Characterizing volumetric deformation behavior of naturally occurring bituminous sand materials

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ABSTRACT: Oil sand materials are natural bituminous sand deposits that are rich in bitumen or asphalt content to the extent that oil can be extracted from these deposits. The presence of high viscous bitumen content in the oil sand composition makes these materials problematic for field operations of off-road haul trucks and shovels. In this paper, volumetric deformation and bulk modulus properties are determined for three oil sand samples with bitumen contents of 8.5%, 13.3% and 14.5% by weight, using a newly proposed hydrostatic compression test procedure. The test procedure applies field loading conditions of off-road construction and mining equipment to closely simulate the volumetric deformation and stiffness behavior of oil sand materials. Based on the test results, bulk modulus properties were characterized as a function of the applied hydrostatic stress for individual oil sand samples. When the entire test data were combined, nonlinear bulk modulus models were successfully developed to account for applied hydrostatic stress states, test temperatures, and bitumen contents for the three oil sand materials. Results from the bulk modulus models show that oil sands are influenced by temperature due to the bitumen contents. The anticipated use of developed bulk stress models should provide essential guidelines for predicting volumetric deformation behavior of oil sand materials in the field.

1 INTRODUCTION

Oil sand is a generic name given to natural deposits of bituminous sand materials that are mined for crude oil production. The world's largest oil sand deposits are found in the Alberta Province of Canada. The significantly high bitumen content in the oil sand composition, which typically ranges from 8% to 15% by weight, makes these naturally occurring sands problematic for routine operations of construction and mining equipment during the warm spring and summer months. Field studies have indicated that the considerable amount of bitumen in the oil sands, high applied loads from mining equipment and seasonal changes in temperature are major factors that control the modulus and deformation behavior of oil sands (Joseph 2002).

To date, no comprehensive laboratory testing has been found to discuss the individual effects of these factors on bulk modulus of oil sand materials. Instead, research on oil sands has traditionally been focused on obtaining laboratory stress-strain test data to describe shear strength and the Young's modulus properties of oil sands (Dusseault & Morgenstern 1978, Agar et al. 1987, Samieh & Wong 1997, Wong 1999). Based on the data collected in these studies, confining stress, peak stress or strain, friction angle and cohesion are the material properties used for modeling the strength and stiffness behavior. Bulk modulus is an important material property that describes the resistance to volume change when an element of soil is subjected to hydrostatic loading. To properly characterize the volumetric deformation and stiffness behavior of oil sands, it is important to take into account its temperature dependent behavior and the bitumen content under hydrostatic loading conditions.

This paper mainly focuses on characterizing the volumetric deformation and stiffness behavior of three types of oil sand materials with bitumen contents 8.5%, 13.3% and 14.5% by weight using a newly proposed hydrostatic compression test procedure. The test procedure considers field loading characteristics of off-road construction and mining haul trucks and shovels. The deformation properties obtained from the laboratory testing program were used to determine bulk moduli at varying hydrostatic stress states, and two test temperatures of 20°C and 30°C. The test results were used to develop bulk modulus characterization models as a function of applied hydrostatic stresses for the individual oil sand samples. Based on the all the test data, a unified bulk modulus model is also developed for the three oil sand materials to include bitumen content and temperature variables in the predictive equations.

2 HYDROSTATIC COMPRESSION TESTING PROGRAM

2.1 *Oil sand materials and properties*

The oil sand materials used in this study were obtained from Suncor Energy, Inc. and Syncrude Canada Ltd. oil sand mines in Canada. Suncor Energy (SE), Inc. provided two types of low and high grades with respect to the bitumen contents, whereas Syncrude Canada Ltd. provided one sample of the Aurora (AU) high grade oil sand. The oil sand materials were initially tested for bitumen and water contents using AASHTO T 308 and AASHTO T 265 test procedures, respectively. The bitumen contents were found to be 8.5%, 13.3% and 14.5% for the SE low grade, SE high grade and AU high grade, respectively; and the water contents were 1.4%, 3.2% and 2.2%, respectively. Accordingly, the Suncor Energy high and low grades samples were designated as SE-09 and SE-14, respectively, and the Aurora high grade 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 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 150 mm in diameter by 150 mm high cylindrical specimens prepared were very close to field density values reported by Joseph (2005). Figure 1 shows gyratory compacted specimens for one of the oil sand samples.

Figure 1. Gyratory compacted oil sand specimens.

2.2 *Laboratory test procedure and testing performed*

The loading characteristics of off-road large capacity construction and mining equipment dictate field loading stress states and therefore directly influence the volumetric deformation and stiffness behavior of oil sands in the field. For instance, Joseph (2005) noted from field studies that a Caterpillar 797B off-road haul truck could produce vertical stresses of about 800 kPa with confining stresses ranging between 250 and 300 kPa. He also observed that the P&H 4100 type BOSS shovels generated a static ground loading of up to 220 kPa, and could induce a ground confinement of about 70 kPa (Joseph 2005). Moreover Joseph (2005) reported that at ambient temperature of 28^{o}C oil sand materials in the field became soft and problematic to mining equipment.

The newly proposed hydrostatic compression test procedure for oil sands is based on the field loading characteristics of the haul trucks, shovels and other mining equipment. Hydrostatic loading stresses ranging from 41.4 kPa to as high as 276 kPa are applied on the oil sand samples at two temperatures, 20 degrees Celsius and 30 degrees Celsius, to account for spring and summer temperatures, respectively. In this study, an innovative advanced triaxial testing device, the University of Illinois FastCell (UI-FastCell) integrated with Universal Testing Machine (UTM) loading device at the Advanced Transportation Research and Engineering Laboratory (ATREL), was used for applying hydrostatic stresses on the specimen. Figure 2 shows the UI-FastCell test setup for asphalt and granular materials testing at ATREL. The UI-FastCell offers unique capabilities in laboratory material characterization including measurement of on sample vertical and radial displacements, and a bladder type horizontal confinement chamber with a built-in membrane which can be inflated to apply hydrostatic stresses to simulate high field loading conditions on granular and bituminous materials in the laboratory (Tutumluer & Seyhan 1999).

During laboratory testing, gyratory compacted oil sand specimens were subjected to a sequence of different applied hydrostatic stresses of 41.4, 69.0, 138.0, and 276.0 kPa. Specimens were loaded from zero stress conditions to these individual hydrostatic stresses, unloaded to zero, and then, reloaded to the next stress state unti; the maximum hydrostatic stress of 276 kPa was reached. A pulsed wave shape with 60-second loading and 60-second unloading was applied on the test specimens. The axial static loading was controlled by the vertical load cell, and the radial loading was measured by a pressure transducer. Both axial and radial deformations were measured by two symmetrical linear variable displacement transducers (LVDTs) for each load cycle and the corresponding axial and radial strains (ε_1 and ε_3) were computed for the test specimens. Two replicate 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 establish the full laboratory test matrix. Overall, 12 tests were conducted on the three oil sand samples at two temperatures, 20 degrees Celsius and 30 degrees Celsius.

Figure 2. UI-FastCell triaxial test setup used in hydrostatic loading of oil sand materials.

3 ANALYSES OF TEST RESULTS

The applied hydrostatic (isotropic) stresses and measured volumetric strains obtained from hydrostatic compression tests were used to calculate bulk modulus of the oil sand samples. Previous research studies have indicated that by graphing the applied isotropic compression stresses against volumetric strains, a nonlinear trend was characterized for the volumetric deformation behavior for soils (Terzaghi & Peck 1967, Vesic & Clough 1968, Quabain et al. 2003). Vesic & Clough (1968) suggested that soil's elastic properties could conveniently be obtained from such a nonlinear curve by drawing straight line approximations that linearly relate increments of both the isotropic stresses and volumetric strains. In this study, the straight line approximation concept was used for analyzing the results of the oil sand tests. The bulk moduli (K) of the oil sand samples were calculated from the ratio of the incremental hydrostatic stress ($\Delta\sigma$) to the incremental volumetric strain ($\Delta\varepsilon_v$). Equation 1 defines the bulk modulus of the tested samples:

$$K = \frac{\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3}{\Delta\varepsilon_v} = \frac{\Delta\sigma}{\Delta\varepsilon_v} \tag{1}$$

where the volumetric strain ε_v is computed from the axial strain ε_1 and the radial strain ε_3 as $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$, and for triaxial compression tests, hydrostatic stress is given by $\sigma = \sigma_1 = \sigma_2 = \sigma_3$.

A total of 270 stress-strain data sets were obtained from testing one oil sand specimen. Each data set represents an average value from two replicate specimens. Thus, about 540 data points were analyzed for each oil sand sample at the two test temperatures. Figures 3 and 4 show the variations of hydrostatic stresses with volumetric strains determined for the three oil sand samples at 20^{o}C and at 30^{o}C, respectively. Note that each point in these figures represents an average of 270 stress-strain data points. A polynomial regression curve was fit to the individual data sets of the three oil sand samples, i.e., SE-09, SE-14 and AU-14 at the two test temperatures, and the straight line approximation method was used to obtain the incremental hydrostatic stresses and the corresponding volumetric strains. The bulk modulus was then computed at each hydrostatic loading stress using Equation 1.

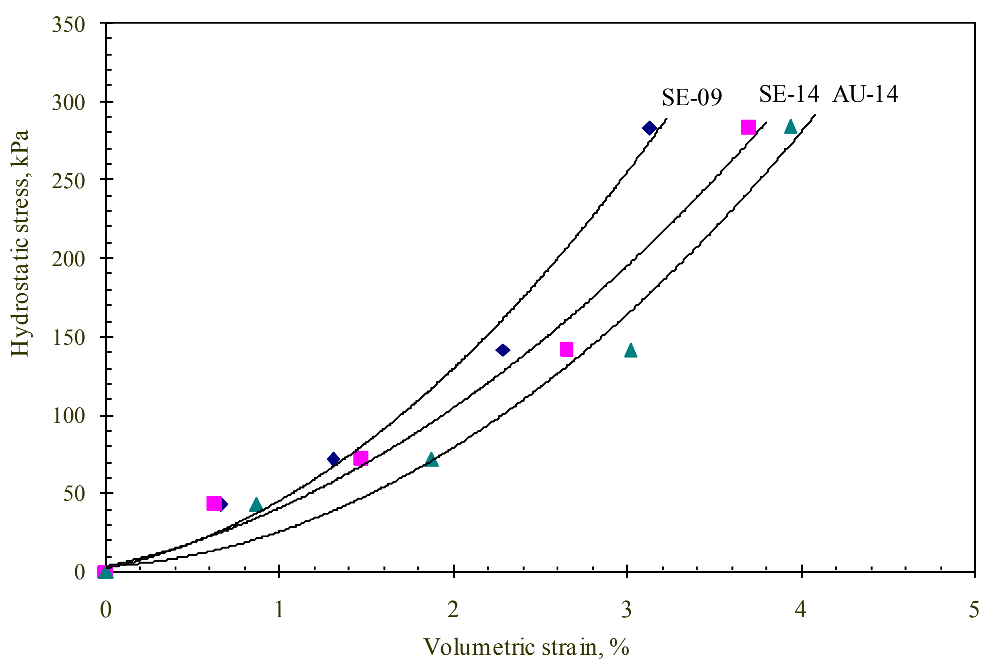

Figure 3. Variations of hydrostatic stresses with volumetric strains for the oil sands at 20^{o}C.

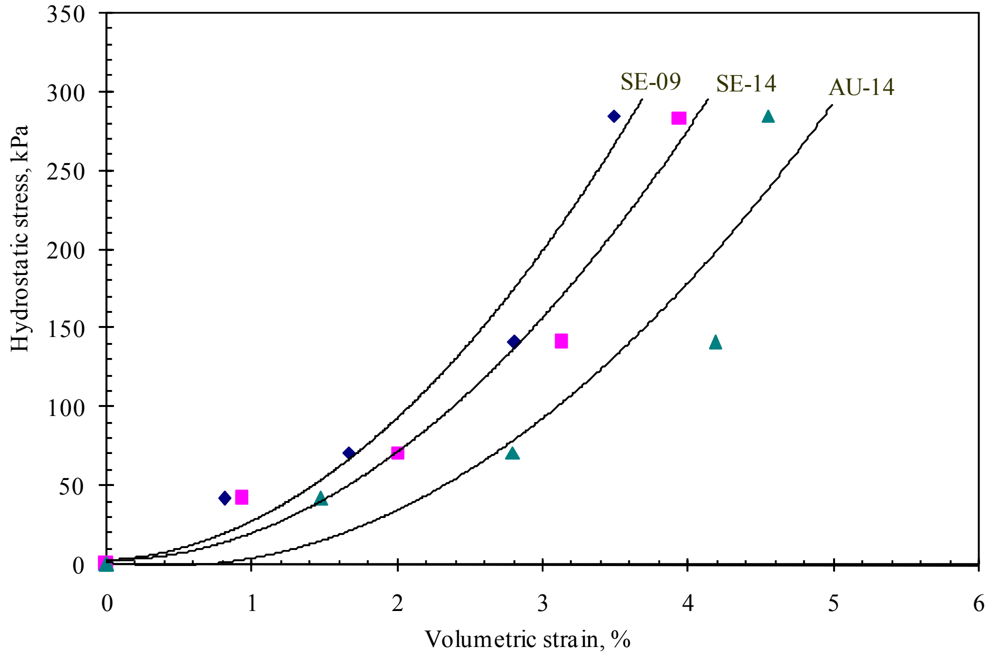

Figure 4. Variations of hydrostatic stresses with volumetric strains for the oil sands at 30°C.

Tables 1 and 2 list the test results for all the oil sand samples at 20°C and 30°C, respectively. As expected, higher bulk modulus values were obtained at 20°C than at 30°C for all the oil sand samples. The SE-09 sample gives the highest bulk moduli while AU-14 sample gives the lowest values. At 20°C, the difference in magnitude between the average bulk modulus of SE-09 and AU-14 samples is 1.61 MPa, i.e., about 26% difference; and the difference between SE-09 and SE-14 is 0.78 MPa, representing about 12.5%. Similar trends in bulk moduli at 20°C are observed for the samples at 30°C. That is, the SE-09 sample has the highest bulk modulus values whereas AU-14 sample has the lowest bulk moduli. It is interesting to note that the magnitude of the bulk moduli of SE-14 and AU-14 samples were comparable at the two test temperatures. The average bulk modulus of SE-14 at 20°C is about 1.2 times greater than the bulk modulus of AU-14 compared to about 1.3 times at 30°C. The amount of bitumen content appears to be a major factor that influenced the overall stiffness of the oil sand materials. Again, the AU-14 sample with the highest bitumen content of 14.5% has the lowest bulk moduli, whereas the SE-09 sample with low bitumen content of 8.5% has the highest bulk moduli.

Table 1. Test results for oil sand samples at 20°C.

$\Delta\sigma$ (kPa)	SE-09		SE-14		AU-14	
	$\Delta\varepsilon_v$ (%)	K (MPa)	$\Delta\varepsilon_v$ (%)	K (MPa)	$\Delta\varepsilon_v$ (%)	K (MPa)
41.4	0.88	4.70	1.02	4.06	1.40	2.96
69.0	1.35	5.11	1.52	4.54	1.90	3.63
138.0	2.10	6.57	2.43	5.68	2.78	4.96
276.0	3.18	8.68	3.60	7.67	3.90	7.08

$\Delta\sigma$ is hydrostatic stress increment; $\Delta\varepsilon_v$ is volumetric strain increment; K is bulk modulus.

Table 2. Test results for oil sand samples at 30°C.

$\Delta\sigma$ (kPa)	SE-09		SE-14		AU-14	
	$\Delta\varepsilon_v$ (%)	K (MPa)	$\Delta\varepsilon_v$ (%)	K (MPa)	$\Delta\varepsilon_v$ (%)	K (MPa)
41.4	1.30	3.18	1.50	2.76	2.18	1.90
69.0	1.65	4.18	1.95	3.54	2.60	2.65
138.0	2.30	6.00	2.80	4.93	3.70	3.73
276.0	3.58	7.71	4.00	6.90	4.90	5.63

$\Delta\sigma$ is hydrostatic stress increment; $\Delta\varepsilon_v$ is volumetric strain increment; K is bulk modulus.

4 STATISTICAL ANALYSES AND MODEL DEVELOPMENT

Statistical regression analyses were performed on the oil sand test results to develop relationships based on power functions for each oil sand sample at 20°C and at 30°C. Figures 5 and 6 show these relationships obtained between bulk moduli and hydrostatic stresses at 20°C and at 30°C, respectively, and the resulting power functions of hydrostatic stress for the three oil sand samples. The significantly high correlation coefficients ($R^2 > 0.97$) for all the three oil sand materials indicate that strong correlations existed between bulk modulus and hydrostatic stress for all the oil sand samples tested at the two temperatures.

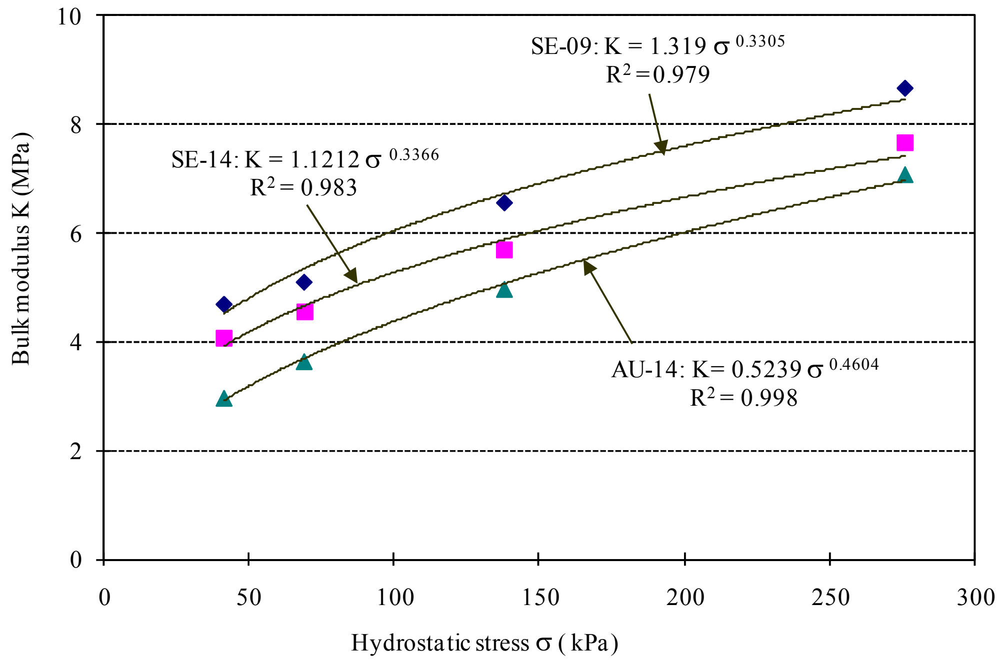

Figure 5. Bulk modulus and hydrostatic stress relationships for oil sands at 20°C.

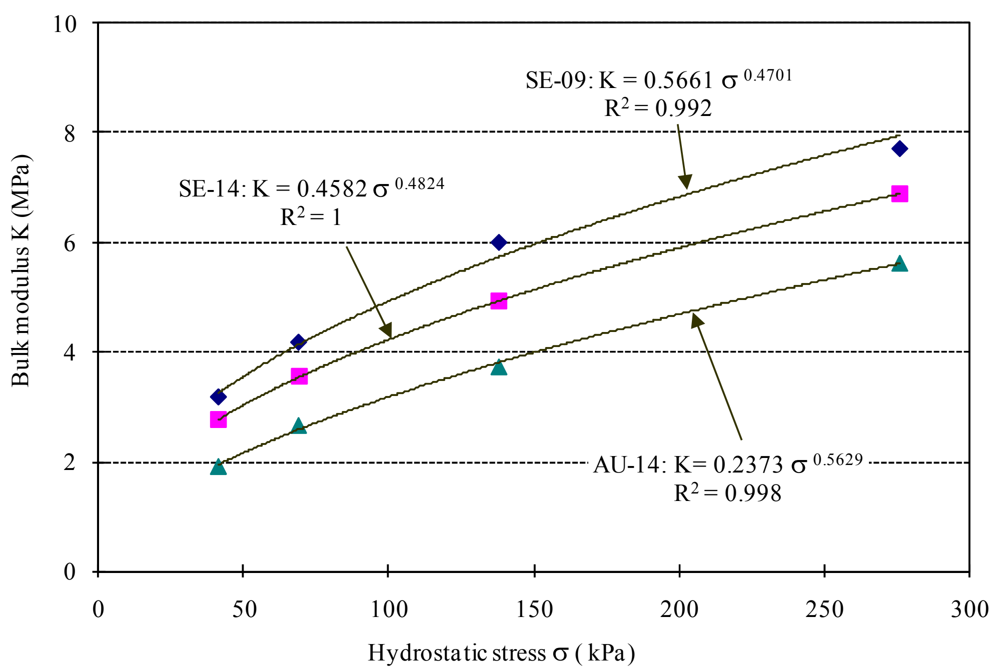

Figure 6. Bulk modulus and hydrostatic stress relationships for oil sands at 30°C.

Bulk modulus of soils and other geomaterials have been successfully used as material constitutive stress-strain properties for numerical analyses such as the finite element analysis. Since the overall objective in this study was to develop practical predictive equations to estimate field volumetric deformation and stiffness behavior of the oil sand materials, the stress-strain data sets obtained from the laboratory testing program were used to develop bulk modulus characterization models to include the loading conditions. A close examination of physical properties of the three oil sands, such as particle size distribution, density, and water content with the assumption of similar bitumen properties suggested that the individual databases of the three oil sand materials could also be combined for analysis. The R-square selection method in the SAS statistical analysis software was first used to ascertain which independent variables were potential candidates for the models. It was found that bulk modulus strongly depended on the hydrostatic compression stress (σ), temperature (T) and bitumen content (w_b). Based on the results, three models were selected to study the volumetric stiffness of oil sand materials. Among other mathematical forms including linear, nonlinear, and hyperbolic, the power function was the most suitable with the correlation coefficients for modeling bulk moduli of the oil sand materials.

Table 3 lists the generalized bulk modulus models developed using the combined test data and gives the model parameters obtained from the SAS stepwise multiple regression analyses. Note that improved models are obtained when temperature (T) and bitumen content (w_b) are included in model 1 although the change in coefficient of correlation (R^2) observed in models 2 and 3 indicates high dependency of bulk modulus on hydrostatic stress. As mentioned earlier, confining stress and shear strength properties have commonly been used to model the elastic modulus of oil sand materials. However, a comprehensive but yet practical model should account for the effects of temperature and bitumen content in the oil sand. High R^2 values obtained for models 2 and 3 indicate that temperature and bitumen content had predominant roles in predicting bulk modulus of oil sand materials. Recall that temperature and bitumen content are important factors that affect field loading behavior of oil sand materials. Model 3 can be proposed for routine use in the estimation field volumetric stiffness or bulk modulus of oil sands.

Next, model 3, which is represented by Equation 2, was used to fit into the individual oil sand test data at 20^{o}C and at 30^{o}C. There is a very good fit overall, for all the three oil sand test data at the two test temperatures (see Figures 7 and 8). Therefore, model 3 can be used for future studies on bulk modulus characterization of oil sand materials. Note that the coefficient representing parameter A in model 3 is proportional to the bulk modulus. Therefore, the value of A should be positive since the bulk modulus cannot be negative. However, parameters k_2 and k_3 in model 3 should be negative since increasing bitumen content and temperature would result in softening of the bituminous sand materials.

$$K = 17.78\,\sigma^{0.44}\, w_b^{-0.59}\, T^{-0.61} \tag{2}$$

Table 3. Bulk modulus characterization models for combined oil sand data.

Model 1: $K = A * \sigma^{k_1}$

Model 2: $K = A * \sigma^{k_1} T^{k_2}$

Model 3: $K = A * \sigma^{k_1} w_b^{k_2} T^{k_3}$

Model	Model Parameters					
	log A	k_1	k_2	k_3	*R^2*	*RMSE*
1	-0.2204	0.4406			***0.690***	*0.096*
2	0.4068	0.4406	-0.5853		***0.821***	*0.075*
3	1.2494	0.4406	-0.5853	-0.6066	***0.926***	*0.049*

σ is hydrostatic stress; T is temperature in degrees Celcius; and w_b is bitumen content.

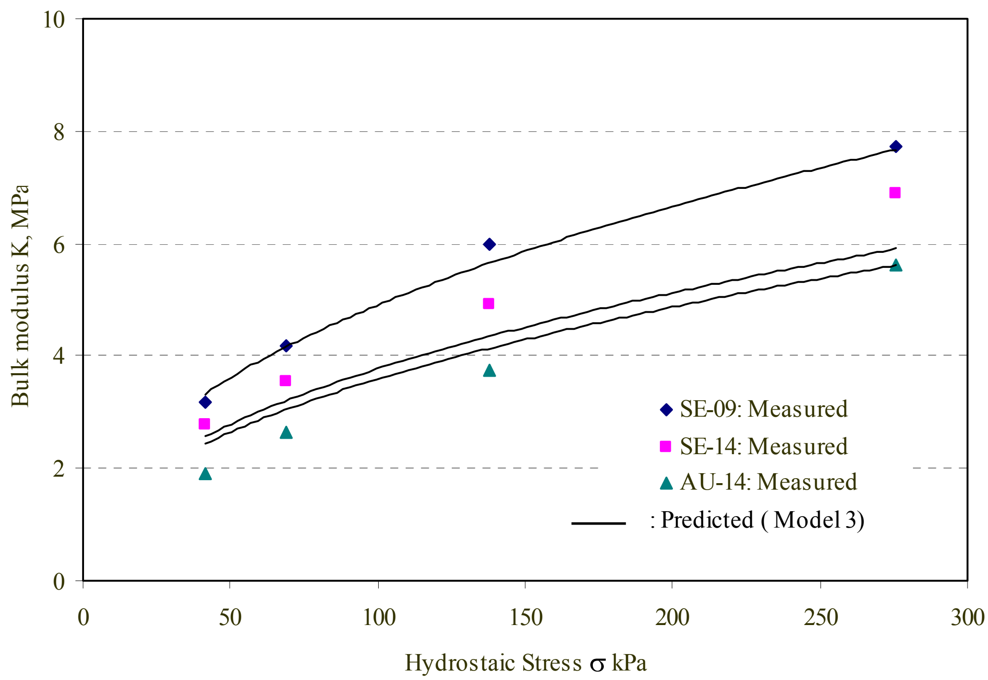

Figure 7. Bulk modulus model 3 performances for oil sand samples at 20^{o}C.

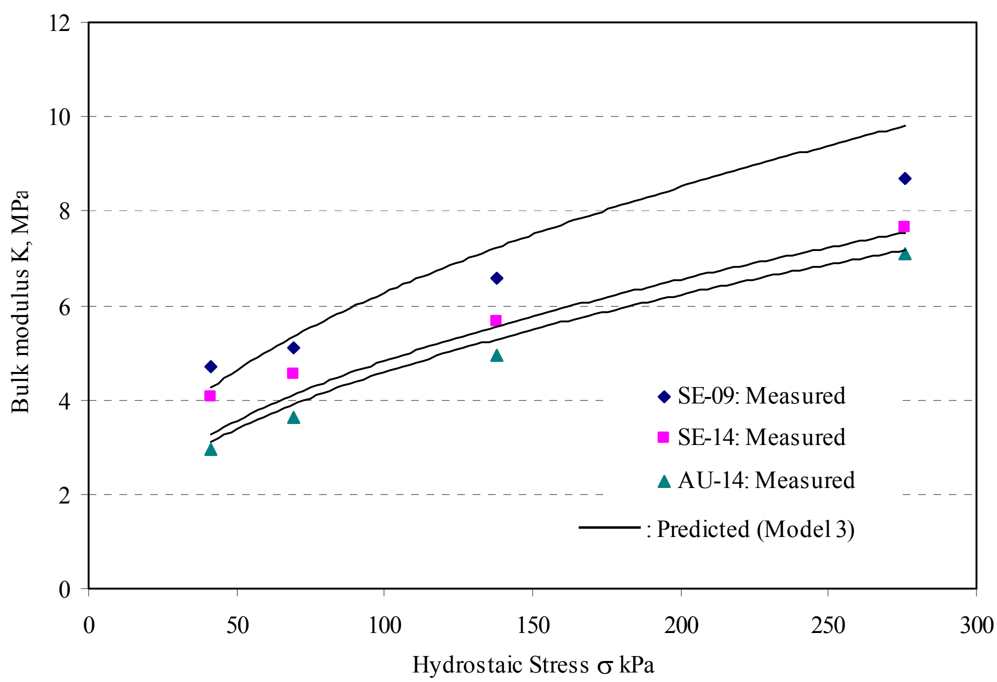

Figure 8. Bulk modulus model 3 performances for oil sand samples at 30^{o}C.

5 SUMMARY AND CONCLUSIONS

The typical 8% to 15% by weight of bitumen or asphalt content in oil sands makes these naturally occurring sands problematic for routine operations of off-road construction and mining 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. However, the volumetric deformation and stiffness behavior of oil sand materials has not been characterized in the laboratory. In this paper, hydrostatic triaxial compression tests were performed in the laboratory to develop bulk modulus models to predict field volumetric deformation and stiffness behavior of oil sand materials.

A newly proposed hydrostatic loading test procedure was used to conduct tests on three types of oil sands with bitumen contents of 8.5%, 13.3% and 14.5% by weight. The test procedure applies low to high hydrostatic (isotropic) stress levels on the specimens at two test temperatures to closely simulate the field loading behavior of the oil sand materials under construction and mining haul trucks and shovels. Bitumen content appears to be a major material property that influenced the overall stiffness of the oil sand materials. The AU-14 sample with bitumen content of 14.5% had the lowest bulk moduli, whereas the SE-09 sample with 8.5% bitumen content gave the highest bulk moduli at the two test temperatures. Also, bulk moduli of the SE-14 sample having a bitumen content of 13.3% were higher than bulk moduli of the AU-14 sample although the average differences in the moduli of the two samples at 20^{o}C and 30^{o}C were comparable.

Based on the test results, bulk modulus characterization models in the form of power functions of the applied hydrostatic stress were established for the oil sand materials using individual test data. A generalized bulk modulus model also developed by combining all the test data from the three oil sands successfully accounted for the applied hydrostatic stress states, test temperatures, and sample bitumen contents. High correlation coefficients obtained for the developed models implied that the models would perform well in the field and could provide essential guidelines for estimating field volumetric deformation and stiffness behavior of oil sand materials.

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