SUSTAINABLE GROUTED HELICAL PILES: MATERIALS AND PERFORMANCE

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ABSTRACT

Cementitious materials are widely used as a construction material all over the world. However, cement industry has high environmental impact such as the release of CO_2 and the consumption of natural resources for its manufacturing energy. Therefore, reducing cement consumption is vital to achieve sustainable green construction practices. In this study, the effects of using treated oil sand waste (TOSW) as a partial replacement of cement in grouted helical pile applications were investigated. Fresh and hardened properties of the green grout incorporating different percentages of TOSW were evaluated. In addition, a model scale grouted helical pile with the green grout was tested to characterize its performance. The experimental results show that the properties of TOSW grout mixes were comparable to conventional grout and satisfy the strength and construction requirements of grouted piles. Moreover, tested grouted helical pile using the developed mixture exhibited similar geotechnical performance as those installed using conventional grout mix. Hence, TOSW can be implemented in grouted helical pile applications, which would assist in achieving sustainable construction.

Keywords: cementitious grout, treated oil sand waste, green grout, grouted helical piles

1. INTRODUCTION

Cement industry is considered one of the top industries with high environmental impact. It consumes a substantial amount of our natural resources, needs a huge amount of energy, and releases large amount of CO_2 leading to the climate changes we are experienced now a days. On the other hand, oil sand industry became one of the main reasons for the development of the Canadian economy in the last decades. However; it is one of the top waste production industries in western Canada as it produces billions of tons of waste every year. Treatment and disposal of such huge amount of waste represent one of the major challenges facing this industry.

Several treatment technologies are applied to oil sand waste to convert it into an environmental friendly product that could be used in different applications, or at least reduce its impact on the environment. Recently, an innovative technology called Thermo-mechanical Cuttings Cleaner (TCC) was proposed for oil sand waste treatment. In the TCC treatment technology, the waste is heated to a high temperature enough to evaporate oil and water from the waste. The oil and water will be brought back to a liquid phase in separate condensers leaving behind a very fine quartzes powder enriched with Silica (Aboutabikh et al., 2016). This opens the way to use the treated oil sand waste (TOSW) as a filler material or as partial replacement of cement in several construction applications. Using TOSW as partial replacement of cement in construction applications has dual benefits: reducing the need of cement in construction industry which is the main cement consumer along with reducing the amount of TOSW that need to be disposed.

Helical screw piles have been widely used as a deep foundation system for different engineering applications. They represent a viable foundation option because of their cost effectiveness, ease of installation, low levels of noise and vibration, and their ability to be installed through ground water without casing. In addition, they allow immediate loading upon installation. However; helical screw piles have some drawbacks that affect their performance. Paramount among these drawbacks is the installation disturbance of the soil within the zone affected by the pile helices (Bagheri & El-Naggar, 2013), the high displacement required to fully mobilize the bearing component of their bearing plates, and the low buckling resistance of their slender shaft under compression loading. In addition the incomplete rigidity of the coupling joints along the pile shaft can affect the pile performance under lateral loading (Vickars & Clemence, 2000).

Several investigations have been conducted to overcome helical screw pile limitations using grouting technology, resulting in what is called "Grouted Helical Pile". The idea of grouted helical pile could be summarized in providing a cylindrical grout column around the helical pile slender shaft to increase its buckling resistance, make the coupling joints more rigid, and increase the pile capacity by increasing the pile shaft resistance contribution to the total pile capacity. Several grouting techniques were developed to inject neat cement grout into the surrounding soil through the helical pile hollow shaft after installation (Ratliff 1966, and Perko 2000), and during installation (Nasr, 2008).

In this study, the effect of using TOSW on grouted Helical Piles performance was investigated. Initially, the effects of TOSW on fresh and hardened properties of cementitious grout were evaluated to ensure that the produced grout meets the construction requirements for grouted helical pile applications. Then, a small scale grouted helical pile model was installed using cement-TOSW grout mixture (green grout) to investigate its effect on the pile geotechnical performance.

2. EXPERIMENTAL TESTING PROGRAM

2.1 Sample preparation and testing

TOSW was added as a partial replacement of cement in the green grout mixtures with different percentages (0, 10, 20, and 30) % by volume, which will be referred to as (M_0, M_{10}, M_{20}, and M_{30}) respectively. The grout mixtures were prepared according to ASTM C305 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency). The effect of TOSW on the flowability of the grout mixtures were evaluated according to ASTM C939 (Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete "Flow Cone Method"). The compressive strength of the specimens was evaluated according to ASTM C109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars "Using 50-mm Cube Specimens"). Specimens were maintained at ambient temperature of (23 ± 1°C) and covered with polyethylene sheets until demolding to avoid any moisture loss. After demolding, the specimens were immediately moved to a moist curing room (Temperature = 23 ± 1°C and relative humidity = 98 %) until the required testing age (7 and 28 days).

2.2 Materials

Ordinary Portland cement Type 10 (OPC 10) with a specific gravity of 3.15 and Blaine fineness of 360 m^2/kg was used as a binder material for the grout mixtures. It consists of 61% Tricalcium Silicate (C_3S), 11% Dicalcium Silicate (C_2S), 9% Tricalcium Aluminate (C_3A), 7% Tetracalcium Aluminoferrite (C_4AF), 5% limestone, and 0.82% equivalent alkalis. The TOSW used in this study was a silicate-based material with a specific gravity of 2.54 and Blaine fineness of 1440 m^2/kg. The chemical composition of TOSW was obtained using energy dispersive X-ray analysis (EDX) as shown in Figure 1, and summarized in Table 1. To adjust the flowability of the green grout mixtures, a polycarboxylate-based high-range water-reducing admixture (HRWRA) was used and included in the specified water-to-cement ratio (w/c). Table 2 summarizes the components of different green grout mixtures.

2.3 Particle size distribution

One of the key parameters controlling the applicability of using a certain particulate material in soil grouting applications is its ability to permeate through the soil voids. This permeation ability depends mainly on the size of smallest soil voids and the size of largest grout particles (Warner, 2004). To assess the applicability of using TOSW as a partial replacement for cement in grouted helical piles applications, its particle size distribution was obtained using laser diffraction and compared to that of OPC 10 as shown in Figure 2. The grain size distribution curves show that the maximum particle size (D_{90}) of TOSW is approximately one fourth that of OPC 10. And hence; it will not adversely affect the grout penetrability when it is used as a partial replacement for cement.

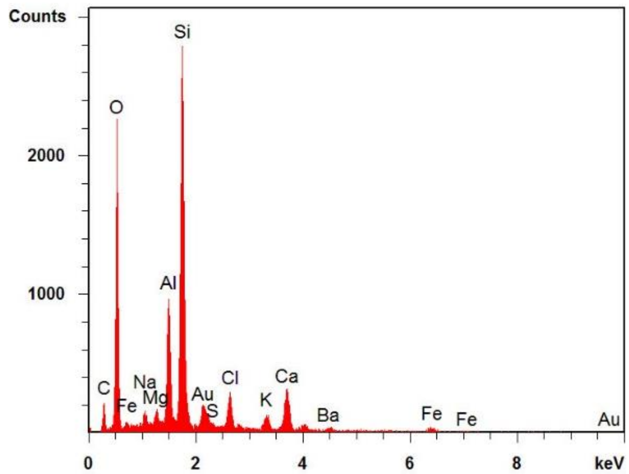

Figure 1: EDX analysis for TOSW

Table 1: Chemical composition of TOSW

Chemical composition	Percentage
SiO_2	61.24
Al_2O_3	8.73
Fe_2O_3	3.00
CaO	5.55
MgO	0.92

Table 2: Grout mixtures compositions

Mixture	Cement (kg/m^3)	TOSW (kg/m^3)	Water/Powder
M_0	1300	0	0.42
M_{10}	1170	105	
M_{20}	1040	210	
M_{30}	910	315	

3. RESULTS AND DISCUSSION

3.1 Flowability

Flow cone test was used to measure the flowability of different grout mixtures and determine the effect of TOSW on the efflux time of the tested mixes. The shorter the efflux time, the higher grout flowability is. It was observed that addition of TOSW decreased the efflux time of the tested mixture as presented in Table 3. This could be attributed to the small particles size of TOSW that allows them to penetrate and fill the space between cement particles leading to freeing the entrapped water and makes them available (Khaleel & Razak, 2012).

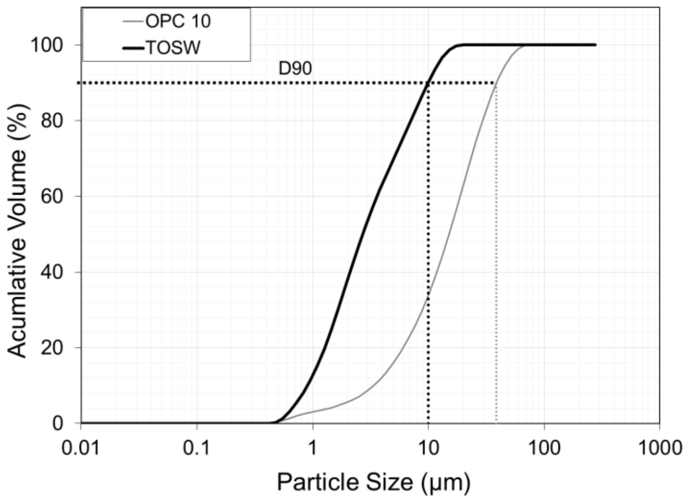

Figure 2: Particle size distribution of TOSW and OPC 10

3.2 Compressive strength

It was observed that addition of TOSW as partial replacement of cement reduces the compressive strength of grout mixtures. This reduction increases as the percentage of TOSW in the mixture increases as shown in Table 3. However, it was also observed that the reduction of the TOSW grout mixtures compared to the conventional grout mixture decrease with time. For instance, a reduction in compressive strength of 17%, 23%, and 37% was observed after 7 days for grout mixtures incorporating 10%, 20% and 30% TOSW, respectively, while at the age of 28 days, this reduction became 5.3%, 11.1% and 27.0% for the same grout mixtures. This is attributed to the relationship between the hardened properties of grout and hydration of its cementitious materials. It had been reported that the hydration reaction between water and cementitious material of grout mixtures depends on many factors such as fineness and cement content (Amen, 2011). Therefore, replacing cement with TOSW will affect the rate of strength gain for cementitious materials. The addition of an inert material like TOSW as a partial replacement of cement will decrease the hydration reaction between the cementitious material and water, causing a reduction in the compressive strength at the early ages. While at later ages, TOSW act as a filler material that fills the voids between cement particles, and hence, it reduce the volume to be filled with the hydration products making the grout denser and more homogenous (Jaturapitakkul et al., 2011).

Based on general practice, a compressive strength between 4000-6000 psi (27.6-41.4) MPa should be provided for the cementitious grouting material used in grouted helical pile applications. This is in good agreement with the recommendation of the Federal Highway Administration (FHWA) to provide a minimum design compressive strength of 28 MPa after 28 days for the grout used in micropiles applications. Based on the results shown in Table 3 and the grain size distribution of both (TOSW and OPC 10) shown in Figure 2, all the TOSW grout mixtures satisfy the requirement of the grouted helical pile applications.

Table 3: Fresh and hardened properties of different grout mixtures

Mixture	Flow cone efflux time (sec)	Compressive strength (MPa)	
		7 days	28 days
M_0	12.5	44.5	52.0
M_{10}	11.9	36.5	48.5
M_{20}	11.3	33.0	46.5
M_{30}	11.1	28.0	39.0

3.3 Geotechnical performance of the grouted helical pile using green grout

To investigate the effect of TOSW on the grouted helical piles geotechnical performance, two small-scale grouted helical piles with hollow shaft and single helix were installed in loose sand with relative density 28% to a depth of 80 cm. The diameters of the piles shaft and helix were 3.3 cm and 15 cm, respectively. During installation, green cement grout with 30% TOSW was injected into the surrounding soil through one of them, while the other is installed using conventional grout mix. The grout was left to be cured for one week, after that the piles were tested under static axial compression loading.

The quick maintained static load test procedure was adopted according to ASTM D1143-07 (Standard Test Method for Deep Foundations under Static Axial Compressive Load). Each pile was loaded in increments of 5% of its expected ultimate capacity until failure. Each load increment was maintained for 5 minutes. The last load increment was maintained for 15 minutes to capture the creep effect. The pile was then unloaded on 5 equal decrements. Each load decrement was maintained for 5 minutes. After applying the last decrement, the pile was left for 15 minutes to fully capture the rebound response. To monitor the pile head displacement, four linear variable displacement transducers (LVDT) were placed on the corners of the loading plate as shown in Figure 3. The applied load was measured using a load cell placed over the pile head. The LVDTs and load cell were connected to a data acquisition system to record readings every 1 second.

Figure 3: Compression test setup

Several criteria had been developed to estimate the piles ultimate capacity through their load-displacement curves. According to (Sakr 2009), the helical pile reaches its ultimate capacity at displacement equal to 10% of the helix diameter. Similar approach was recommended by (Livenih & El-Naggar 2008) where the pile ultimate capacity corresponds to a displacement of 8% of the helix diameter plus the elastic deformation of the pile shaft. Butler & Hoy (1977) suggested a different criterion, in which the load-displacement curve is divided into three parts. A first linear segment followed by a nonlinear segment, then a secondary linear segment with lower slope. The pile ultimate capacity is calculated as the intersection between the extensions of the first and secondary linear segments.

The two piles were found to have similar performance as shown in Figure 4. The ultimate capacity of the two piles determined using the pre-mentioned failure criteria are summarized in Table 4. The ultimate capacity of the grouted helical pile using conventional grout mix was found to be (54 kN), which is slightly less than that of the green grouted helical pile (58 kN). The results are in good agreement with the findings of Aboutabikh (2016) who reported that the capacities of two micropiles installed with conventional grout and green grout with 30% TOSW were similar. Based on the data shown in Table 4, and the piles responses shown in Figure 4, addition of TOSW as a partial replacement of cement had no effect on the grouted helical pile performance.

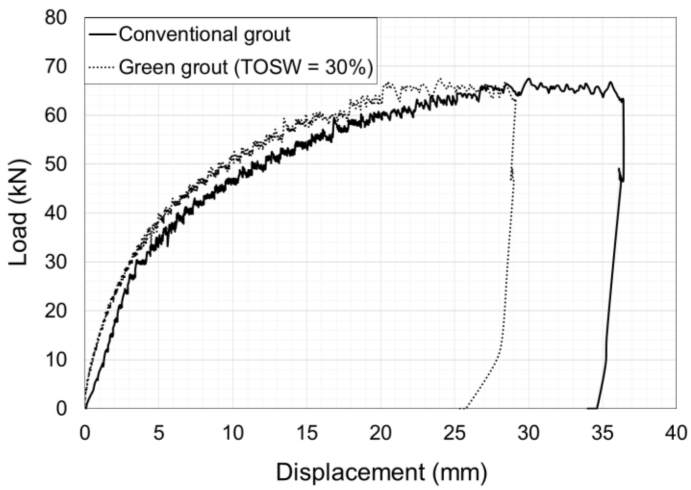

Figure 4: Load-Displacement curves of the tested piles

Table 4: Ultimate pile capacity

Failure Criteria	Conventional grouted helical pile	Green grouted helical pile
Sakr 2009	54 kN	58 kN
Livenih & El-Naggar 2008	52 kN	56 kN
Butler & Hoy 1977	60 kN	58 kN

4. CONCLUSIONS

TOSW is a very fine powder with smaller grading size than that of cement, its surface is rich of aluminum/silica; thus it has the potential to be used in construction applications. A full experimental program was conducted to study the effect of TOSW on the fresh and hardened properties of grout mixes. For the grout flowability, addition of TOSW as partial replacement of cement increased the flowability of grout mixtures slightly. Addition of TOSW was found to reduce the compressive strength of green grout compared to that of the conventional grout especially at the early ages (7 days). This reduction could be attributed to the replacement of cement with an inert material (TOSW) which decrease the hydration reaction, and hence; the gain of strength. However, the grout strength still meets the requirements for grouted helical piles applications. Replacement 30% of cement with TOSW in grouted helical pile test was successful, and found to have no effect on the pile geotechnical performance. Finally, incorporating of waste materials in construction applications can be an effective solution for waste management challenges.

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Reply to the Reviewers' comments

Paper reference no. 78
Title: Sustainable grouted helical piles
Author: Mohamed Mansour

Reviewers comment	Reply
1- Referring to the TOSW as "an inert material" implying that it does not contribute to the strength gain of the grout - i.e. it does not act as a supplementary cementing material (pozzolan). If that is the case, I wonder whether the whole concept of "replacing cement" has any validity.	Oil sands consists of (3-5) % water, (8-14) % bitumen, and (83-88) % mineral solids. This huge amount of the mineral solids represents the oil sand waste that has to be treated and disposed. What we are doing is investigating the effect of re-using the treated waste as a filler material in different geotechnical applications (i.e. grouted helical piles) to decrease the amount of waste to be disposed. And hence, we will help in solving one of the major challenges facing this industry now a days.
2- If the TOSW is inert, is it not more like adding aggregate to the mix - i.e. simply creating a different grout mix with a lower cement content? All the trial mixes meet the "strength requirement", but with decreasing strength at higher replacement levels - implying that the base mix could have been reworked with a lower cement content (but no TOSW) to save cement and give a strength closer to what is required for design. Had that been done, the additional mixes with TOSW replacement would not have met the requirements - i.e. the replacement only works because the original mix design was richer than it needed to be.	The hydration reaction between water and the cementitious material of grout mixtures depends on many factors such as **fineness** and **cement content**. Addition of TOSW increases the fineness of the grout mixtures as its average grain size is nearly one fourth that of the ordinary Portland cement. Therefore, addition of TOSW will decrease the hydration reaction between the cementitious material and water at the early ages causing a reduction in the compressive strength. While at later ages, the small particle size of TOSW helps it to act as a filler material that fills the voids between cement particles, and hence, it reduce the volume to be filled with the hydration products making the grout denser and more homogenous. Therefore, the reduction in the compressive strength of TOSW grout mixtures compared to the conventional grout mixture dropped from (17, 23, and 37) % after 7 days to (5.3, 11.1 and 27.0) % after 28 days for grout mixtures incorporating 10%, 20% and 30% TOSW respectively. Preparing a grout mixture with lower cement content only, will lose the increase in the strength gaining rate at later ages, and it will not help in decreasing the amount of TOSW that has to be disposed.
3- **T**he paper needs to be reviewed for proper English/grammar prior to final submission.	As recommended the paper had been reviewed for proper English and grammar.