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Utilization of Treated Oil Sand Waste in Cementitious Materials for Sustainable Geotechnical Applications

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ABSTRACT

Oil sand drill cuttings waste is a major challenge for the oil sand mining sector. Thermo-Mechanical Cuttings Cleaner (TCC) is a new technology that separates water and oil from the solid waste. The remaining part of the tailing is fine particles of mainly quartz crystals, which is referred herein as Treated Oil Sand Waste (TOSW). The present work offers innovative utilization of TOSW in cementitious materials for sustainable geotechnical applications. The physical, chemical and mineralogical characteristics of the treated oil TOSW as well as fresh and hardened properties for grouts, concrete and controlled low strength material (CLSM) incorporating the TOSW were evaluated. The results demonstrated that TOSW can partially replace cement or sand, and fully replace fly ash in the considered applications. For example, grout used for constructing micropiles was manufactured utilizing TOSW as partial replacement of cement. In addition, TOSW partially replaced natural sand in concrete mixture used for piles, and fully replaced fly ash in the manufacture of controlled low strength material (CLSM) to improve its important fresh properties such as flowability. The results of the study demonstrated that grout and concrete mixtures incorporating TOSW meet all the performance and environmental requirements of these applications.

Keywords: Oil sands; Drill cutting waste; Grout; Compressive strength; Shrinkage; Leaching

1 INTRODUCTION

Implementing industrial waste in cementitious material manufacture offers a sustainable approach for its recycling. Employing materials that would otherwise be considered waste in designing grouts or concrete mixtures can increase its sustainability along with reducing harmful impact of waste disposal on the environment. Correspondingly, several industrial wastes are used in cementitious materials as binders, as additives or as a replacement of aggregate. However, incorporating the industrial waste in the mixture would alter its fresh and hardened properties (Aggarwal and Siddique, 2014, Yang *et al.*, 2015). The required properties of the cementitious material govern the type, proportion and properties of the used waste. Materials used in construction material should have certain performance characteristics such as mechanical strength and durability, to achieve specified performance levels to meet the intended application requirements. Meanwhile, any injurious effect on human wellbeing or environment must be avoided.

Oil is produced in Canada primarily through its extraction from oil sands, which represents a significant contribution to Canada's GDP but the resulting waste has a serious environmental and ecological impacts (Söderbergh *et al.*, 2007; Carson, 2011) This motivated the development of pre-treatment processes to reduce this solid waste or convert it to a reusable product. Thermo-Mechanical Cuttings Cleaner (TCC) is one such novel technique, in which drill cuttings solid waste is thermally treated to recover hydrocarbons (Ormeloh, 2014). However, the by-product of this treatment technique (i.e. the remaining solids) is very fine quartzes powder, denoted here as treated oil sand waste (TOSW), which is currently disposed of as waste. The TOSW fineness makes it an excellent candidate to be used as a filler material in manufacturing cementitious materials, which can improve workability, mechanical strength and durability of the final product.

The hydration kinetics of cement, both chemically and physically, can be affected by the addition of TOSW, and consequently the properties of the cementitious materials could be altered (Lawrence *et al.*, 2003). The composition and solubility of TOSW may modify the chemical equilibrium of ionic species in pore solutions leading to acceleration or retardation of the hydration reactions. In addition, TOSW can affect the cement hydration through diluting the cement or modifying the particle size distribution and heterogeneous nucleation. These effects become more significant as the replacement proportion of cement or aggregate by the TOSW increases. The effect of the particle size distribution depends on the fineness and the amount of added TOSW as it modifies the mixture porosity. Meanwhile, heterogeneous nucleation causes chemical activation of the cement hydration due to the nucleation of hydrates on foreign mineral particles. The TOWS is not reactive itself but it provides nucleation sites for hydrates.

Grout is a fluid form of concrete and it is a *mixture of water, cement and sand.* It is employed in several geotechnical and structural applications. Its geotechnical applications include pressure grouting, filling voids, constructing micropiles and stabilizing slopes. Controlled low strength materials (CLSM) typically consist of a mixture of Portland cement, water, aggregate and sometimes fly ash. CLSM is a self-compacted self-levelling cementitious material with compressive strength typically less than 8 MPa. It is used as an alternative of soil backfill materials in geotechnical and infrastructure applications. Concrete is the most widely used construction material worldwide, and is used in many geotechnical applications such as forming deep foundations (piles), shallow foundations, retaining walls, etc. Ordinary concrete is a composite material that is created from a mixture of cement, fine and coarse aggregates (*sand and gravel), water, and other admixtures, and* typically has strengths exceeding 21 MPa. However, its environmental impact represents a major sustainability challenge. Thus, green concrete mixtures that incorporate waste materials as a partial or total replacement for cement and/or aggregates can increase its sustainability along with reducing harmful impact of waste disposal.

These different cementitious materials are used in the geotechnical/construction industry in large quantities. Therefore, this study investigates the effect of incorporating TOSW on the properties of produced cementitious materials such as grout, concrete and CLSM. This can lead successful utilization of TOSW as a construction material and transforms oil sands drill cuttings waste into to a high-value resource. This paper summarizes the findings from this comprehensive study.

2 EXPERIMENTAL PROGRAM

2.1 Materials

This paper describes a method of producing cementitious formulations comprising treated oil sands drill cuttings obtained by separating water and hydrocarbons from solid constituents of the oil sands drill cuttings employing the Thermo-Mechanical Cuttings Cleaner (TCC). The produced TOSW comprises solid SiO_2 particles having a size distribution in a range from about 0.8 to about 30 microns, and with about 90% of a sample volume below about 9.9 microns. The TOSW comprising solid SiO_2 particles is mixed with constituents used in preselected cementitious formulations in different geotechnical applications, with TOSW being in an amount of about 10 to about 40% by volume.

The cementitious formulations considered are either grout, concrete or CLSM. In a grout formulation, the TOSW is mixed with at least cement and water, and wherein its particles are used to replace some of the cement in an amount between 10 to 50 % by volume. Additionally, another grout formulation comprising TOSW mixed with water, cement and sand, wherein TOSW particles are used to replace some of the cement and sand. In this mixture, the TOSW replaces the cement in an amount between 10 to 30 % by volume, and replaces the sand in an amount between 10 to 20 % by volume. In addition, concrete mixtures incorporating 10%, 20%, 30% and 40% TDSW as partial replacement of sand are investigated. Finally, CLSM mixtures are investigated where TOSW replaces sand in the amount of 5%, 10%, and 15% by volume. Another nine CLSM mixtures are investigated with TOSW replacing 100% of fly ash along with partial replacement of sand by volume at rates 5%, 10% and 15%. Ordinary Portland cement (OPC) Type 10 with a Blaine fineness of 360 m^2/kg and specific gravity of 3.15 was used in all mixtures as a binder material. The TOSW material used had a Blaine fineness of 1440 m^2/kg and specific gravity of 2.23. Figure 1 shows a scanning electron microscopy photograph and an energy dispersive X-ray analysis (SEM/EDX) for the TOSW. Table 1 presents the chemical compositions for OPC and TOSW obtained through XRD while Fig. 2 displays their grain size distribution. Aboutabikh et al. (2016) describe the different tests used to characterize the TOSW and OPC.

Table 1. Chemical composition and physical properties of cementitious materials

Types	OPC	TOSW
Chemical analysis		
SiO_2	21.60	61.24
Al_2O_3	6.00	8.73
Fe_2O_3	3.10	3.00
CaO	61.41	5.55
MgO	3.40	0.92
K_2O	0.83	1.60
Na_2O	0.20	0.85
P_2O_5	0.11	0.15
SO_3	1.76	3.00
TiO_2	---	0.46
Loss on Ignition	0.81	12.60

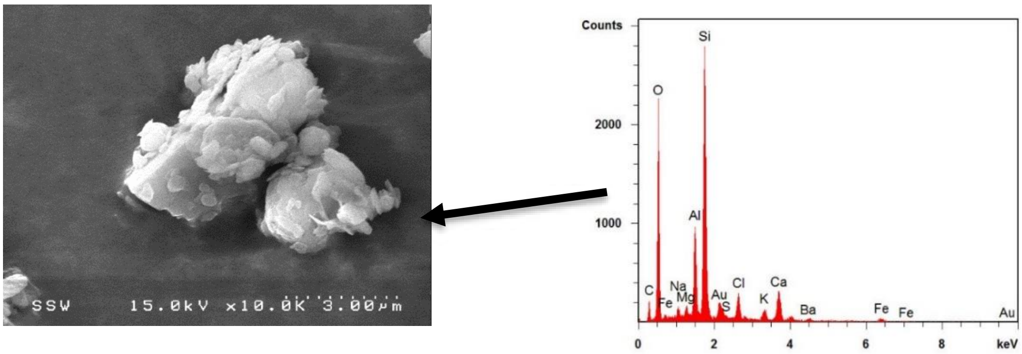
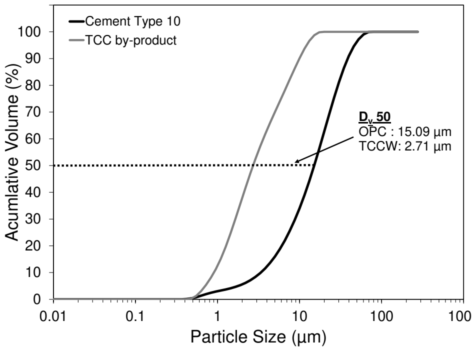


Figure 1: SEM image and EDX for TCCW.



*Dv50: the maximum particle diameter below which 50% of the sample volume exists.

Figure 2: Particle size distribution using Laser diffraction for OPC and TCCW.

2.1.1 Grout mixtures

As shown in Table 2, 5 mixtures with TOSW contents varying from 0%, 10%, 20%, 30% to 50% by volume as a partial replacement of cement were tested to evaluate the effect of incorporating TOSW on the grout characteristics. Further details of the tests can be found in Aboutabikh et al. (2016).

Table 2. grout mixtures composition

	TOSW %				
Materials	**0%**	**10%**	**20%**	**30%**	**50%**
Cement	400 g	360 g	320 g	280 g	200 g
TOSW	----	28 g	57 g	85 g	142 g
Water	168 g	167.81 g	168.21 g	168.03 g	168.24 g

2.1.2 Concrete Mixtures

Washed round gravel with sizes 5 to 10 mm was used as coarse aggregate with fines content less than 1%, and natural siliceous sand was used as fine aggregate. A water to cement ratio of 0.42 was used in all concrete mixtures. A superplasticizer (HRWRA) was utilized to adjust mixture flowability and air entraining admixture was used. All concrete mixtures were designed to achieve a slump of 220 mm ± 50 mm and minimum 28-day compressive strength of 35 MPa. The concrete mixtures composition is shown in Table 3. Further details are given in Kassem et al. (2018).

Table 3: Concrete mixtures composition

Property	Control	10% TOSW	20% TOSW	30% TOSW	40% TOSW
Cement	1	1	1	1	1
Sand	1.79	1.6	1.42	1.24	1.07
Gravel	2.45	2.45	2.45	2.45	2.45
TDSW (%)	0	10	20	30	40
Superplasticizer (%)	0.80%	0.85%	1.0%	1.15%	1.6%
Air entrainment (%)	0.05	0.05	0.05	0.05	0.05
Slump (mm)	225	225	220	220	215
Concrete temperature (C°)	17	18	18	23	23
Air temperature (C°)	22	24	24	23	23

2.1.3 CLSM Mixtures

The testing program involved 3 groups, one control and two groups of grout mixtures containing TOSW. The control mixture (Group 1) had no TOSW and was prepared according to ACI PRC-229R-13 (2022). All mixtures were mixed with OPC and natural sand with a specific gravity of 2.65. Group 2 comprised 6 mixtures with TOSW partially replacing sand in the amount of 5%, 10%, and 15% by volume. Group 3 included nine mixtures with TOSW replacing 100% of fly ash and partially replacing sand by volume at rates 5%, 10% and 15%. **Table 4** presents the mixtures proportions. Mneina et al. (2018) provide further details on the testing program.

Table 4. CLSM mixtures proportions

	Mix Code	Cement kg/m^3	Fly ash kg/m^3	Aggregate kg/m^3	TOSW kg/m^3	Water kg/m^3	W/Powder[1] kg/m^3
(Group 1) Control Mixtures	G130	30	148	1727	0	297	4.3
	G160	60	148	1691	0	297	3.8
	G190	90	148	1655	0	297	3.4
(Group 2) TOSW replacing aggregate	G260W5	60	148	1606	84	221	1.9
	G260W10	60	148	1522	168	226	1.5
	G260W15	60	148	1437	253	221	1.2
	G290W5	90	148	1572	82	270	2.2
	G290W10	90	148	1490	165	245	1.5
	G290W15	90	148	1407	247	244	1.13
(Group 3) TOSW replacing fly	G330W5	30	0	1641	205	209	2.1
	G330W10	30	0	1554	277	177	1.3
	G330W15	30	0	1468	350	165	1.0

ash and aggregate	G360W5	60	0	1606	205	246	2.2
	G360W10	60	0	1522	274	227	1.6
	G360W15	60	0	1437	341	232	1.3
	G390W5	90	0	1572	205	224	1.9
	G390W10	90	0	1490	274	212	1.4
	G390W15	90	0	1407	341	213	1.2

[1] The ratio of water content to fly ash, cement and TOSW

2.2 Mixing Procedure

2.2.1 Grout mixtures

Grout mixtures were prepared according to ASTM C305. Specimens for different tests were prepared from each mixture batch. The casted specimens were maintained at ambient temperature of 23 ± 1°C and with covered plastic sheets to maintain moisture. After demolding, specimens were placed in curing room with same temperature and relative humidity of 98 % until tested.

The effects of TOSW on the mixture are evaluated in terms of water demand for normal consistency (ASTM C187), cement reactivity (ASTM C191), compressive strength at ages 7, 28 and 90 days (ASTM C109 using 50-mm cube specimens and drying shrinkage (ASTM Method C490 using prismatic specimens of 25 × 25 × 280 mm). Thermo-gravimetric analysis was also conducted to evaluate the microstructure development. Finally, leaching tests were conducted on specimens 50 × 50 × 50 mm following the procedure proposed by Dransfield (2004).

2.2.2 Concrete mixtures

All test mixtures were prepared to achieve strength, workability and durability requirements for continuous flight auger piles with slump of 220 mm ± 50 mm and a minimum 28 days compressive strength of 35 MPa (Brown *et al.*, 2007). Different tests were conducted to measure fresh properties (i.e., slump (ASTM C143) and bleeding (ASTM C232) as well as hardened properties (i.e., compressive and tensile strengths, and modulus of elasticity (ASTM C39 and ASTM C496), flexural strength (ASTM C78), and bond strength between the concrete and the rebar). All specimens were produced in triplicate and were cured in curing room with temperature = 23 ºC ± 2 ºC and relative humidity of 95% ± 5% until tested at ages 7, 28 and 120 days. Furthermore, the durability performance of the specimens was evaluated by conducting freezing and thawing tests on prismatic concrete specimens (ASTM C666). Finally, leaching tests were performed following ASTM 1315 on concrete specimens with and without TOSW immersed in the same water volume. Presented results are the average of six leachate samples.

2.2.3 CLSM mixtures

Dry mixture components, including OPC, TOSW and fly ash were mixed for 1 minute without water, then half of the mixing water was added gradually to the mixture and mixed for another minute, followed by adding the remaining water and mixing for another minute. After allowing the mixture to rest for 1 minute, mixing continued for 2 minutes before sampling. The flowability of the mixture was continuously measured during the addition of water to reach the desired normal flowability range of 150mm to 200mm as recommended by ACI PRC-229R-13 (2022).

3 RESULTS AND DISCUSSION

3.1 Grout Mixtures

3.1.1. Water of consistency

The mixture water of consistency decreased slightly as the percentage of TOSW increased up to TOSW dosage of 20%, beyond which a lower reduction in water of consistency was observed (e.g., water demand for normal consistency for mixtures incorporating 20% and 30% of TOSW was 6.7% and 4.3% less than that of the control mixture). Two competing effects caused this behaviour: adding the very fine particles of TOSW increased the specific surface area of the powder and hence higher water demand; meanwhile, the fine TOSW particles enhanced the packing density of powder and reduced the interstitial void, which decreased the entrapped water between cement particles. Therefore, the overall effect of adding TOSW would depend on the volume of the used fine material and 20% TOSW could be considered as the threshold value.

3.1.2 Heat of hydration

Adding TOSW as a partial replacement of cement reduced the hydration heat and the higher the replacement ratio, the greater the reduction in the main hydration peak. The dilution effect (Rahhal and Talero, 2005) caused this behaviour. However, a chemically inert behaviour does not mean that the hydration kinetics cannot be influenced and only retarded due to the dilution effect. Lawrence *et al.* (2005) demonstrated that adding chemically inert mineral in mortars alters the degree of hydration, which explains the observed increase in the slopes of hydration curve during the acceleration periods (i.e., up to the second peak) that indicates nucleation effect. The slight variation in the measured setting time confirmed this analysis (e.g., initial setting time for all tested mixtures ranged between 2.68 hrs and 2.93 hrs). On the other hand, changes in the value and location of the third peak were more pronounced as ratio of TOSW increased.

3.1.3 Compressive strength

The compressive strength increased for all mixtures with time, but adding TOSW reduced the achieved compressive strength. The 7-day compressive strength of mixtures with 10% and 30% of TOSW as a partial replacement of cement decreased by 12% and 34% compared to the control mixture due to both dilution and filler phenomena. Adding a fine filler to cement modifies the early hydration rate due to dilution effect; and replacing cement by inert TOSW decreases the total cement content leading to a lower formation of hydration products. On the other hand, the large specific surface of the fine TOSW particles increases its potential as nucleation sites, which promotes the precipitation of hydration products and partially compensates for the reduction in the hydration rate due to the dilution effect (Cyr *et al.*, 2006). The results indicated that the percentage reduction in mixture compressive strength decreased as sample age increased; however, replacing more than 20% of cement by TOSW caused significant reduction in the compressive strength regardless of the sample age. This indicates that the dilution effect in mixtures with TOSW > 20% dominated the behaviour. Even though adding TOSW reduced the compressive strength, it was still within the range for micropile application, which requires minimum design compressive strength of grout as 28 MPa (FHWA, 2005).

3.1.4. Drying shrinkage

The results demonstarted that regardless of the TOSW percentage, shrinkage and mass loss of mixtures incorporating TOSW were higher than the control mixture, and the difference increased as percentage of TOSW increased. For example, mixtures with TPSW replacing 10% and 20% of cement exhibited 11% and 19% higher shrinkage than the control mixture at 28 days. This shrinkage was primarily due to the water leaving the test specimens. The presence of TOSW influences the mixture microstructure including the total porosity, critical pore diameter and connectivity of capillary pores. Therefore, shrinkage and mass loss are attributed to two concurrent effects of TOSW addition: filling and diluting. The fine TOSW acted as a filler leading to finer pores, which in turn lead to higher shrinkage. Meanwhile, replacing cement with TOSW reduced the cement content leading to formation of lower amounts of hydration products and lower amount of water was consumed in the hydration reactions. Hence, more free water became available for evaporation leading to a higher mass loss (e.g., mixtures with TOSW replacing 20% and 50% of cement exhibited 5% and 29% higher mass loss than the control mixture at 7 days).

3.1.5. Leaching

Adding TOSW to replace more than 20% of cement adversely affected the grout performance. Therefore, the leaching test was conducted only on mixtures with TOSW replacing 10% and 20% of cement. Both mixtures with 10% and 20% TOSW exhibited a reduction in metal leaching compared to the raw TOSW sample. Moreover, metal leaching results was below groundwater standard of the Canadian Council of Ministers of Environment (CCME). For example, leaching of Aluminum, Arsenic, Cadmium, Copper, Nickel, and Vanadium from mixtures with TOSW was well below CCME standards due to the solidifying of the TOSW in the mixture microstructure. In addition, the fine TOSW acted as a filler decreasing the void spaces and entrapped higher amount of metal.

3.2 Concrete Mixtures

3.2.1 Fresh properties

To examine the effect of adding TOSW on the concrete workability, all mixtures slump was adjusted to 220 ± 5 mm while monitoring the change in HRWRA demand. The results indicated that adding TOSW reduced slump, and increased required HRWRA dosage to maintain the slump value (e.g., HRWRA increased by 0.2% for mixture with 20% TOSW to achieve the same slump of the control mixture). This is because the fineness of TOSW, which confers a very high viscosity to the fresh mixture and greater cohesivity and lower slump (Frontera *et al.*, 2013). Meanwhile, no mixtures showed any sign of segregation or bleeding. In addition, all concrete mixtures incorporating TOSW maintained up to 90 min slump retention time after mixing which far exceeded the 30 minutes slump retention required for installation of continuous flight auger. Therefore, mixtures incorporating TOSW can be used successfully in this application from workability point of view.

3.2.2 Compressive strength

Compressive strength decreased for mixtures incorporating TOSW as partial replacement of sand and the reduction was higher as the TOSW percentage increased (e.g., adding 10% and 30% of TOSW reduction the 28-day compressive strength by 4% and 16% compared to the control mixture). This reduction can be ascribed to the increase in the amount of fine materials and inadequate dispersion of TOSW particles due to coagulation. Nonetheless, all tested mixtures meet the targeted 28-day compressive strength for CFA piles (i.e. 35 MPa), except for mixture incorporating 40% TOSW; the compressive strength for mixtures incorporating 20% and 30% were 52.31 MPa and 46.75 MPa.

3.2.3 Splitting tensile strength

Tensile strength of all mixtures had the same trend of the compressive strength results; as TOSW amount increased, the tensile strength decreased (e.g., adding 10% and 40% of TOSW reduced the tensile strength by 6% and 23% compared to the control mixture). Similarly, adding TOSW had insignificant effect on the development rate of the tensile strength. The results also showed that the tensile strength of mixtures with TOSW was 10% or greater of the compressive strength. Thus, equation that are used to predict tensile strength of regular concrete can be applied to concrete mixtures incorporating TOSW based on its compressive strength.

3.2.4 Flexural strength

The results clearly demonstrated that flexural strength was consistent with compressive and tensile strength results. The flexural strength for all mixtures was around 13% ± 1% of the compressive strength (e.g., ratios between flexural and compressive strengths for mixtures incorporating 20% and 40% of TOSW were 11.6% and 13.2% at 28 days). Thus, flexural strength of mixtures incorporating TOSW can be predicted from its compressive strength employing the ACI formula (ACI 318, 2008; ACI 363R, 2010).

3.2.5 Pullout strength

Rebars with a diameter of 10 mm were used in the pullout test. At age 7 days, all tested mixtures exhibited pull-out strength more than 75% of the final strength (e.g., control mixture without TOSW and mixture with 30% TOSW achieved 77% and 87% of their final pull-out strength). Moreover, adding TOSW reduced the pull-out strength compared to the control mixture, and the reduction was more for mixtures with higher TOSW content (e.g., increasing the TOSW content from 10% to 40% reduced the pull-out strength by 30% with respect to the control mixture at 28 days).

3.2.6 Leaching

Leaching of heavy metals from the TOSW was initially evaluated for raw TOSW. According to the Canadian Council of Ministers of Environment (CCME) guideline limits, incorporating TOSW in concrete mixtures significantly reduced the leaching for different metals compared to raw TOSW (e.g., the leaching of leaching values for Vanadium, Arsenic, Aluminum and Nickel for concrete mixtures with TOSW were below CCME standards by about 20% to 93%). The main leaching metal concerned in TOSW was the Barium, which was reduced below the CCME. This is because the densification and reduction in porosity of concrete microstructure due to the fine TOSW particles.

3.3. CLSM Mixtures

3.3.1 Flowability

The targeted flow of CLSM mixtures is150 to 200 mm, which is controlled by the amount of water used in the mixture. The results revealed that changing the cement content while maintaining the same fly ash content had an insignificant effect on the flowability of CLSM. The flowability of CLSM control mixtures ranged from 185 to 250 mm. Adding TOSW reduced the amount of water required to achieve the same flowability by about 25%; mixtures containing TOSW required considerably lower water/powder ratios while having the same flowability. The very fine TOSW increased the particles surface area, which increased the water demand; However, it enhanced the powder packing and released the water entrapped between cement particles making it available for lubrication and hence increased the flowability. In addition, the very fine TOSW particles acted as a “lubricant” between the coarse aggregate particles. This was clearly obvious in Group 3 mixtures where fly ash was replaced by TOSW. TOSW addition was more efficient in increasing flowability than fly ash.

3.3.2 Density

Density of the fresh and hardened CLSM samples were measured at different ages up to 28 days of curing. The fresh density of control mixture ranged from 2190 to 2195 kg/m^3. The density of Group 2 ranged from 1816 to 1901 kg/m^3, i.e., a reduction of 17% compared to the control mixtures, but still lies within the range of normal CLSM (ACI Committee 229). For Group 3 mixtures, the fresh density increased by 6% for G390 and G360 mixtures, but decreased with age at a rate slower than Group 2 mixtures. The fresh density ranged from 2067 to 2325 kg/m^3 for all Group 3 mixtures, which was also within the range of normal CLSM.

3.3.3 Bleeding

Increasing the cement content reduced the bleeding in all mixtures as more water was consumed in hydration resulting in less free water. For instance, increasing the cement content in control mixtures from 30 to 90kg/m^3 reduced bleeding by about 34%. The bleeding results range matches the range found in the literature for CLSM mixed with fly ash (Yan et al. 2014) [31]. The settlement during placement was also measured based on volume reduction due to released water and entrapped air; the subsidence results ranged from 1.8% to 3.1%.

Mixtures with TOSW showed a significant reduction in bleeding ranging from 76% to ~100% for G260 mixtures and from 17% to 95% for G290 mixtures and up to 17% and 70% for G360 and G390 mixtures compared with bleeding control mixtures as shown in Figure 3. This reduction can be attributed to the increase in fine materials content in the mixture which is directly related to the water/powder ratio.

Incorporating waste that includes large amounts of fines (i.e., large surface area) increases the amount of water needed to cover the fine particles, which keeps water from escaping to the surface as bleed water during setting of the mixture (Katz and Kovler 2004). Bleeding values of all mixtures, however, were well below the maximum of 5% for stable CLSM (Yan et al. 2014).

3.3.4 Drying shrinkage

The drying shrinkage of all mixtures was measured as the change of the sample initial length. Measurements were taken until no significant change was recorded. Measurements for control mixtures G160 and G190 showed that increasing cement content reduced the shrinkage which has been reported in the literature (Katz and Kovler 2004) as the hydration products were increased, leading to less free water for evaporation.

Mixtures containing TOSW experienced increases in shrinkage. For example, shrinkage of G260 and G290 mixtures increased from 0.031% to 0.082% and from 0.038% to 0.072% compared to that of the control mixtures, respectively. This behaviour is related to the water/powder ratio and amount of bleeding observed. Mixtures with high bleeding values exhibited lower shrinkage as the water dried from the surface rather than from the bulk of the material (Katz and Kovler,2004). Moreover, incorporating a fine inert material like TOSW as a filler material resulted in finer capillary pores in the hardened mix, which increased the internal tensile stresses leading to more shrinkage (Aboutabikh et al., 2016).

The normal range of ultimate shrinkage in CLSM is between 0.02% and 0.05% (ACI Committee 229R, 2013). The range of the measured shrinkage for G260 mixtures exceeded the normal range for CLSM yet was still below the typical ultimate shrinkage of 0.1% for concrete. The mixture design can be optimized to keep the shrinkage closer to the lower limit (i.e., 0.031%) however, shrinkage dose not affect the performance of CSLM (ACI Committee 229R, 2013).

3.3.5 Leaching of Heavy Metals

Table 4, Figure 5 and Figure 6 show the results of the conducted (ICP-MS) analysis on the leachates. It is noticed from Figure 5 that the TOSW has little to no contribution to the concentration of Lithium and Chromium of the leached material. The concentration of these metals increased with age only for mixtures containing cementitious materials (fly ash and cement), while measurements for the same elements in raw TOSW samples were within minimum detectable concentration. On the other hand, leaching of Arsenic, Strontium, Cadmium and Barium were prominent for the raw waste sample and greatly reduced for samples containing cementitious materials with fly ash, which indicates stabilization of these elements in CLSM mixtures. However, concentration of Strontium and Barium were noticeably higher in Group 3 mixtures as the amount of cementitious materials reduced by replacing fly ash with TOSW. Figure 6 reveals a clear reduction in the concentrations of Lithium and Chromium for samples with TOSW replacing fly ash (Group 3) compared with mixtures containing fly ash (Group 2) after 28 days of leaching. All leaching results were below the concentration limits of the groundwater standard of the Canadian Council of Ministers of Environment (CCME).

3.3.6 Compressive strength

The compressive strength was investigated for the 3 control mixtures of CLSM and 15 mixtures with different cement, TOSW and fly ash contents, CLSM samples were tested after 7, 14 and 28 days of curing. The compressive strength values of the tested mixtures are presented in Table 5 and Figure 7. Control mixtures with cement content of 30 and 60 kg/m^3 (i.e. G130 and G160) exhibited a very slow strength gain rate compared with 90 kg/m^3 mixture (G190). The class F fly ash used in these mixtures had no cementitious properties and needed cement in order for the pozzolanic reaction to occur; in the presence of cement, the silicate minerals in fly ash react with the calcium hydroxide released during the hydration process of the cement (Thomas 2007). For mixtures incorporating TOSW, the compressive strength depended mainly on the water/powder ratio. The strength of G290 mixtures increased as the water/powder ratio decreased regardless of TOSW content. However, in Group 2 mixtures, the TOSW enhanced flowability, which reduced the amount of water needed for the mixture, and consequently the strength increased (e.g., G260 mixtures). On the other hand, replacing fly ash with TOSW in Group 3 mixtures reduced the strength due to decreased bonding between particles owing to the lack of fly ash pozzolanic activity that was available in Group 2 mixtures. However, the strength reduction can be compensated for by increasing the cement content. For example, increasing the cement content from 60kg/m^3 to 90 kg/m^3, led to an increase in the achieved compressive strength of about 300% (i.e. from 423 kPa for G360 mixture to 1233 kPa for G390 mixture). In addition, for some CLSM applications, it may be important to maintain a low strength to facilitate future excavation. The ACI committee 229 recommends a compressive strength lower than 2.1 (MPa) if future excavation is anticipated.

CLSM cylinders were also tested for tensile strength according to ASTM test method C496/C496M and a good linear relationship between the tensile and compressive strengths was observed. The tensile strength ranged from 7% to 17% of the compressive strength, which is close to the range of normal concrete (8% to 14%).

4 CONCLUSIONS

This paper summarizes the results of a comprehensive experimental study on the feasibility of incorporating TOSW in cementitious materials used in geotechnical applications. The following conclusions may be drawn from the results.

- Water of consistency of grout mixtures slightly decreased as TOSW percentage increased.
- The compressive strength of grout mixtures decreased as TOSW increased. For mixtures with TOSW > 20%, the strength decreased by 30%.

- Adding TOSW increased shrinkage. Therefore, it is suggested to apply a shrinkage mitigation method (i.e. the use of shrinkage reducing admixture) for cementitious materials mixtures incorporating TOSW.
- Increasing the HRWRA dosage can overcome the reduction in concrete slump of mixtures incorporating TOSW and maintain its workability within the required range for CFA application.
- Mixtures incorporating up to 30% TOSW replacement of sand satisfy the compressive strength requirement for CFA piles (i.e., 35 MPa).
- The correlations between compressive strength and other mechanical properties of concrete incorporating TOSW are the same as those applicable to conventional concrete.
- TOSW increased the flowability of CLSM mixtures, which reduced the water demand and lead to higher compressive strength in Group 2 mixtures. TOSW was more effective in increasing flowability compared with fly ash in Group 3 mixtures.
- Lower dry density was achieved for mixtures with TOSW, which makes it suitable for field applications encountering weak soils. Some mixtures could be classified as Class VII low-density CLSM (LD-CLSM) according to ACI committee 229R, which makes TOSW a suitable material for application in LD-CLSM mixtures.
- Incorporating TOSW in CLSM mixtures has significantly reduced bleed water.
- The 28-day compressive strength of CLSM mixtures ranged from 0.6 MPa to 4.7 MPa for control mixtures with different cement content and from 2.8 MPa to 6.8 MPa for Group 2 mixtures with different cement and TOSW contents. Higher strength values were achieved for mixtures with higher TOSW content. Replacing fly ash with TOSW in Group 3 mixtures lowered the strength and elastic modulus compared to the control mixtures. Higher cement content can compensate for reduced strength due to elimination of fly ash. Increasing cement content from 60 kg/m^3 to 90 kg/m^3 increased the CLSM mixture strength from 423 kPa to 1233 kPa.
- Fly ash can be replaced by TOSW in CLSM mixtures while maintaining the properties for CLSM within the limits of ACI committee 229 report.
- Incorporating TOSW in cementitious materials mixtures lowered the pollutant potential of the TOSW in terms of leaching of heavy metals with concentrations within the limits of the groundwater standard of the Canadian Council of Ministers of Environment (CCME).

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