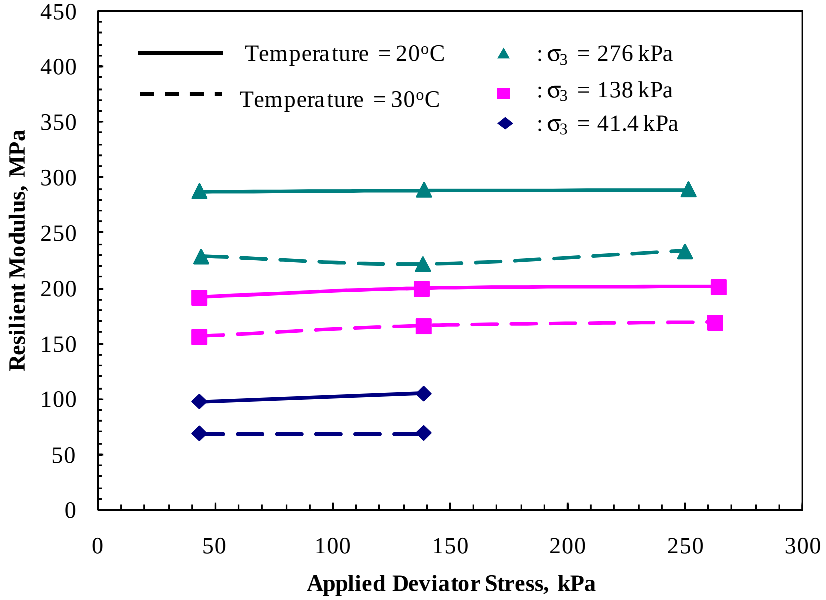

Fig. 2. Variation of M_R with applied σ_d for SE-09 sample

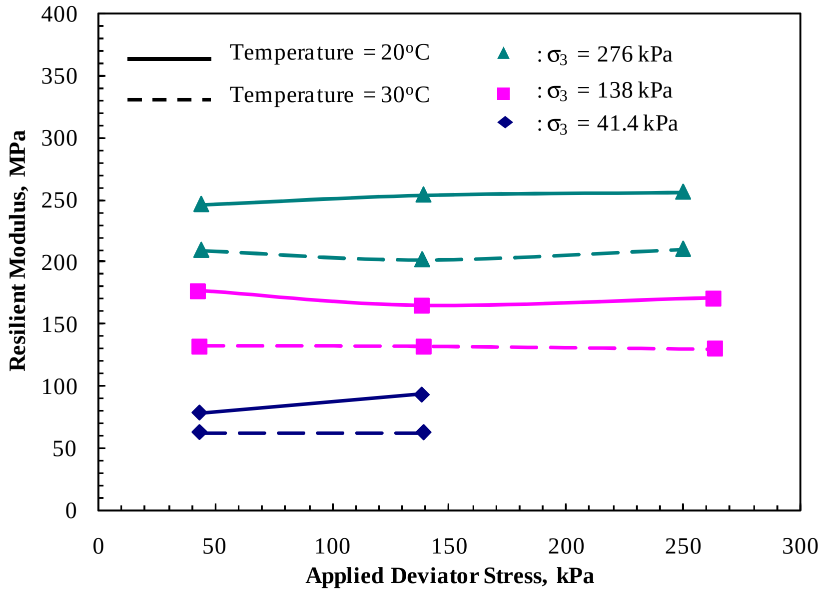

Fig. 3. Variation of M_R with applied σ_d for SE-14 sample

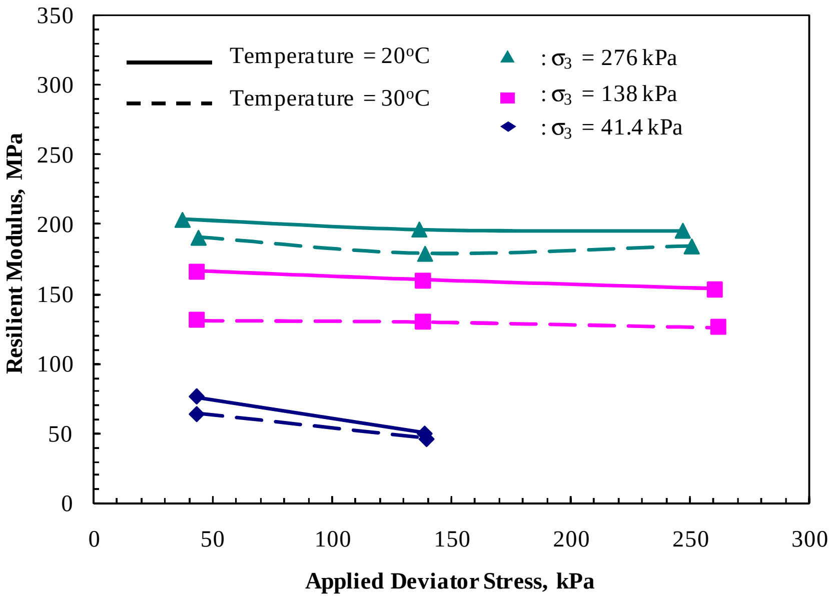

Fig. 4. Variation of M_R with applied σ_d for AU-14 sample

Table 5. Regression Models Developed for Resilient Modulus of Each Oil Sand

Model 1:
$$M_R = k_1 \theta^{k_2} T^{k_3}$$

Model 2:
$$M_R = k_1 \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} T^{k_4}$$

Model 3:
$$M_R = k_1 \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} T^{k_4}$$

Sample ID	Model Parameters					
	k_1	k_2	k_3	k_4	*R^2*	*RMSE*
Model 1:						
SE-09	17	0.685	-0.632	-	*0.94*	*0.051*
SE-14	14	0.694	-0.619	-	*0.94*	*0.052*
AU-14	5	0.691	-0.347	-	*0.79*	*0.101*
Model 2:						
SE-09	336	0.746	-0.123	-0.631	*0.97*	*0.036*
SE-14	266	0.767	-0.145	-0.618	*0.98*	*0.031*
AU-14	83	0.797	-0.217	-0.332	*0.88*	*0.078*
Model 3:						
SE-09	433	0.747	-0.362	-0.632	*0.97*	*0.038*
SE-14	358	0.769	-0.438	-0.619	*0.98*	*0.032*
AU-14	132	0.798	-0.636	-0.338	*0.87*	*0.082*

Table 6. Generalized Resilient Modulus Models Developed for Oil sand Materials Tested

Model 1: $M_R = k_1 \theta^{k_2} T^{k_3}$

Model 2: $$M_R = k_1 \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} T^{k_4}$$

Model 3: $$M_R = k_1 \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3} T^{k_4}$$

Model	Model Parameters					
	k_1	k_2	k_3	k_4	*R^2*	*RMSE*
Model 1	10.5	0.690	-0.533	-	*0.83*	*0.087*
Model 2	196.0	0.770	-0.161	-0.528	*0.88*	*0.074*
Model 3	274.0	0.771	-0.476	-0.530	*0.88*	*0.076*

Resilient Modulus Model Performances

The performances of the three generalized resilient modulus models were further investigated with an objective to evaluate how each model would perform in the field for oil sand materials with similar properties to those of SE-09, SE-14 and AU-14 samples. The results of the measured and predicted resilient moduli are presented in Figures 5 through 7 for the SE-09, SE-14 and AU-14 samples.

Overall, the modified K-theta model, i.e., model 1, predicted M_R quite well for all the three oil sand materials when compared to models 2 and 3. Increasing bitumen content appears to improve model performances as observed in models 2 and 3. The explanation for the relatively weak performances of the modified Witczak-Uzan and MEPDG models is that they perform better with stress-hardening granular materials such as clean sands, gravels, and crushed limestone compared to the stress-softening oil sand materials. Recall that, at constant confining pressure, resilient moduli of all the oil sand materials were statistically the same when the applied deviator stress was increased. Therefore, an increase in shear through the higher deviator stresses applied often tends to cause dilation of the specimen decreasing the overall stiffness of the specimen.

It is reasonable to suggest that the amount of bitumen in the oil sand materials affected the model predictions. However, since the properties of bitumen in the three samples are not known, no firm conclusions can be established. This is because no new information could be gathered from field studies conducted on these oil sands in relation to the rheological properties of the bitumen to report in this paper.

Based on the performances of the three models, model 1 can be proposed as a more practical model for field validation to estimate resilient modulus behavior of these oil sands. A reasonably high R^2-value associated with model 1 indicates that the selected model would give a fairly good resilient modulus prediction in the field. The selected resilient modulus model of the oil sand materials is given as follows:

$$M_R\ (\text{MPa}) = 10.5\,\theta^{0.690}\,T^{-0.533}; \qquad R^2 = 0.83, \text{RMSE} = 0.087 \tag{5}$$

where, M_R = resilient modulus;

θ = bulk stress;

T = temperature (^{o}C).

In this equation, the coefficient representing model parameter k_1 is proportional to the resilient modulus of the oil sand materials. This implies that the value of k_1 should be positive since resilient modulus cannot be negative. Also, increasing the bulk stress in the model should produce a stiffening of the oil sand materials to result in a higher resilient modulus. That is, parameter k_2 of the bulk modulus term should be positive. The parameter k_3 in the model is associated with temperature. Therefore, k_3 should be negative since increasing temperature generally results in a softening of bituminous materials. This suggests that at higher temperatures the resilient modulus or stiffness of the oil sand material would be mainly influenced by the sand skeleton, and increase as the mining trucks get heavier in the field. It appears the modulus or stiffness of oil sand materials would exhibit stress hardening behavior similar to the case of granular materials in the field.

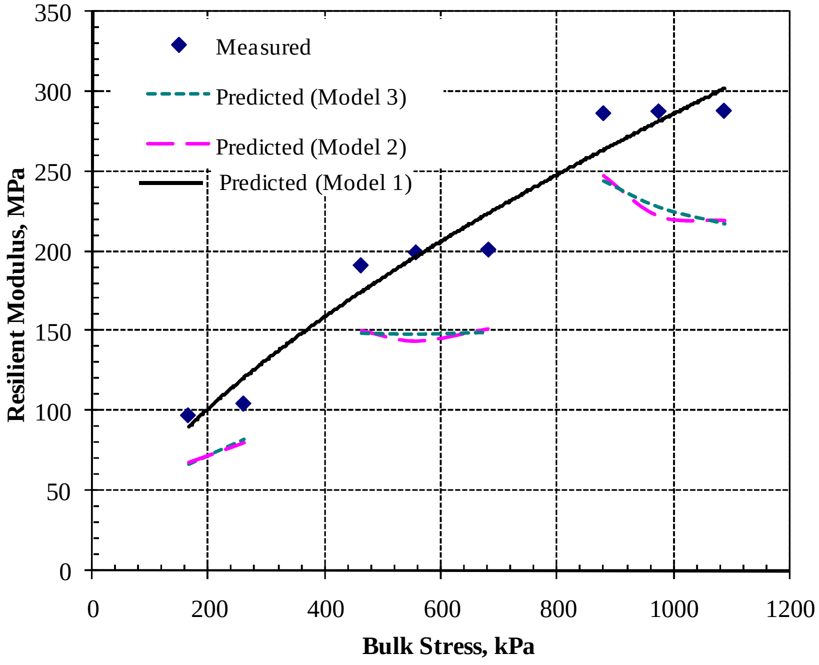

Fig. 5. Performances of the SE-09 oil sand sample M_R models

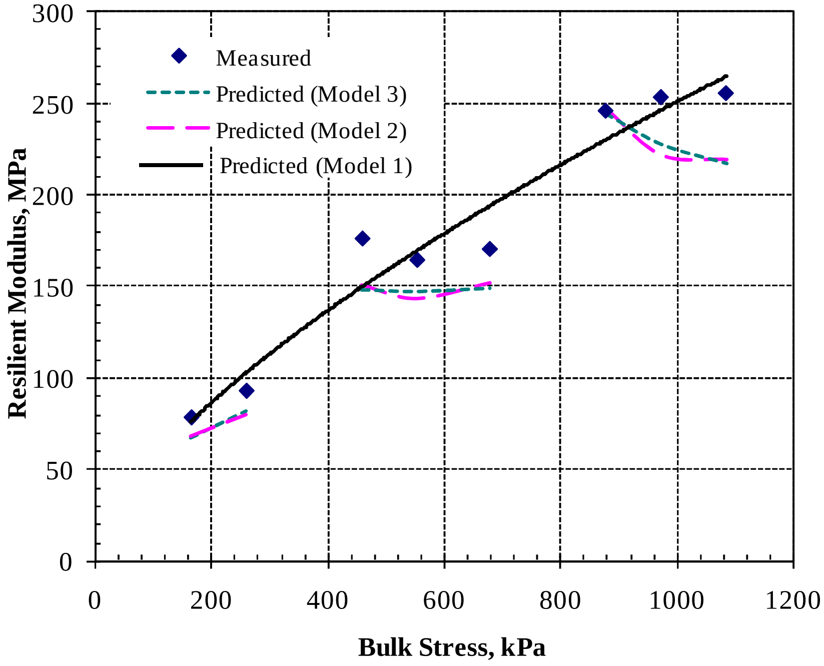

Fig. 6. Performances of the SE-14 oil sand sample M_R models

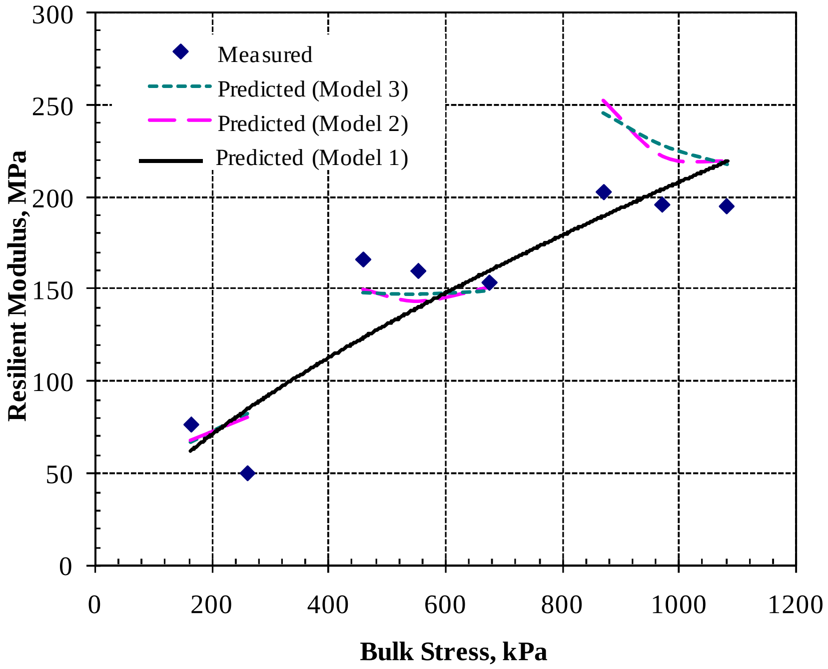

Fig. 7. Performances of the AU-14 oil sand sample M_R models

Summary and Conclusions

Oil sand materials are currently used as subgrade/unbound materials for temporary and permanent roads in oil sand fields for hauling activities. The typical 8% to 15% by weight of bitumen content in the oil sands makes these naturally occurring sands low load-bearing materials for haul trucks and shovels. Field studies have shown that oil sands with high bitumen contents experience deformation and stiffness problems during the warm spring and summer months compared to those with low bitumen content oil sand subgrade materials. However, the stiffness behavior of these materials has not been characterized in the laboratory.

In this paper, the resilient properties of a newly established repeated load test procedure, which applied stress states determined from field loading characteristics of haul trucks and mining equipment at two different load pulse durations or loading frequencies (related to field trafficking speeds), were used to characterize the resilient behavior of three types of oil sands, i.e., SE-09, SE-14, and AU-14, with bitumen contents of 8.5%, 13.3% and 14.5% by weight, respectively. Results obtained from the laboratory testing program constituted extensive database for the oil sand materials tested. Based on the database, resilient modulus was evaluated at nine different stress states for the three oil sands. The resilient moduli of the three oil sand materials were generally higher at 20°C than at 30°C. This behavior is also observed in most bituminous materials that stiffen at lower temperatures. There was statistically little or no significant difference between resilient modulus values at load pulse durations of 0.1 and 0.5 seconds, which is typical of unbound aggregate road materials.

Three commonly used resilient modulus models, i.e., K-theta, Witczak-Uzan and the recent MEPDG, for pavement foundation geomaterials were modified and to obtain model parameters to develop resilient modulus models for the oil sand materials. When the entire test data from the three oil sands were combined, generalized resilient modulus models were successfully developed to account for the applied stresses and temperature. The modified K-theta model appeared to give better predictions of resilient moduli for all the three oil sands. Stronger correlation coefficient values for the modified K-theta model indicate that the model can perform well on predicting resilient modulus of oil sand materials with similar characteristics for road construction. Fairly good M_R predictions obtained for the modified K-theta model could not be repeated for the modified Witczak-Uzan and the recent MEPDG models.

Overall, the resilient modulus data, and the proposed model may provide essential guidelines for estimating the stiffness behavior of oil sand materials under off-road haul trucks, shovels and other mining equipment. Moreover, this study possibly would enhance establishing standard laboratory test procedure for characterizing stiffness behavior of oil sand materials. Further validation and verification of the proposed resilient modulus model (modified K-theta) can be accomplished using results of additional laboratory and field tests.

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