Shear strength properties of naturally occurring bituminous sands

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ABSTRACT: Shear strength properties of three oil sand materials were determined in the laboratory by simulating field loading conditions of large capacity mining trucks and shovels. Both monotonic triaxial compression and direct shear tests were performed on the oil sand materials with bitumen contents of 8.5%, 13.3% and 14.5% at 20^{o}C and 30^{o}C test temperatures. Results from the two tests could not be effectively compared since the triaxial tests produced zero friction angles for all the oil sand materials because of the cohesive nature of bitumen contents. However, results from the direct shear tests were comparable to properties of oil sands reported earlier from various other laboratory tests. Based on the direct shear test results, Mohr-Coulomb failure envelopes were determined to establish shear strength properties of the three oil sand samples. The results presented in this paper may be used to estimate friction angles and cohesion intercepts of oil sand materials with similar characteristics in the field.

1 INTRODUCTION

Shear strength of any geomaterial, i.e., fine-grained soil or granular material, is generally mobilized either due to a cementing action or cohesion and/or grain-to-grain interlock, i.e., angle of friction or repose, under applied loading. Commonly referred to as shear strength properties, cohesion and friction angle are determined from laboratory and field tests performed on constituted specimens and undisturbed in-situ samples, respectively. For several decades, the triaxial compression and direct shear tests have been recognized as some of the standard laboratory tests for determining shear strength properties of soils and granular materials. The results from these tests are often used for analyzing the bearing capacity and stability of slopes and foundations of structures and pavements.

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. During the past decade, monotonic triaxial compression and direct shear tests have been performed with certain success to determine oil sand shear strength properties using the traditional shear strength test procedures (ASTM D 2166, 2850, 3080, 4767).

In this study, both triaxial compression and direct shear tests were used to determine shear strength properties of three oil sand materials in the laboratory. The test procedure was based on field loading conditions of the oil sand materials under large capacity mining trucks and shovels. The laboratory test program focused on conducting shear strength tests on the oil sand samples at two test temperatures at 20^{o}C and 30^{o}C representing typical spring and summer conditions in Saskatchewan, Canada. Based on the laboratory test data, this paper presents the cohesion intercepts and friction angles determined for the individual oil sand samples to establish Mohr-Coulomb failure envelopes.

2 LABORATORY TESTING PROGRAM

2.1 *Materials tested and properties*

Three types of oil sand materials, designated herein as SE-09, SE-14 and AU-14, 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-09, SE-14 and AU-14, respectively; and the water contents were 1.4%, 3.2% and 2.2%, respectively. 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 following AASHTO T 27 procedure.

Figure 1 shows the sieve analysis test results. All the three oil sands are uniformly graded fine to medium sands with the smallest to largest size particles ranging from 0.6 mm to 2.36 mm. The fines contents, i.e. passing No. 200 sieve or 0.075 mm, range from 7% to 15%. Similar grain size distributions for oil sand materials were reported by Cameron and Lord (1985).

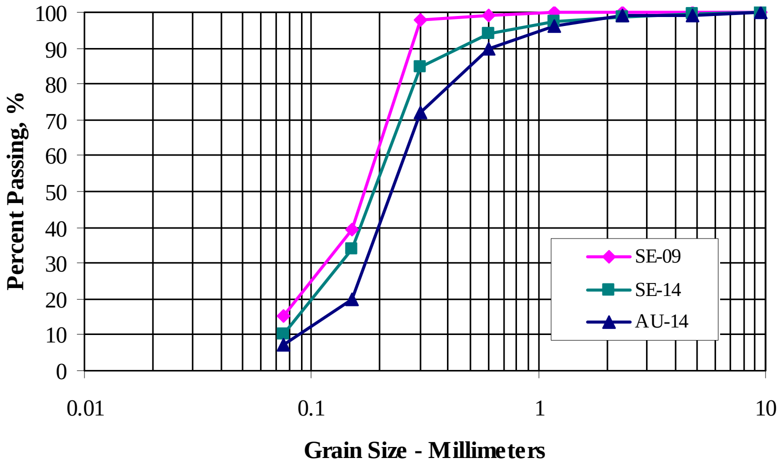

Figure 1. Particle size distributions of oil the sand samples.

2.2 *Specimen preparation*

The amount of oil sand material required to achieve a predetermined field density was computed to prepare specimens for shear strength testing. For monotonic triaxial compression tests, oil sand specimens were mechanically compacted in a split aluminum compaction mold using a standard Proctor compaction hammer in three lifts to achieve the target density. Approximately 71-mm diameter cylindrical specimens were prepared for testing. Specimen density was controlled by measuring the weight of material and compacted thickness of each lift, referenced to the top of the mold. The surface of each lift was scarified down to a depth of approximately 10 mm to achieve uniform compaction in 3 lifts.

The direct shear test specimens were prepared from gyratory compacted specimens. An Industrial Process Controls (IPC), Ltd. Servopac gyratory compactor available at the University of Illinois was used to produce 150 mm in diameter by 150 mm high cylindrical specimens. Using a masonry saw, the gyratory compacted specimens were cut into square prismatic specimens of size 100 mm and approximately 30 mm high. Following compaction and direct shear specimen cutting and trimming, the oil sand test specimens were conditioned for a minimum of six hours in an environmental temperature chamber before testing. Figure 3 shows compacted specimens of one of the oil sand samples prepared for conducting monotonic triaxial compression and direct shear tests.

(a) Cylindrical triaxial test specimens

(b) Square prismatic direct shear test specimens

Figure 2. Compacted oil sand sample specimens for shear strength tests.

2.3 *Test procedure and laboratory testing*

A new shear strength test procedure proposed for oil sand testing was used to determine the shear strength properties of the three types of oil sand materials. The proposed test procedure, which is based on the field loading characteristics of the haul trucks and mining equipment for oil sands, considers confining or normal stresses as high as 552 kPa. In addition, the test procedure is based on testing at temperatures of 20^{o}C and 30^{o}C, which represent warmer months in spring and summer, respectively, as observed in oil sand fields (Joseph, 2005). Shear strength tests were conducted on the three samples with bitumen contents of 8.5%, 13.3% and 14.5% using both triaxial and direct shear test procedures.

The triaxial tests were performed on the cylindrical specimens, 71 mm in diameter and 142 mm high, by applying five confining stress levels, i.e., 20.7, 41.4, 69, 138 and 276 kPa. Specimens were conditioned and tested at temperatures of 20^{o}C and 30^{o}C to obtain the friction angle ϕ, and cohesion c properties. The test specimens were monotonically loaded at a strain rate of 1% strain/minute using an IPC UTM-5P pneumatic testing system, and pressurized in a triaxial chamber with air pressure. The load was measured through the load cell, whereas, the deformations were measured using the actuator linear variable displacement transducer (LVDT).

Direct shear tests were also performed on the oil sand samples to compare test results with the triaxial compression tests. The same test conditions for the triaxial compression tests were repeated during direct shear testing except that the applied confining or normal stresses were increased up to 552 kPa in the Humboldt pneumatic direct shear test setup at the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL). The shear stress was measured through the load cell, whereas, the horizontal and vertical deformations were measured using horizontal and vertical LVDTs.

3 ANALYSIS OF TRIAXIAL COMPRESSION TEST DATA

Tables 1 and 2 show the results for all the three oil sand samples tested at 20^{o}C and at 30^{o}C, and Figures 3 and 4 present the shear strength test results in Mohr's circles to indicate that the oil sand samples were found to give essentially similar shear strength properties regardless of the applied confining pressure. Apparently, the oil sand materials did not densify as confining pressure increased, hence the shear strength did not increase. It is worth mentioning that none of the specimens tested failed in shear; rather, all the test specimens bulged when the applied shear stress reached the peak value. This failure mode resulted in zero friction angles for all the oil sand samples, i.e., there is no or negligible interlock between the sand grains of the materials and the oil sands are primarily cohesive in nature. The zero friction angles obviously are not reflective of the dense nature of the tested oil sand materials. Dusseault & Morgenstern (1978b) and Agar et al. (1983) report that oil sand derives its strength from the dense interlocking grain structure it exhibits. Therefore, the test results can be interpreted as there was no significant contact between the grains of the oil sands tested, which resulted in zero friction angle.

In a related case, Dusseault & Morgenstern (1978b) abandoned triaxial tests in favor of direct shear testing for Athabasca oil sands. One of the reasons was that sample uniformity and the required number of similar specimens to describe Mohr-Coulomb envelopes could not be obtained from triaxial testing. Similarly, in this study, direct shear tests were also performed, however, the small cohesion values obtained for all the samples appear to reasonably agree with findings by Round (1960), Dusseault & Morgenstern (1978b), and Agar et al. (1987). Generally, no significant difference was found between cohesion of the three oil sand samples at 20^oC and at 30^oC. Cohesion was found to be relatively higher at 20^oC than at 30^oC for all the oil sands with the AU-14 sample giving the highest cohesion value of 24.8 kPa at 20^oC. Note that in Figure 3c, the Mohr circles lying above the failure envelope (test #1 and test #3) were not considered for determining the cohesion property of the AU-14 sample.

Table 1. Triaxial shear strength test results for oil sand samples at 20^oC.

Sample ID	Peak shear stress @ confining stress in kPa					Strength properties	
	20.7	41.4	69	138	276	ϕ (degrees)	c (kPa)
SE-09	32.5	26.7	35.5	33.9	27.0	0	15.7
SE-14	40.6	43.9	43.9	41.6	50.9	0	22.3
AU-14	62.7	51.1	69.0	41.3	41.9	0	24.8

Table 2. Triaxial shear strength test results for oil sand samples at 30^oC.

Sample ID	Peak shear stress @ confining stress in kPa					Strength properties	
	20.7	41.4	69	138	276	ϕ (degrees)	c (kPa)
SE-09	24.5	33.3	34.0	31.3	21.5	0	15.0
SE-14	22.2	20.7	24.5	25.9	21.4	0	13.0
AU-14	28.7	22.9	22.9	28.7	30.2	0	15.4

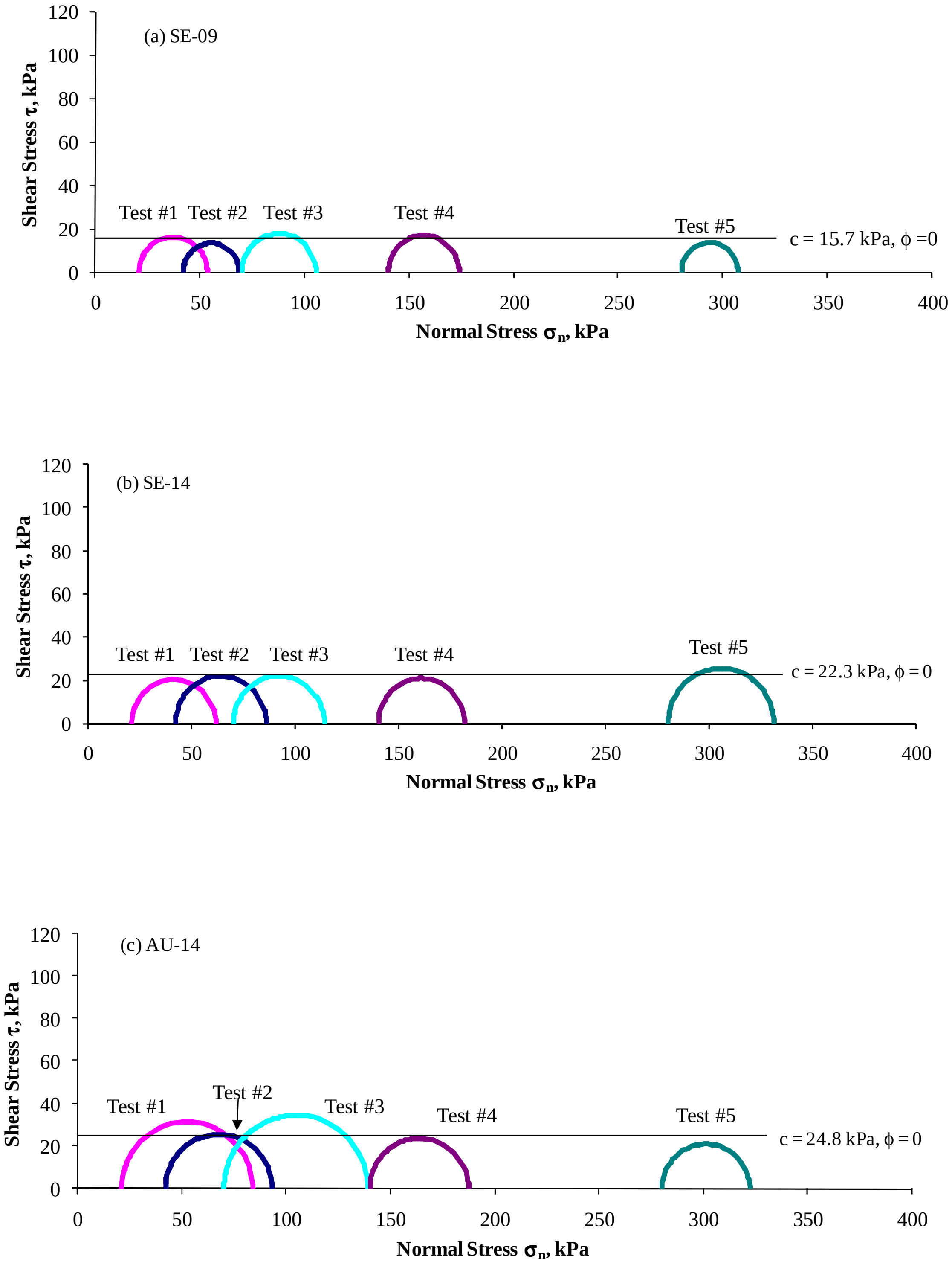

Figure 3. Mohr circles for the three oil sand samples tested at 20°C.

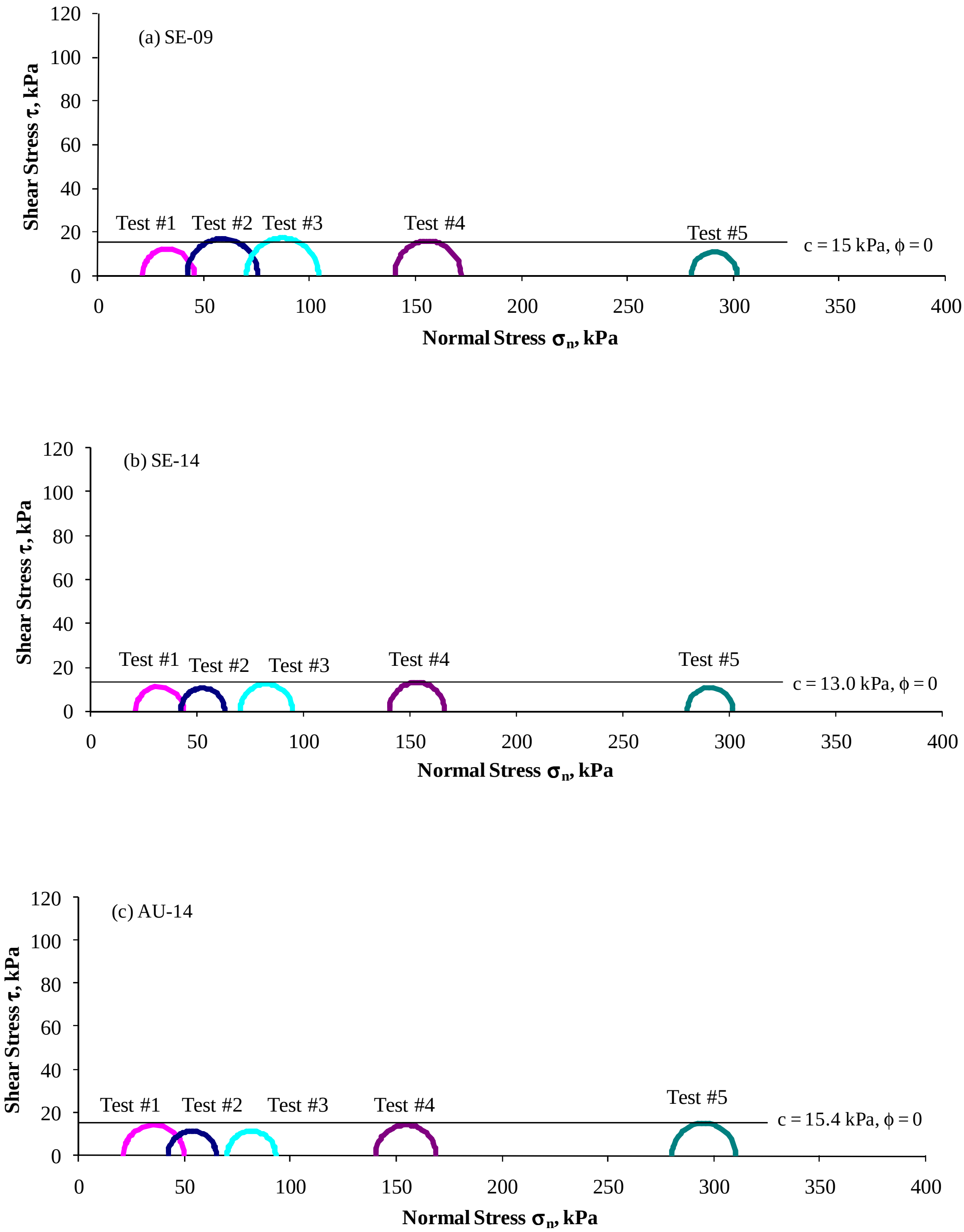

Figure 4. Mohr circles for the three oil sand samples tested at 30^{o}C.

4 ANALYSIS OF DIRECT SHEAR TEST DATA

The results for the direct shear tests for all three oil sand samples are reported in Tables 3 and 4 which list the maximum deviator stress at failure, the applied normal stresses, and the shear strength properties determined at test temperatures 20°C and 30°C. Note that only 4 direct shear tests were performed for the oil sand samples at 30°C. There were insufficient oil sand samples to conduct the tests at all the six confining stresses.

Comparisons among the test results indicate that the oil sand materials exhibit higher friction angles at 20°C than at 30°C. On the other hand, the cohesion parameter was found to be higher at 30°C than at 20°C. Overall, the SE-09 sample has the highest friction angle and the lowest cohesion, whereas AU-14 has the lowest friction angle and highest cohesion. There is apparently no significant difference between friction angle and cohesion values of SE-14 and AU-14 samples. Both AU-14 and SE-14 samples have higher cohesion intercepts compared to SE-09 sample.

The high ϕ values imply ability of the oil sand materials to develop strength under confinement and resist permanent deformation, and high c values relate to high resistance of the oil sand materials to shearing stresses. Although, the differences between the test parameters are not large, the SE-09 sample is expected to have greater potential to resist permanent deformation when compared to SE-14 and AU-14 samples, which behaved somewhat similar. This could be expected since the difference between their bitumen contents is not significant. It appears that bitumen content has an effect on the shear strength properties of oil sand materials. This effect could be explained in more detail if the characteristics of the bitumen were better known.

Generally, the high friction angles and low cohesion values exhibited by the three oil sand samples are in agreement with research findings of Round (1960) and Dusseault & Morgenstern (1978b). All these studies reported low or negligible cohesion and high friction angles for oil sand materials in direct shear tests. Typical "c" values for oil sand materials from direct shear tests under different test conditions are less than 20 kPa; whereas typical "ϕ" values range mostly between 30 and 60° (Round 1960, Dusseault & Morgenstern 1978b). These researchers also noted that oil sand with high quartz content or highly coarse-grained in nature had high shear strength properties.

Table 3. Direct shear test results for oil sand samples at 20°C.

Sample ID	Peak shear stress @ normal stress in kPa						Strength properties	
	20.7	41.4	69.0	138.0	276.0	552.0	ϕ (degrees)	c (kPa)
SE-09	27.3	45.7	59.8	126.3	218.3	473.4	39.4	6.2
SE-14	26.2	52.1	77.6	94.1	223.1	417.9	35.7	15.2
AU-14	32.2	41.8	61.2	123.0	210.2	365.9	32.1	22.9

Table 4. Direct shear test results for oil sand samples at 30°C.

Sample ID	Peak shear stress @ normal stress in kPa				Strength properties	
	69.0	138.0	276.0	552.0	ϕ (degrees)	c (kPa)
SE-09	63.8	113.5	190.6	384.4	33.0	17.6
SE-14	56.6	120.4	209.7	355.2	30.7	29.5
AU-14	65.0	98.8	210.1	332.4	29.0	31.4

Based on the direct shear test results, Mohr-Coulomb failure envelopes were developed for each oil sand sample. The Mohr-Coulomb failure envelope is expressed by Equation 1. Generally, the Mohr-Coulomb failure criterion is the most widely known strength definition used to characterize shear strength behavior of geomaterials within limited stress ranges. The results from such characterization provide parameters, which are employed in analyzing the stability of the tested materials. In this study, linear Mohr-Coulomb envelopes were used to analyze the direct shear test data of the oil sand samples at the different bitumen contents and test temperatures of 20°C and 30°C.

$$\tau_{max} = c + \sigma_n \tan \phi \qquad (1)$$

where, τ_{max} = shear strength; σ_n = normal stress at failure; c = cohesion intercept, tan ϕ = slope of the failure envelope (ϕ is friction angle).

Figures 5 and 6 show the Mohr-Coulomb failure envelopes developed from the cohesion c and angle of internal friction ϕ values for the three oil sand materials. It can be observed that at normal stresses below 200 kPa, no significant difference can be ascertained with respect to the mobilized shear strength in the three oil sand materials. However, at normal stresses higher than 200 kPa, the SE-09 sample with lower bitumen content (8.5%) mobilized higher shear strength than the SE-14 and AU-14 with bitumen contents of 13.3% and 14.5%, respectively. Similarly, the SE-14 sample had higher shear strength than the AU-14 sample at high normal stress levels. This trend suggests that the ability of oil sand materials to mobilize shear strength in direct shear testing depends to a large extent on the amount of bitumen content present in the material. Therefore, the applied normal stress has a significant influence on the shear strength properties of the oil sand samples. The results may be used to estimate friction angles and cohesion intercepts of oil sand materials with similar characteristics in the field. In addition, the shear strength properties obtained may be used as inputs into finite element analyses to model permanent deformation behavior of oil sands in order to account for mobility and trafficability of large capacity haul trucks and shovels in oil sand mine fields.

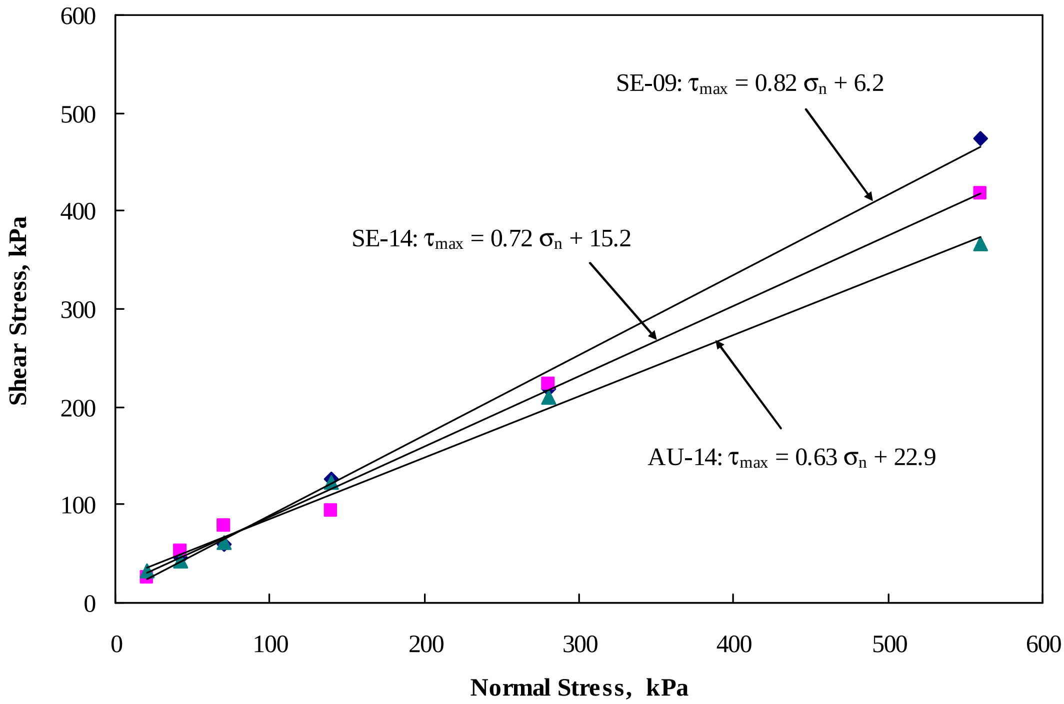

Figure 5. Mohr-Coulomb failure envelopes for oil sand samples tested at 20°C.

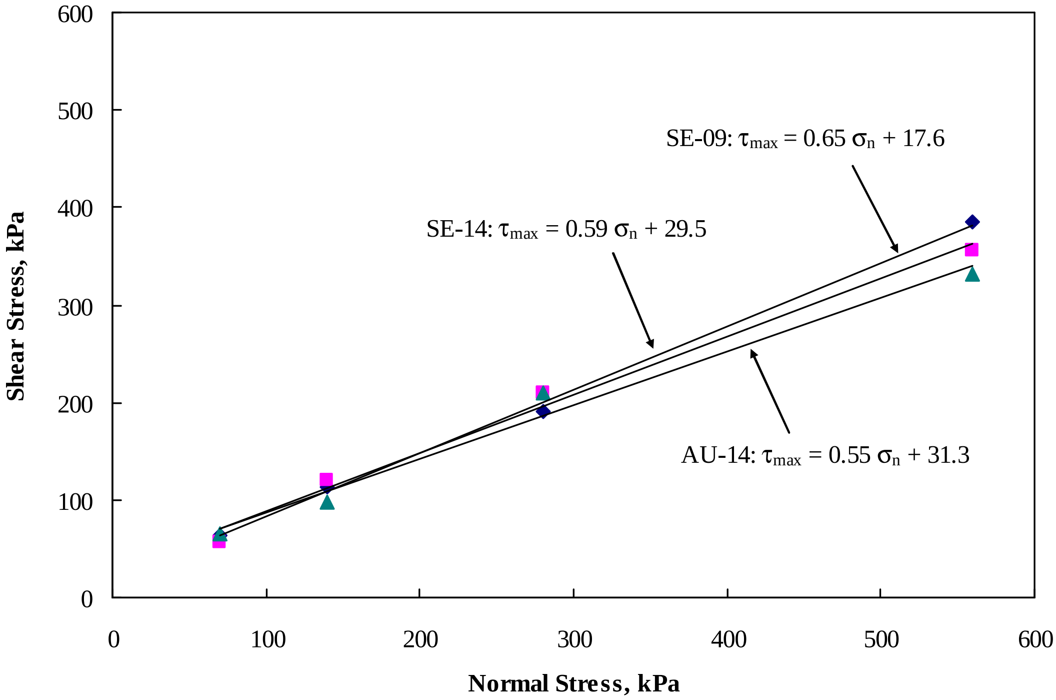

Figure 6. Mohr-Coulomb failure envelopes for oil sand samples tested at 30°C.

5 SUMMARY AND CONCLUSIONS

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. A newly proposed shear strength test procedure allowed application of somewhat high confining or normal stresses during testing to adequately determine strength properties of three types of oil sand materials. Both monotonic triaxial compression and direct shear tests were performed on the oil sand materials with bitumen contents of 8.5%, 13.3% and 14.5% at test temperatures of 20°C and 30°C. The triaxial compression tests performed on the three oil sand materials gave zero friction angles and all specimens failed by specimen mid-height bulging, which suggests that the samples behaved cohesive in nature and there were apparently no interparticle contacts between the sand grains in the oil sand samples. The results obtained for cohesion intercept was rather reasonable and agreed with results reported in the literature for similar oil sand samples.

Direct shear tests results indicated that the oil sand samples had higher friction angles at 20°C than at 30°C, and lower cohesion values were obtained at 20°C. Generally, SE-09 sample had the highest friction angle and lowest cohesion, whereas AU-14 had the lowest friction angle and highest cohesion at the two test temperatures. Thus, the oil sand sample with lowest bitumen content would have greater ability to resist potential rutting in the field. This observation was evident from high friction angles obtained for the oil sand sample with less bitumen content. Based on the direct shear test results, Mohr-Coulomb failure envelopes were established for the three oil sand samples at the two test temperatures. The shear strength data provided will be useful for engineers and equipment manufacturers to estimate load bearing capacities of oil sand materials under operating haul trucks and shovels in the field.

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