Revised CD-ROM Version **Paper: 08-1907**

Permanent Deformation Behavior of Naturally Occurring Bituminous Sands

Joseph Anochie-Boateng - Graduate Research Assistant
E-mail: anochieb@uiuc.edu
Tel.: (217) 333-1773

Dr. Erol Tutumluer - Associate Professor
(Corresponding Author)
E-mail: tutumlue@uiuc.edu
Tel.: (217) 333-8637

Dr. Samuel H. Carpenter – Emeritus Professor
E-mail: scarpent@uiuc.edu
Tel.: (217) 333-4188

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 N. Mathews Avenue, Urbana, IL 61801, USA
Fax: (217) 333-1924

Accepted for Presentation and Publication
87th Annual Meeting of Transportation Research Board

Words = 4,294; Tables = 4 x 250 = 1,000 words; Figures = 8 x 250 = 2,000 words
Total Word Equivalents = 7,294

ABSTRACT

Oil sand, or tar sand, is a generic name given to bituminous sand deposits that are rich in bitumen or asphalt content to the extent that oil can be extracted from these deposits. The typical 8% to 15% presence of bitumen in the soil composition makes these naturally occurring sands low load-bearing materials. In this study, repeated load triaxial tests were conducted on three types of oil sand materials with natural bitumen contents of 8.5%, 13.3%, and 14.5% by weight. The oil sand specimens were compacted close-to-field densities and then tested for permanent deformation at two temperatures using a newly proposed test procedure, which applied stress states/ratios 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). Both the test data and axial permanent strain models developed in the form of power functions of the number of repeated load applications indicated a strong dependency of oil sand permanent strain development on the applied vertical to horizontal (or major to minor principal) stress ratio. Using all the test data, unified permanent deformation models were developed with high correlation coefficients to account for the applied stress states/ratios, test temperature, and bitumen content. These unified models combined for oil sand deformation behavior may be used as practical predictive equations to estimate amount of rutting in oil sand materials and alleviate potential sinkage problems faced by off-road haul trucks, shovels and other mining equipment in the field.

Keywords: Bituminous/Oil Sands, Permanent Deformation, Repeated Load Triaxial Tests, Bitumen Content, Temperature, Load Pulse Duration, Stress Dependency.

INTRODUCTION

Oil sands, or tar sands are 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 in Canada. The typical 8% to 15% by weight of bitumen or asphalt content in the oil sand composition makes these naturally occurring sands low load-bearing materials for haul trucks, shovels and other mining equipment. Joseph et al. (*1*) observed trucks and shovels operating on these soft materials in summer were faced with sinkage (rutting) and trafficability problems. This is due to the fact that equipment mobility and/or rolling resistance is adversely affected by equipment tire sinkage, which is measured when the wheel is loading the soil as opposed to the permanent deformation or rutting accumulating at an observation point in the soil when the wheel is making a number of passes (*2*).

The modulus and deformation behavior of oil sands is primarily dependent upon the applied load magnitude (wheel load in the field), rate of loading or frequency, and number of load applications (*3*). Field plate load tests indicated that as the number of load applications or truck passes increased, the total deformations in oil sand increased and the stiffness decreased (*3*). The oil sands exhibit stress-softening behavior, which is typically observed instead in fine-grained type silty or clayey soils. The composition governed by the fluid content (bitumen + water), grain size and physical properties as well as the type of applied loading, i.e., static and/or dynamic, and nature of stresses acting upon them primarily dictate the behavior. The cyclic tests produced lower peak stresses than the static ones making a static correlation invalid and thus necessitating a cyclic evaluation under field conditions (*3*).

It is recognized that the considerable amount of bitumen in the oil sands, high applied loads from the mining equipment and seasonal changes in temperature are major factors that control deformation behavior of oil sands. To date, no comprehensive laboratory testing has been found to discuss the individual effects of these factors on permanent deformation behavior. Instead, research on oil sands has traditionally been focused on obtaining laboratory stress-strain test data to describe shear strength and elastic behavior of oil sands (*4-9*). Based on the data collected in these studies, confining pressure, peak stress or strain, friction angle and cohesion are the material properties used for modeling the strength and elastic behavior. Recent field studies on oil sand and equipment interaction also resulted in a proposed model in which oil sand stiffness was defined as a function of ground deformation (*6*). To properly characterize behavior of these bituminous sands, laboratory tests should closely simulate field densities and loading conditions and adequately address the actual time and temperature dependent plastic deformation accumulation under dynamic, repeatedly applied wheel loading conditions.

The majority of permanent deformation behavior models for geomaterials are based on the applied stress states and the number of load repetitions (*10-13)*. Recently, it has been shown from laboratory studies that load pulse duration or frequency of loading linked to field trafficking speeds also has a significant influence on the permanent deformation accumulation in geomaterials (*12,13*). Studies on rutting potential of paving and bituminous base mixes in general indicate that permanent deformation is closely related to asphalt content (*14,15*). Vehicular loading characteristics are one of the major factors affecting permanent deformation in the field (*16*). The field loading characteristics of large capacity mining equipment is a major factor that could affect permanent deformation behavior of oil sands due to the large nominal payloads and high tire pressures. For instance, Joseph (*3*) 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 3.20. He 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 (*3*). Properly simulating such field loading conditions in laboratory testing and developing prediction models for the oil sand permanent deformation behavior would help better understand mobility and equipment sinkage related problems for a smoother operation.

A new repeated load triaxial test procedure is proposed in this paper to characterize the permanent deformation behavior of oil sand materials in the laboratory. The test procedure is based on realistic field loading conditions of the oil sand materials. The experimental program carried out on three types of oil sands with varying bitumen contents focused on conducting permanent deformation tests under simulated close-to-field densities and applied stress states/ratios at two different load pulse durations (or loading frequencies) and two temperatures. Based on the laboratory test data, permanent (plastic) deformation models are developed for each oil sand material and their performances are checked with additional replicate test results to consider even a larger number of load applications. Using all the test data for the three oil sands, unified permanent deformation or sinkage models are also developed to include applied stress states/ratios, bitumen content, and temperature variables in the predictive equations.

OIL SAND MATERIALS AND EXPERIMENTAL PROGRAM

Materials Tested and Properties

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. Suncor Energy Inc. provided two types, SE 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. All the three oil sand materials were shipped to the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL) in separate barrels for the laboratory tests.

The oil sand materials were initially tested for bitumen and water contents using AASHTO T 308 and AASHTO T 265 test procedures, respectively (*17*). 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. After separating bitumen from the oil sands through burning in the oven, washed sieve analysis tests were conducted on the sand ingredients to determine particle size distributions of the three oil sands using AASHTO T 27 (*17*). Figure 1 shows the gradation test results. All the three oil sand samples are 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%. Similar grain size distributions for oil sand materials were reported by Cameron and Lord (*18*).

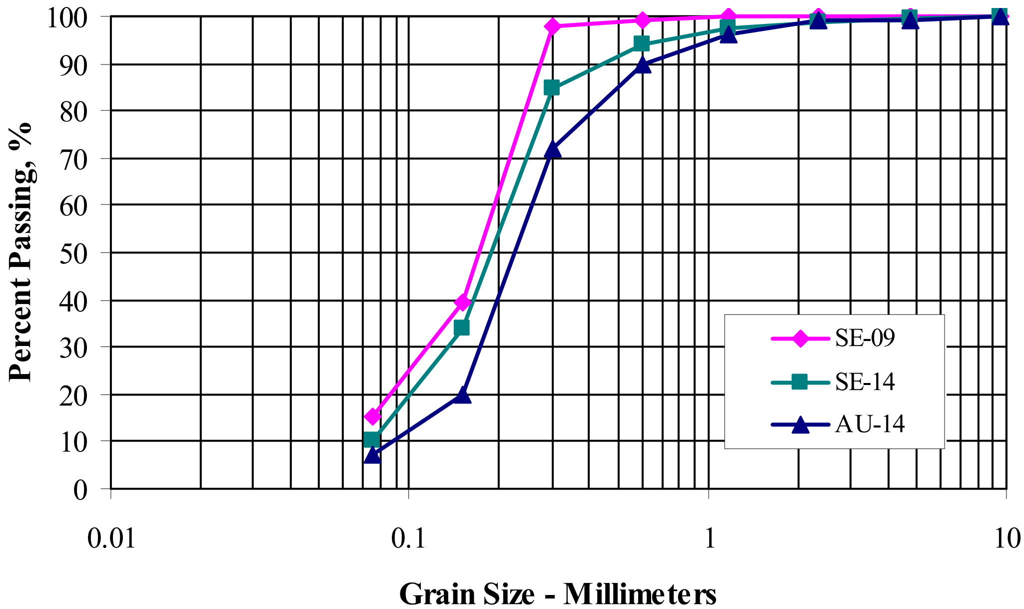


FIGURE 1 Particle Size Distributions of Oil Sand Samples

Field density levels and compaction properties of the oil sands were next studied in the laboratory using a gyratory compaction device. The number of gyrations to reach the specific 150-mm specimen height and the actual bulk (wet) density to achieve this height were recorded for the preparation of permanent deformation test specimens. During compaction, changes in bulk (wet) density of the specimen were recorded. Figure 2 shows the bulk density levels varying with number of gyrations for the three oil sand materials. A considerably higher number of gyrations was needed to compact the lower bitumen content SE-09 oil sand (see Figure 2) when compared to the higher grade ones. The typical bulk densities achieved 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 were very close to field values reported by Joseph (*2*) and computed from the following equations:

$$\text{Dry density (kg/m}^3\text{)} = 2{,}150 - 37*(\text{\% bitumen content}) \quad (1a)$$

$$\text{Bulk density (kg/m}^3\text{)} = 804 + 0.7*(\text{dry density in kg/m}^3) \quad (1b)$$

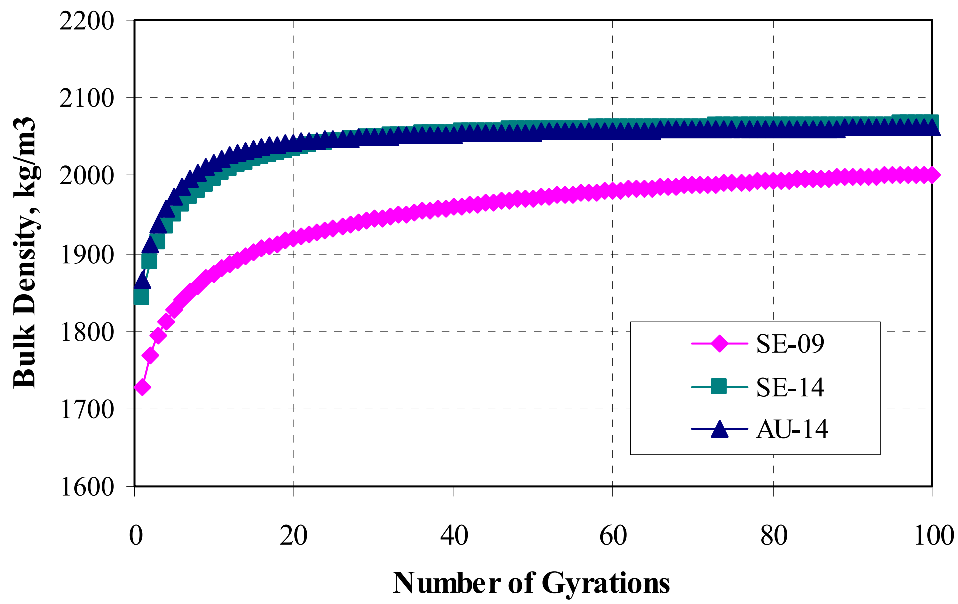


FIGURE 2 Gyratory Compaction Properties of Oil Sand Samples

Specimen Preparation

An Industrial Process Controls (IPC), Ltd. Servopac gyratory compactor available at the University of Illinois ATREL was used to produce 150 mm in diameter by 150 mm high (approximately 6 in. in diameter by 6 in. high) cylindrical specimens. The amount of oil sand material required to achieve the expected density was determined from the compaction process which continued until the target height (150 mm or approximately 6 in.) of the specimen was obtained. Following compaction, specimens were conditioned at the desired temperatures for a minimum of 6 hours using a temperature chamber, and placed in 0.6-mm (0.025-in.) thick latex membrane for testing. Figure 3 shows one of the oil sand samples in loose and compacted states.

(a) Oil Sand Sample in Natural State

(b) Gyratory Compacted Specimens

FIGURE 3 Naturally Occurring Oil Sand Sample and Gyratory Compacted Specimens

Test Procedure and Laboratory Testing

The new repeated load triaxial test procedure developed for oil sand testing was similar to the current AASHTO T307 test procedure used for determining resilient modulus of soils and aggregate materials, referred to herein as geomaterials (*17*). However, from the initial conditioning stage of the T307 test procedure, permanent deformation properties of granular materials are often obtained at only one stress state using equal confining and deviator stresses of 103.5 kPa (15 psi), or a total vertical stress (σ_1) to horizontal confining stress (σ_3) ratio of 2. A haversine load pulse with 0.1-second loading and 0.9-second rest period is applied on the specimen for 1,000 load cycles. Thus, the AASHTO T307 test procedure is limited in terms of applied stress states. In this study, the newly proposed test procedure based on the field loading characteristics of the haul trucks and mining equipment for oil sands considers stress ratios ranging from 1.15 to as high as 7.67 and total vertical stresses (σ_1) as high as 552 kPa (80 psi) (see Table 1). Joseph (*3*) reports that oil sands experience extreme temperatures of +40^{o}C in summer and -40^{o}C in winter to make them more problematic to mining equipment during summer or warmer months than in winter. He observed that oil sands became soft at an ambient temperature of 28^{o}C. In this study, permanent deformation tests were accordingly conducted at two temperatures, 20 degrees Celsius (68^{o}F) and 30 degrees Celsius (86^{o}F), to account for spring and hotter summer periods, respectively. Further, two different haversine load pulse durations of 0.1 and 0.5 seconds were also included in the laboratory testing program to consider the effects of different trafficking speeds of haul trucks and other mining equipment on the oil sand sinkage and rut development in the field.

An innovative cyclic/repeated load triaxial testing device at ATREL, the University of Illinois advanced triaxial cell (UI-FastCell) integrated with IPC Universal Testing Machine (UTM) loading device, was used for applying stresses on the specimen (see Figure 4). The UI-FastCell has unique capabilities of simulating various dynamic field loading conditions in the laboratory (*19*). During testing, gyratory compacted oil sand specimens were subjected to different applied stress states and σ_1/σ_3 stress ratios as listed in Table 1. Each deviator stress σ_d (= σ_1-σ_3) and constant confining stress σ_3 pair was applied on one specimen with the deviator stress repeatedly pulsed in the vertical direction for a total of 1,000 load cycles except for the replicate tests, which were performed at σ_d = 138 kPa (20 psi) and σ_3 = 138 kPa (20 psi) only for a total of 10,000 load cycles and later used to check permanent deformation model performances. The specimen's vertical displacement was determined by averaging readings of the two axial linear vertical displacement transducers (LVDTs). Permanent deformations (δ_p) were recorded for each cycle and the corresponding plastic strains (ε_p) were computed. A total of 36 tests were designed for each type of bituminous sand material, i.e., SE-09, SE-14, and AU-14, to establish a full factorial test matrix. That is, nine applied stress states with the σ_1 to σ_3 stress ratios listed in Table 1 were repeated at two temperatures, 20 degrees Celsius (68^{o}F) and 30 degrees Celsius (86^{o}F), and two load pulse durations of 0.1 and 0.5 seconds with 0.9- and 0.5-second rest periods, respectively.

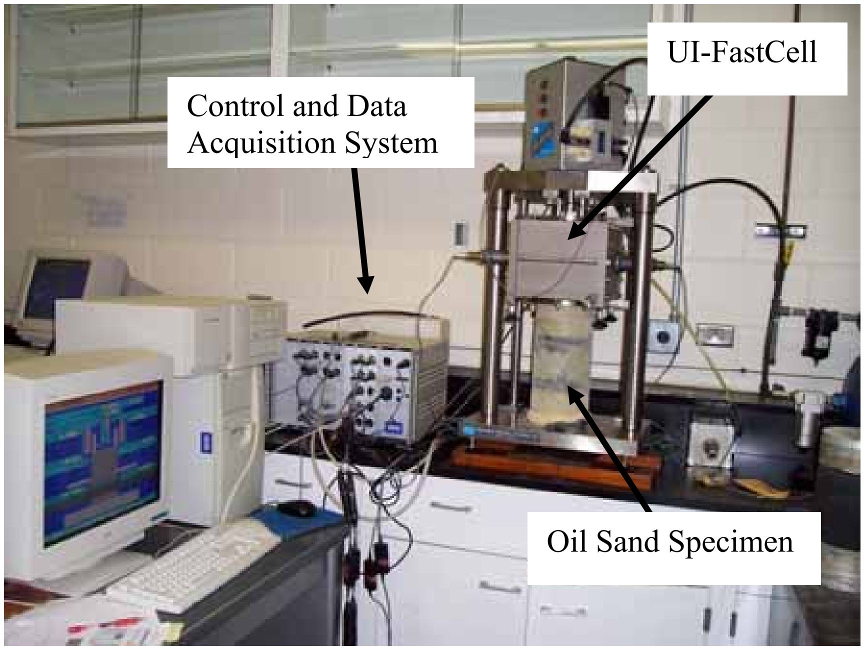


FIGURE 4 UI-FastCell Advanced Triaxial Test Setup Showing an Oil Sand Specimen

ANALYSIS OF TEST RESULTS

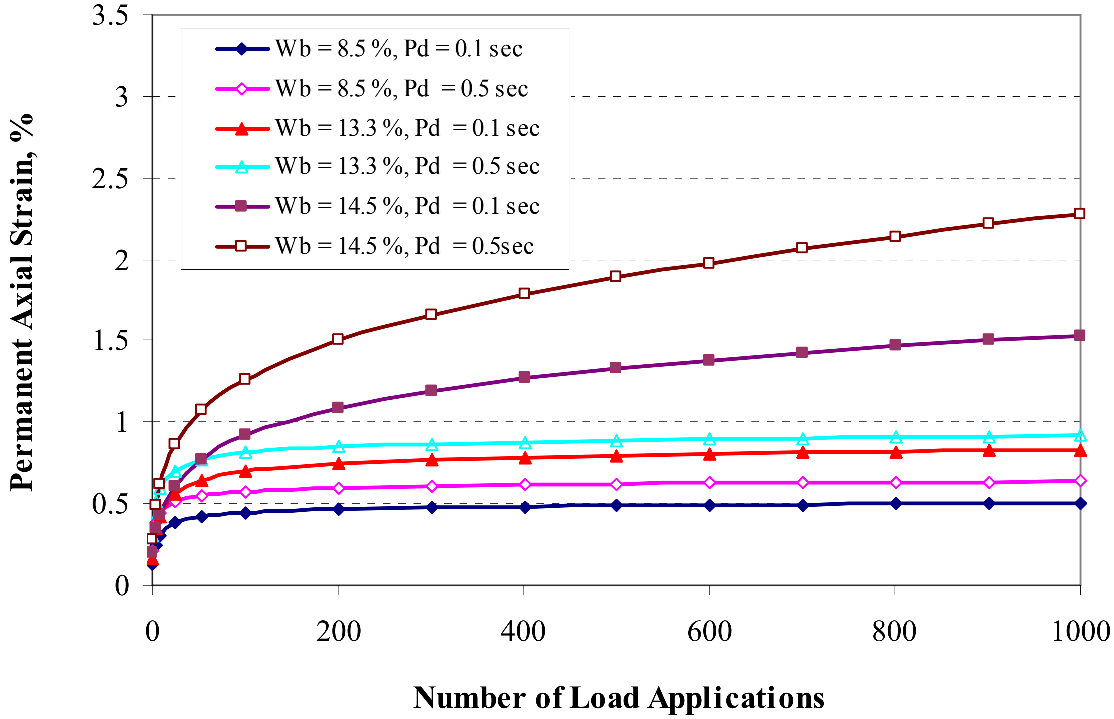
Permanent deformation test data obtained for all three oil sand materials showed that permanent strains typically accumulated as power functions with increasing number of load applications. Figures 5a and 5b show the permanent strain accumulations for the three oil sand samples recorded at the applied confining stress of 41.4 kPa (6 psi) and deviator stress of 138 kPa (20 psi) for σ_1/σ_3 = 4.33. As expected, higher permanent deformations accumulated at 30°C when compared to the results at 20°C. Similar trends of higher permanent deformation accumulations were observed for the higher grade SE-14 with 13.3% bitumen content (W_b) when compared to SE-09 results and for the tests conducted with the longer 0.5-second load pulse duration (P_d). In regard to load pulse duration effects on permanent deformation, these ε_p test results were in very good agreement with the test data on granular base materials reported earlier by Kim and Tutumluer (*16*). As shown in Figures 5a and 5b, the AU-14 sample (W_b = 14.5%) had the highest permanent strain accumulations, followed by the SE-14 sample (W_b = 13.3%), and the SE-09 sample (W_b = 8.5%) had the smallest strains. These laboratory findings also agree very well with the observed field behavior of oil sand materials (*3*). It should be noted that rheological properties of bitumen in the oil sands were not considered in detail. However, because the three oil sands samples were obtained from the same deposit, it can reasonably be assumed that the rheological properties should be similar. Further, no information was found from the most recent field study conducted on these oil sand materials in relation to the rheological properties of the bitumen (*3*).

TABLE 1 Applied Stress States in the Oil Sand Permanent Deformation Test Procedure

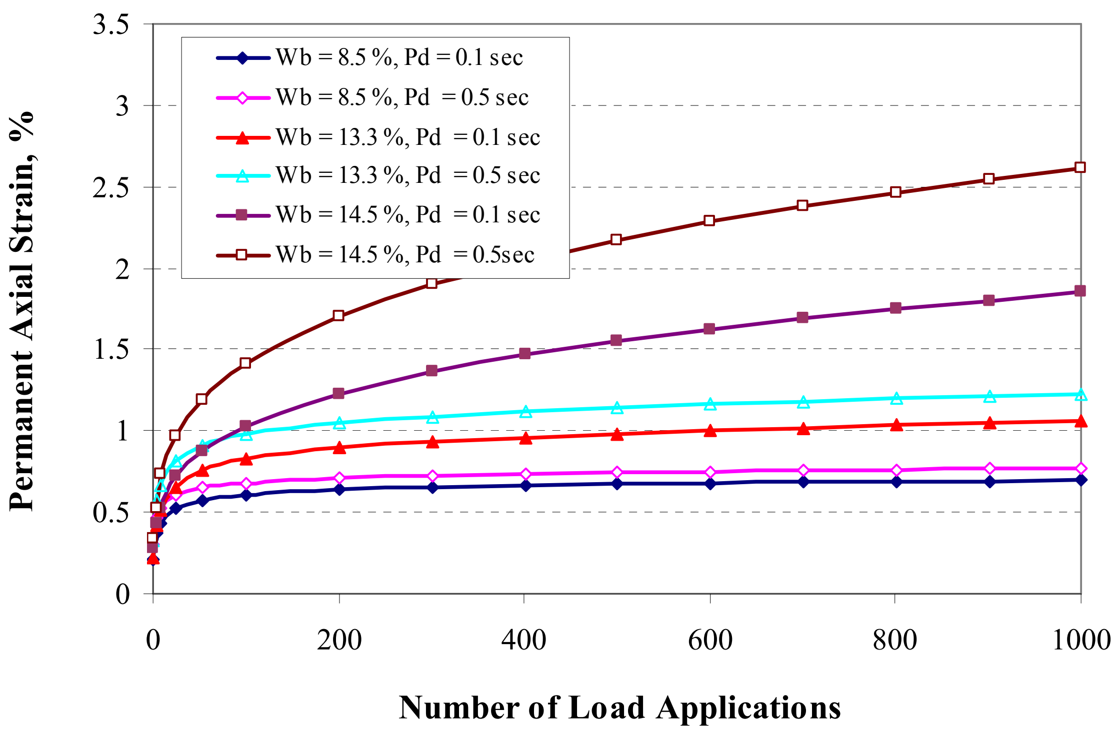
Specimen Number	Stress States[a] (kPa)			Stress Ratio
	Confining Stress (σ_3)	Deviator Stress (σ_d)	Total Vertical Stress (σ_1)	(σ_1/ σ_3)
1	41.4	41.4	82.8	2.00
2	41.4	138	179.4	4.33
3[b]	41.4	276	317.4	7.67
4	138	41.4	179.4	1.30
5	138	138	276	2.00
6	138	276	414	3.00
7	276	41.4	317.4	1.15
8	276	138	414	1.50
9	276	276	552	2.00

[a]: 1 psi = 6.89 kPa

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



(a)

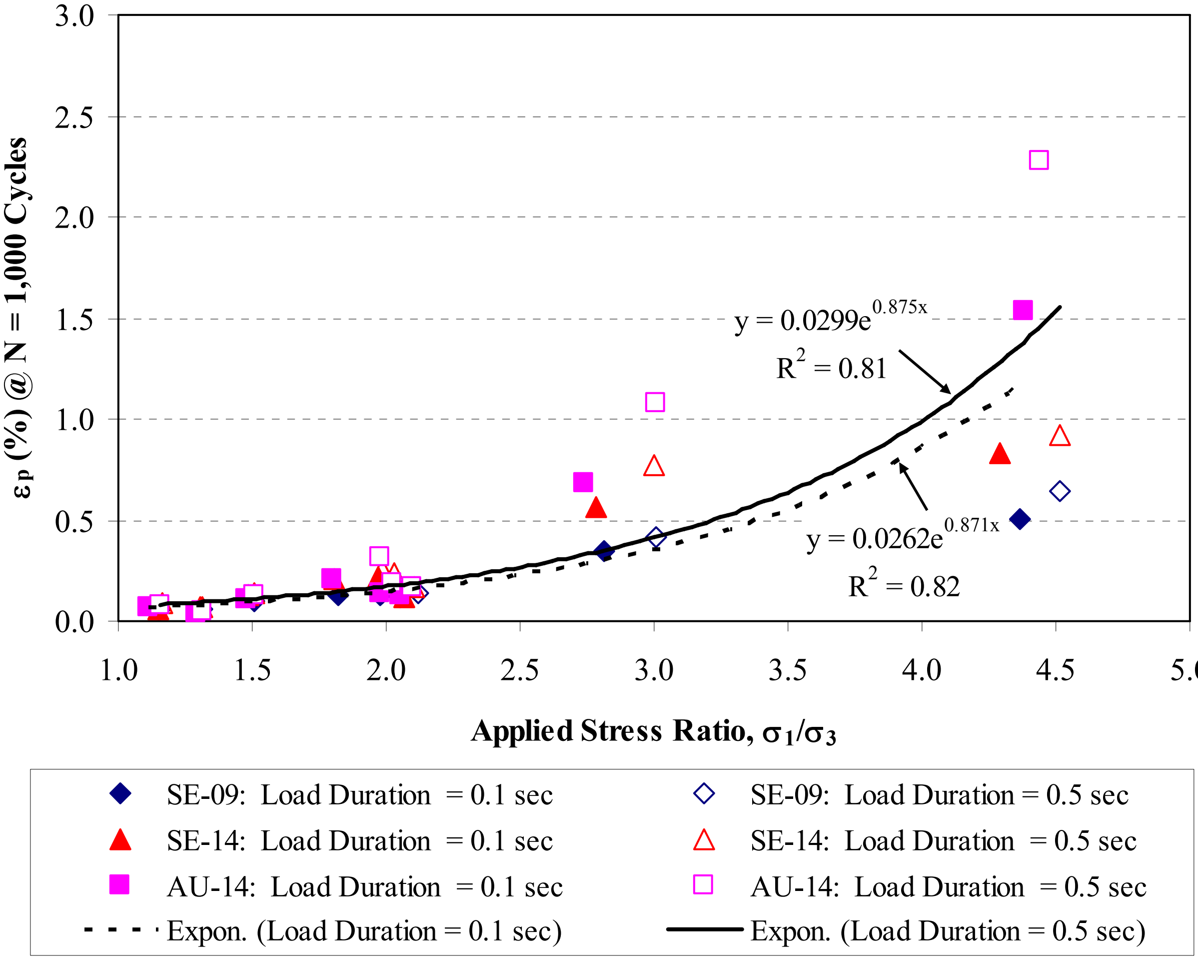


(b)

FIGURE 5 Permanent Axial Strain Accumulations at σ_3 = 41.4 kPa, σ_d = 138 kPa: (a) Temperature = 20°C and (b) Temperature = 30°C (1 psi = 6.89 kPa)

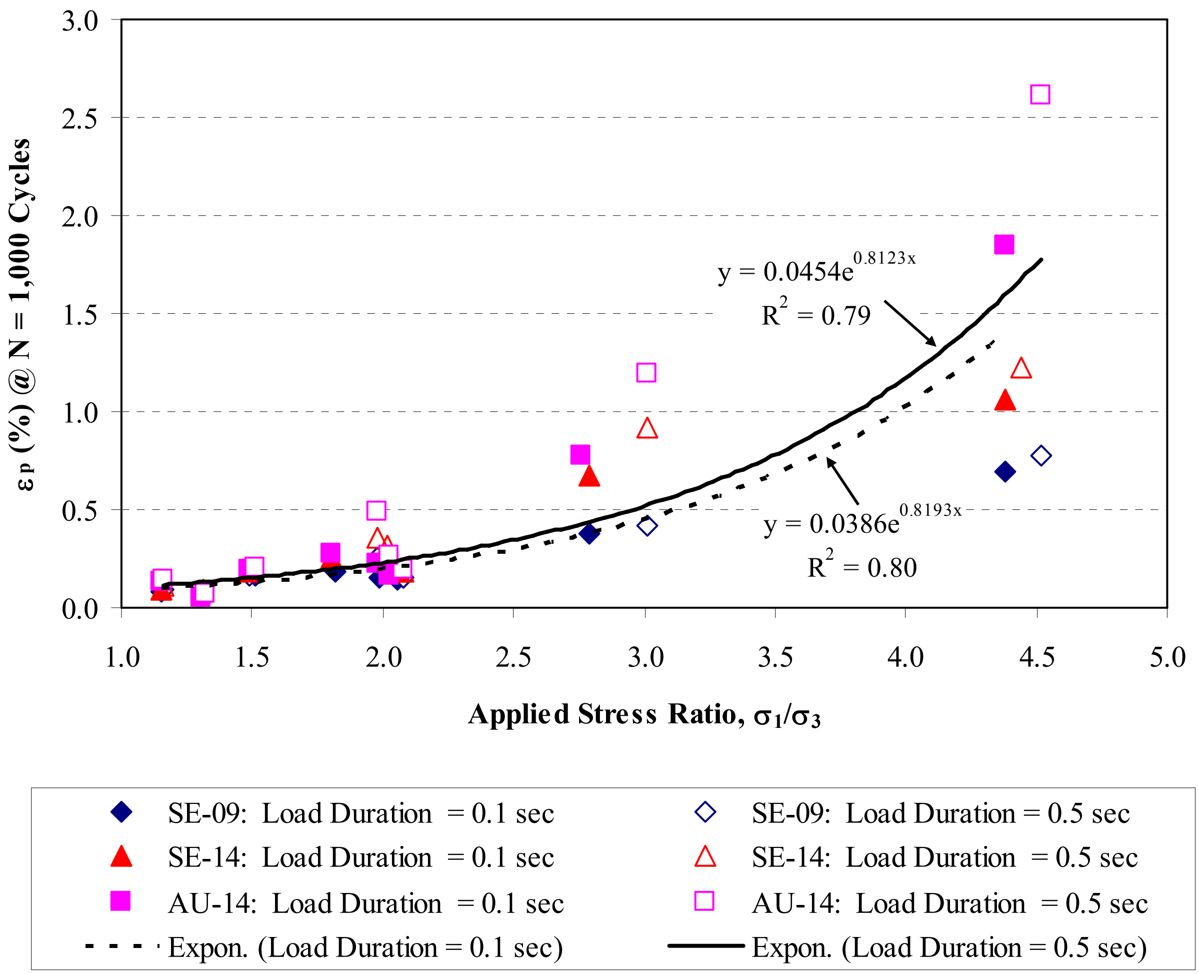
Effects of applied stress levels on permanent deformation were further investigated for the three oil sand materials tested at different load pulse durations and temperatures. Figures 6a and 6b show permanent strains recorded at the 1,000th load cycle (@ N=1,000 cycles) graphed with the applied stress ratios for the test temperatures of 20^oC and 30^oC, respectively. Note that 1,000th load cycle permanent strains are generally higher at 30^oC than at 20^oC. A similar situation was reported from the field studies, where oil sands experienced higher permanent deformations under heavy mining equipment during summer than winter seasons (*6*). At low stress ratios, i.e., $\sigma_1/\sigma_3 < 2.00$, there was a gradual accumulation of permanent strain in the oil sand samples compared with the significantly higher accumulations when the stress ratio was greater than 2.00 (see Figure 6). It appears that there is no significant difference in permanent strains between the two load pulse durations, and between the three oil sand materials when the stress ratio is below 2. However, for stress ratios greater than 2.00 ($\sigma_1/\sigma_3 = 7.67$ in Table 1 could not be applied since specimens did not survive this high stress ratio), the effect of stress ratio on permanent strain accumulation becomes quite significant. There is a clear difference in the trend lines of permanent strain accumulation between the two load pulse durations (P_d = 0.5 seconds and 0.1 seconds) supported by the exponential curve-fitting in the combined test data. A large scatter is observed in the test data especially at high stress ratios. This was due to the increased noise and fluctuations at the applied high deviator and low confining stresses. Overall, the permanent strains in the AU-14 sample were significantly higher at the large stress ratios than those of the SE samples. At a stress ratio of 4.33, the 1,000th load cycle permanent strains in AU-14 were found to be about 1.8 to 2.5 times higher than those of the SE-14, and 3.0 to 3.5 times higher than those of the SE-09 for the two test temperatures. Whereas at a stress ratio of 3.0, permanent strains in AU-14 were found to be in the range of 1.2 to 1.4 times higher than those of the SE-14 and 2 to 2.8 times higher than those of the SE-09.

There are significant effects of applied stresses, especially the stress ratios, and the bitumen content on the permanent deformation behavior of naturally occurring bituminous sands. The amount of bitumen content appears to be the main factor that differentiates between the observed permanent deformation trends for the oil sands. The SE-09 sample, with the lowest bitumen content, had the lowest permanent strain accumulation, whereas AU-14 sample with the highest bitumen content generally had the highest accumulation of permanent strain.



(a)

FIGURE 6 Permanent Axial Strains Recorded at the 1,000th Load Cycle as a Function of Applied Stress Ratios: (a) Temperature = 20^{o}C and (b) Temperature = 30^{o}C



(b)

FIGURE 6 Permanent Axial Strains Recorded at the 1,000th Load Cycle as a Function of Applied Stress Ratios: (a) Temperature = 20°C and (b) Temperature = 30°C

Permanent Deformation Model Development

A total of 32 test results corresponding to 32 different applied stress states (see Table 1 with the exception of σ_1/σ_3 = 7.67) were obtained from the experimental program for each oil sand material at two temperatures and two load pulse durations. Overall, 96 test results were therefore obtained for the three oil sands. A single test data set consisted of about 250 stress-strain data sets giving 8,000 data points for each material and therefore 24,000 data points altogether.

The phenomenological power model, expressed by ε_p (%) = $A*N^B$, was used to evaluate the permanent strain accumulation of the oil sand materials with number of load applications N. Statistical regression analyses were performed using this power model to obtain the model parameters A and B. Tables 2 and 3 list in summary format the model parameters obtained for individual tests conducted at 20°C and 30°C, respectively. The power model adequately predicted the permanent strain accumulations from individual tests as observed from the generally high correlation coefficients (R^2 values) also given in Tables 2 and 3. The model parameters A and B were next investigated to identify their dependence on the applied stress states, temperature, load pulse duration, and bitumen content. The parameter A accounts for the permanent strain accumulated at the first load cycle and parameter B describes the rate (slope) of permanent strain accumulation when logarithm of ε_p is plotted against logarithm of N to give in a linear relationship (*16*). As indicated in Tables 2 and 3, parameter A generally increased with increasing deviator stresses, thus indicating higher immediate permanent strain (or sinkage) development under heavier wheel loading, whereas parameter B had a slight decreasing trend not affecting notably the rate of permanent strain accumulation with increasing load applications.

TABLE 2 Permanent Deformation ε_p=A*N^B **Model Parameters – Test Temperature=20°C**

Applied Stress (kPa)		Load Duration = 0.5 sec			Applied Stress (kPa)		Load Duration = 0.1 sec		
σ_3	σ_d	A (%)	B	R^2	σ_3	σ_d	A (%)	B	R^2
Suncor Energy Low Grade Oil Sand Sample (SE-09)									
39.8	44.7	0.0695	0.0999	0.905	40.4	42.5	0.0461	0.1462	0.958
40.4	141.9	0.3881	0.0754	0.743	40.4	135.9	0.2720	0.0940	0.714
139.3	43.6	0.0148	0.2023	0.997	138.8	42.0	0.0123	0.2179	0.996
139.3	143.0	0.0957	0.0885	0.944	138.8	135.3	0.0850	0.0863	0.921
138.8	278.4	0.2796	0.0578	0.791	138.2	250.8	0.1934	0.0870	0.871
278.0	44.2	0.0216	0.1537	0.989	279.1	42.0	0.0116	0.2409	0.982
278.6	135.9	0.0407	0.1712	0.979	278.6	140.8	0.0245	0.2085	0.994
278.0	272.8	0.0527	0.1424	0.919	278.0	229.2	0.0417	0.1706	0.930
Suncor Energy High Grade Oil Sand Sample (SE-14)									
40.4	44.7	0.0756	0.1173	0.933	40.4	43.1	0.0327	0.1939	0.962
40.4	141.9	0.5224	0.0856	0.804	40.9	134.8	0.3597	0.1276	0.807
138.2	43.6	0.0227	0.1685	0.997	138.2	42.5	0.0155	0.2149	0.997
138.2	141.9	0.1312	0.0811	0.937	138.8	134.8	0.1126	0.1017	0.949
138.8	277.9	0.4656	0.0765	0.825	138.8	247.5	0.3088	0.0919	0.804
278.0	44.7	0.0240	0.1955	0.941	278.6	41.4	0.0123	0.2397	0.936
278.6	141.4	0.0402	0.1834	0.854	278.0	135.9	0.0229	0.2493	0.995
278.0	272.8	0.1137	0.1233	0.839	277.5	223.7	0.0657	0.1694	0.966
Aurora High Grade Oil Sand Sample (AU-14)									
40.4	44.2	0.0735	0.1227	0.914	40.4	42.5	0.0327	0.2075	0.889
40.9	140.8	0.3576	0.2683	0.994	40.4	136.4	0.2706	0.2554	0.984
138.8	43.6	0.0161	0.1585	0.979	138.8	40.9	0.0079	0.2221	0.996
138.8	141.9	0.0948	0.1045	0.928	138.8	135.3	0.0783	0.1277	0.946
138.5	278.4	0.4425	0.1333	0.931	138.2	240.8	0.2406	0.1553	0.922
278.6	43.6	0.0167	0.2168	0.998	278.6	30.4	0.0085	0.3024	0.998
278.6	140.8	0.0513	0.1389	0.985	278.6	133.1	0.0226	0.2238	0.997
278.6	272.8	0.1535	0.1060	0.967	278.6	222.1	0.0846	0.1347	0.938

TABLE 3 Permanent Deformation ε_p=A*N^B Model Parameters – Test Temperature=30^{o}C

Applied Stress (kPa)		Load Duration = 0.5 sec			Applied Stress (kPa)		Load Duration = 0.1 sec		
σ_3	σ_d	A (%)	B	R^2	σ_3	σ_d	A (%)	B	R^2
Suncor Energy Low Grade Oil Sand Sample (SE-09)									
40.4	43.6	0.0706	0.1127	0.961	40.4	42.5	0.0632	0.1252	0.962
40.4	141.9	0.4648	0.0759	0.849	40.4	136.4	0.3797	0.0919	0.813
138.2	43.6	0.0175	0.2057	0.998	138.2	42.5	0.0126	0.2296	0.997
138.8	141.4	0.1036	0.1024	0.962	138.2	135.9	0.0983	0.0954	0.935
138.8	279.0	0.2577	0.0727	0.881	138.8	248.6	0.2248	0.0784	0.808
278.0	44.7	0.0178	0.2502	0.978	278.6	42.5	0.0103	0.2995	0.950
278.0	137.0	0.0553	0.1629	0.963	278.0	142.5	0.0538	0.1598	0.976
278.6	271.7	0.1218	0.1075	0.944	277.5	227.0	0.0631	0.1615	0.937
Suncor Energy High Grade Oil Sand Sample (SE-14)									
40.4	43.6	0.0849	0.1176	0.961	40.4	43.1	0.0688	0.1453	0.953
40.9	140.8	0.5299	0.1241	0.918	40.4	136.4	0.4049	0.1432	0.908
138.2	43.6	0.0225	0.1979	0.998	138.2	43.1	0.0187	0.2180	0.997
138.8	141.4	0.1631	0.0974	0.944	138.2	137.0	0.1285	0.0969	0.928
138.2	278.4	0.4786	0.0972	0.932	138.2	247.5	0.3303	0.1060	0.920
278.0	44.2	0.0229	0.2331	0.979	278.0	42.5	0.0144	0.2663	0.967
278.0	141.4	0.0671	0.1547	0.972	278.0	135.9	0.0553	0.1767	0.970
278.6	272.3	0.1578	0.1191	0.961	278.0	224.3	0.0767	0.1794	0.946
Aurora High Grade Oil Sand Sample (AU-14)									
40.4	43.6	0.0895	0.1116	0.958	40.9	42.0	0.0592	0.1546	0.939
40.4	141.9	0.3930	0.2752	0.998	40.4	136.4	0.3061	0.2612	0.999
138.2	44.2	0.0204	0.1888	0.995	138.2	42.2	0.0128	0.1902	0.995
138.8	141.9	0.1316	0.1059	0.968	138.2	135.3	0.1059	0.1102	0.974
138.8	279.0	0.4525	0.1434	0.963	138.2	243.6	0.3019	0.1418	0.888
278.0	44.2	0.0268	0.2512	0.978	278.0	43.1	0.0195	0.2798	0.993
278.0	141.9	0.0650	0.1714	0.978	278.6	135.3	0.0547	0.1855	0.977
278.0	272.8	0.2047	0.1289	0.960	277.5	222.6	0.0769	0.1949	0.952

To better evaluate the main factors controlling permanent deformation behavior of the oil sand materials, simple correlation analyses were conducted to establish those noteworthy dependencies between the model parameters A and B and the applied stress states. Equations 2a to 2e and Figure 7 summarize the correlation results between the model parameters and the applied stress levels including the entire database of all oil sand material test results. Parameter A in the power model ε_p=A*N^B is in general known to be primarily a function of applied stress states whereas B largely depends on the soil or geomaterial type (*20, 21*). As shown in Figure 7, the strongest correlation obtained for parameter A was with the applied stress ratios (σ_1/σ_3) giving a high correlation coefficient of $R^2 = 0.84$. This indicates that parameter A is a function of stress ratios and its values increased exponentially with the increasing σ_1/σ_3 ratios. High stress ratios would induce large permanent deformation in the oil sand materials, especially at the initial load application. A relatively strong correlation was also obtained between parameter A and the applied deviator stress but not with the confining stress σ_3 (see Equations 2a and 2b). On the other hand, weaker correlations were typically found between parameter B and the applied stress levels (see Equations 2c-2e) indicating that applied stresses had little effect on parameter B. These are all in agreement with others who reported in general that confining stress had little impact on parameter A, and the applied stress states did not influence much the B parameter (*20, 21, and 22*).

$$A = 0.0003\,\sigma_d^{1.1666} \quad ; \quad R^2 = 0.53 \tag{2a}$$

$$A = 2.0719\,\sigma_3^{-0.6857} \quad ; \quad R^2 = 0.19 \tag{2b}$$

$$B = 0.2075 \cdot \left(\sigma_1 / \sigma_3 \right)^{-0.5034} \quad ; \quad R^2 = 0.28 \tag{2c}$$

$$B = 0.5177\,\sigma_d^{-0.2705} \quad ; \quad R^2 = 0.26 \tag{2d}$$

$$B = 0.0726\,\sigma_3^{0.1451} \quad ; \quad R^2 = 0.08 \tag{2e}$$

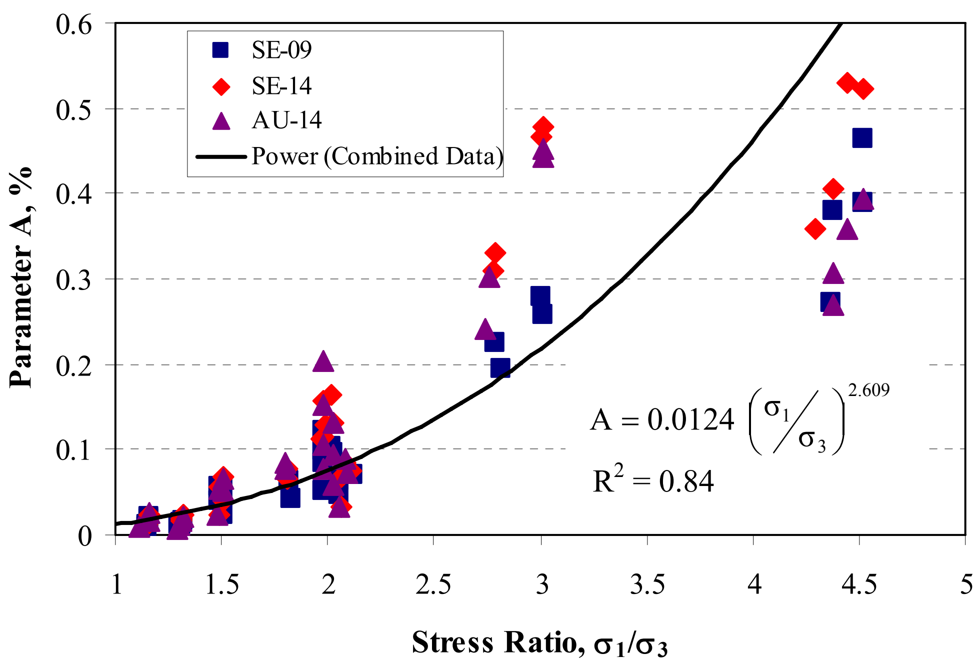


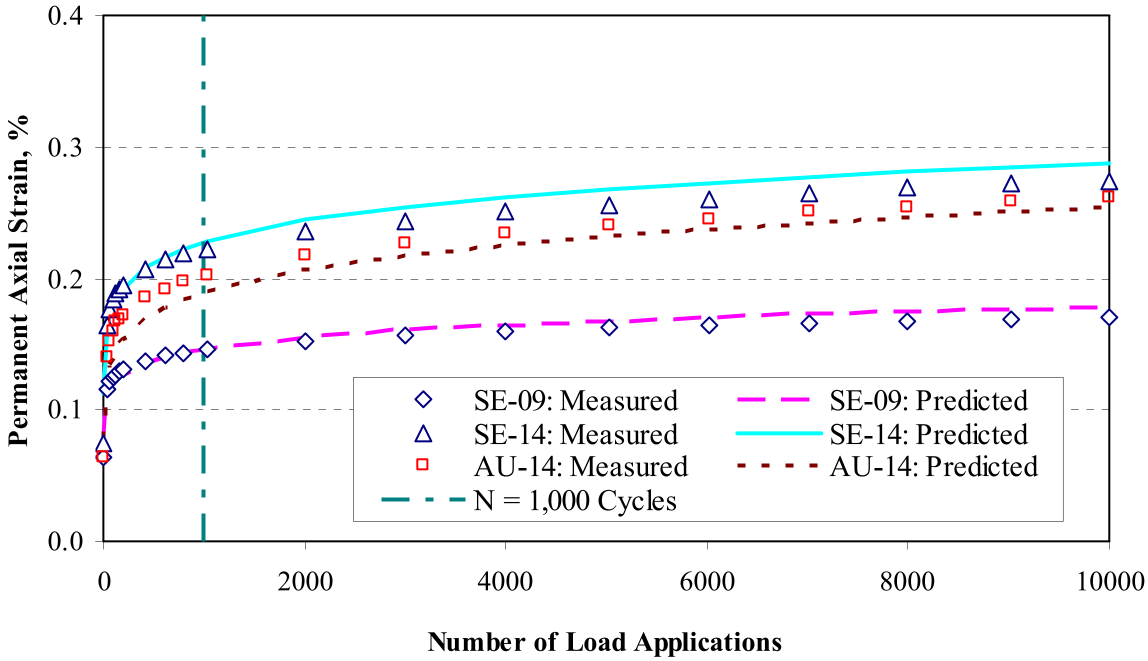
FIGURE 7 Model Parameter A as a Function of Applied Stress Ratio, σ_1/σ_3

No significantly strong or noteworthy correlations, such as shown in Figure 7 for parameter A, were obtained individually between parameters A and B and the other test variables, i.e., test temperature, load pulse duration and bitumen content. Detailed statistical analyses conducted using the SAS software package, however, indicated that parameter B had somewhat stronger correlations with bitumen content and load pulse duration than parameter A. On the other hand, parameter A could be more significantly linked to test temperature than parameter B suggesting that temperature, in relation to the applied stress states, could influence oil sand permanent deformation at the initial load application.

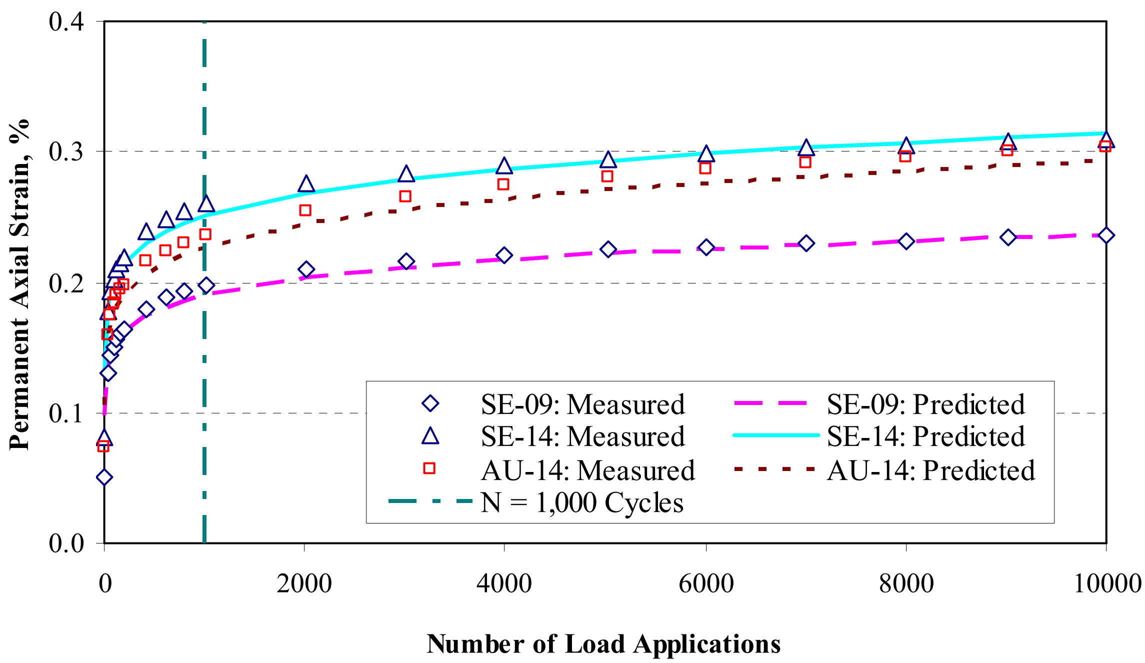
Laboratory Validation and Unified Model Development

Additional laboratory tests were conducted next on newly prepared specimens of all the three oil sand materials to check performances of the permanent deformation models. These tests were limited to only the 0.1-second load pulse duration, one applied stress state of 138 kPa (20 psi) equal confining and deviator stresses, and the two test temperatures of 20 and 30 degrees Celsius. This time, a total of 10,000 load cycles were applied on the replicate specimens in order to adequately validate the performances of the corresponding permanent deformation models, i.e., the models listed for the fourth stress state in Tables 2 and 3, for up to 1,000 load cycles and further, check their prediction abilities at larger number of load applications.

Figures 8a and 8b show both the experimental and model prediction results of permanent axial strain with number of load applications using the models listed for the fourth stress state in Tables 2 and 3 at 20 and 30 degrees Celsius, respectively. Note that unlike in Figure 5, due to different stress states applied, AU-14 specimens this time did not yield the highest plastic strains. In general, the close agreements between the laboratory measured and predicted results demonstrate the good repeatability of the test data and likewise good performances of the individually developed permanent deformation models for predicting plastic strains beyond 1,000 cycles, for up to 10,000 load applications.



(a)



(b)

FIGURE 8 Permanent Strain Model Predictions for Additional Test Specimens: (a) Temperature = 20°C and (b) Temperature = 30°C

Since the overall objective was to develop a better basic understanding as well as to come up with practical predictive equations to estimate field sinkage or permanent deformation behavior of oil sands, the stress-strain data sets were combined to create individual databases of the three oil sand materials. A close examination of the 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 could also be combined for analysis. The R-square selection method in the SAS software was first used to ascertain which independent variables were potential candidates for the models. It was found that permanent strain strongly depended on the stress ratio, number of load applications, the applied deviator stress, temperature and bitumen content. Based on the results, four models were selected to study oil sand permanent deformation behavior.

Table 4a lists three unified permanent strain models developed for each oil sand material and the model parameters obtained from multiple regression analyses. No significant differences were found among the model parameters for the three oil sands. Therefore, it was reasonable to combine the test data to develop a generalized model for oil sands. The combined data allowed bitumen content to be included as a variable in the analyses assuming similar bitumen properties among the three oil sands. Table 4b lists the generalized permanent strain models developed using the combined test data and gives the model parameters obtained from stepwise multiple regression analyses. Note that high coefficient of correlation (R^2) values were obtained for all the models, including models 1 and 2, thus indicating stress dependency had the predominant role in predicting permanent strain accumulation. Since a comprehensive but yet practical model should also account for the additional effects of temperature and bitumen content in the oil sand, slightly improved models of 3 and 4 in Table 4b can be proposed for routine use in the estimation field sinkage or permanent deformation behavior of oil sands.

TABLE 4a Unified Permanent Strain Models Developed for Each Oil Sand Material

Model 1

$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta}$$

Model 2

$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta} \cdot \sigma_d^{\gamma}$$

Model 3

$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta} \cdot \sigma_d^{\gamma} \cdot T^{\lambda}$$

Model Parameters	Log A	α	β	γ	λ	R^2
SE-09 Sample						
Model 1	-1.8445	0.1686	1.9726	-	-	***0.90***
Model 2	-2.3245	0.1683	1.7109	0.2763	-	***0.93***
Model 3	-3.1247	0.1683	1.7109	0.2762	0.5762	***0.95***
SE-14 Sample						
Model 1	-1.8080	0.1832	2.1951	-	-	***0.89***
Model 2	-2.5325	0.1827	1.8004	0.4170	-	***0.95***
Model 3	-3.3448	0.1827	1.8001	0.4167	0.5852	***0.96***
AU-14 Sample						
Model 1	-1.95374	0.2059	2.5624	-	-	***0.86***
Model 2	-2.7523	0.2063	2.1127	0.4619	-	***0.91***
Model 3	-3.8764	0.2058	2.1152	0.4575	0.8157	***0.93***

TABLE 4b Generalized Permanent Strain Models Developed for Oil Sand Materials

Model 1
$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta}$$

Model 2
$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta} \cdot \sigma_d^{\gamma}$$

Model 3
$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta} \cdot \sigma_d^{\gamma} \cdot W_b^{\eta}$$

Model 4
$$\varepsilon_p = A \cdot N^{\alpha} \cdot \left(\sigma_1 / \sigma_3\right)^{\beta} \cdot \sigma_d^{\gamma} \cdot W_b^{\eta} \cdot T^{\lambda}$$

Model Parameters	**Log A**	**α**	**β**	**γ**	**η**	**λ**	R^2
Model 1	-1.8689	0.1858	2.2435	-	-	-	***0.85***
Model 2	-2.5371	0.1856	1.8752	0.3853	-	-	***0.90***
Model 3	-1.9415	0.1858	1.8744	0.3868	0.6450	-	***0.92***
Model 4	-2.8574	0.1857	1.8750	0.3855	0.6499	0.6614	***0.93***

SUMMARY AND CONCLUSIONS

The typical 8% to 15% by weight of bitumen or asphalt content in the bituminous/oil sands makes these naturally occurring sands low load-bearing materials for haul trucks, shovels and other mining equipment. A comprehensive permanent deformation testing program was undertaken in the laboratory to develop permanent strain models for predicting field rutting (sinkage) potentials of oil sand materials. A newly proposed permanent deformation 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 considered repeated load triaxial testing at two temperatures to apply on specimens stress states/ratios close to the field loading characteristics of haul trucks and mining equipment, and included two different load pulse durations to investigate effects of loading frequency or trafficking speed. Based on the database established from the testing program, oil sand permanent strain models, developed as power functions of the number of load applications in the form of ε_p=A*N^B, were found to be primarily dependent on the applied total vertical to horizontal or major to minor principal stress ratios (σ_1/σ_3). The statistical analyses showed that there was a strong correlation between model parameter A and the stress ratio (σ_1/σ_3), which could give the immediate sinkage at the first load application as a function of the applied stress states/ratios. Using additional replicate test data, it was demonstrated that some of the developed permanent deformation models could reasonably predict permanent strain accumulations in the oil sand materials within the limits of selected loading conditions. When the entire test data from the three oil sands were combined, unified and generalized permanent deformation models were successfully developed to account for applied stress states/ratios, temperature, and bitumen content although a more accurate approach would be to use permanent deformation models for each oil sand material with known bitumen property separately. Overall, the developed permanent deformation models may provide essential guidelines and practical predictive equations for estimating field rutting potentials of oil sand materials under off-road haul trucks, shovels and other mining equipment.

ACKNOWLEDGEMENT

The authors would like to acknowledge Dr. Liqun Chi of Caterpillar, Inc. of Peoria, Illinois for his help and collaborative efforts in funding this research and providing the oil sand samples and his valuable insights in this study.

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