A PRELIMINARY VALUE-ADDED ASSESSMENT OF A THERMALLY TREATED DRILL MUD WASTE

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ABSTRACT
Drill mud waste management can be a significant consideration in many oil and gas exploration and development projects. In Atlantic Canada, regulations result in a portion of this drill mud waste being transported onshore where it undergoes a blending and Low Temperature Thermal Desorption (LTTD) remediation process. The purpose of this paper is to: 1) review some pertinent offshore and onshore regulatory requirements related to disposal of this waste, and, 2) examine the potential value-added properties of an unblended thermally treated drill mud waste (TTDMW) that undergoes a different thermal treatment approach, Indirect Thermal Recovery (ITR). It is hypothesized that unblended ITR treated drilling mud waste solid may have desirable properties applicable to reactive barrier applications in landfill base liners. Preliminary results of chemical, mineralogical and physical testing performed on an ITR thermally treated synthetic-based mud (SBM) are presented in the paper.

RÉSUMÉ
La gestion des boues de forage usées peut être de considération importante lors de projets d’exploration et de développement pour le pétrole et le gaz. Sur la côte Est canadienne, l’imposition des régulations résulte en le transport d’une portion des boues de forages usées à terre, où ces dernières subissent un processus de mélange et de remédiation en utilisant une Désorption à Basse Température (DBT). Le but de ce papier est de: 1) revoir quelques exigences réglementées quant à la disposition à terre et en mer des boues de forage usées et, 2) examiner le potentiel ajouté des propriétés des boues de forage non mélangées et traitées thermiquement par un processus thermique différent, soit la récupération thermique indirecte (RTI). Il est anticipé que les boues de forages non mélangées et traitées par RTI peuvent avoir des propriétés désirables, applicables à des barrières réactives dans les couches de base de sites d’enfouissement. Les résultats de tests préliminaires chimiques, minéralogiques et physiques réalisés sur des boues de forage à base synthétique traitées par RTI sont présentés dans ce papier.

1. INTRODUCTION

The offshore oil and gas industry in Atlantic Canada is currently in its infancy with the Sable Offshore Energy project operating offshore of Nova Scotia and the Hibernia, Terra Nova, and White Rose projects offshore of Newfoundland (see Figure 1). In Nova-Scotia, the Sable Offshore Energy Project currently involves the development of natural gas fields near Sable Island. In Newfoundland, Hibernia, Terra Nova and White Rose produce mainly oil with differing amounts of natural gas (CNOPB, 2004). Several new exploration wells are planned, with more anticipated in the future offshore Atlantic Canada.

Each production or exploration well drilled requires the use of drilling muds to mitigate formation pressures, to lubricate the drill bit, to stabilize the wellbore, and to remove drill cuttings away from the hole. As summarized by offshore regulations set forth by the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB, 2004), varying types of drilling muds are used in this regard: water-based muds (WBMs), synthetic-based muds (SBMs), oil-based muds (OBMs) and enhanced mineral oil-based muds (EMOBMs). The muds and accumulation of fluids and cuttings from drilling operations are subjected to various waste management regulations after their use due to the inorganic and organic constituents present in the muds. This material is referred to in this paper as drill mud waste. Effort is usually made offshore to separate the majority of the drill solids from the drill mud waste. According to offshore waste treatment guidelines developed jointly by the Canada-Nova Scotia Offshore Petroleum Board and Canada-Newfoundland Offshore Petroleum Board (CNOPB, 2004), WBM drill waste solids may be discharged at sea, while SBM drill waste solids and EMOB drill solids can possibly be re-injected into a geological formation (Guo and Abou-Sayed, 2003) or discharged at sea when oil to wet solid concentrations are less than 6.9 percent. Onshore disposal is another potential option for the drill waste solids (Page et al, 2003). Although not generally used in Atlantic Canada, OBM waste solids may not be discharged to sea, under any circumstance.

Drill mud waste that is not discharged at sea or re-injected into geological formations is often transported onshore for disposal/treatment. Currently, approximately 1000 to 6000 tonnes of drill mud waste are received each year in Nova Scotia. As a comparison, Wait and Thomas (2003) report as many as 100,000 tonnes per year are transferred onshore in the UK sector of the North Sea. Although there are currently several methods utilized for onshore treatment in Atlantic Canada, a portion of the drill mud waste is transported to Envirosoil Limited in Halifax, Nova Scotia where it undergoes a blending operation with other approved impacted soils and a subsequent Low Temperature Thermal Desorption (LTTD) treatment process. The regulatory approved facility reduces the treated blend of soil to non-detect levels for hydrocarbons. Unfortunately, much of the potential value-added properties of the treated mud are lost when mixed with the heterogeneous soil mixture in this process. Envirosoil Limited is currently investigating thermally treating unblended drill mud waste using an Indirect Thermal Recovery (ITR) process (Wait and Thomas, 2003). This would allow recovery of hydrocarbons and potentially improve upon the value-added capability of the treated drill mud waste.

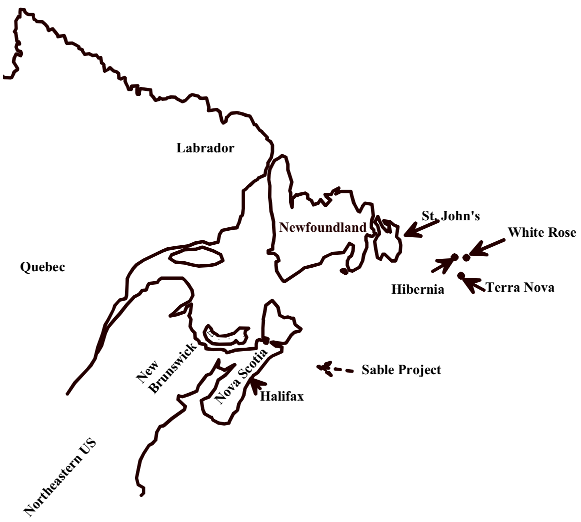

Figure 1. Schematic of Atlantic Canada's current offshore oil and gas project locations (modified from CNOPB, 2004).

The purpose of this paper is two-fold. Firstly, to provide some insight on waste management issues related to the regulated disposal of drilling muds in Atlantic Canada (with a focus on Nova Scotia) as well as to briefly describe the LTTD and ITR treatment methods utilized for the treatment of some of these drilling mud wastes. Secondly, to present results of preliminary chemical, mineralogical and physical testing performed on an unblended SBM subjected to thermal treatment with the ITR process. It is hypothesized that unblended ITR treated drilling mud waste solids may have desirable properties applicable to waste containment applications. The testing presented herein attempts to provide a preliminary assessment of the ITR treated drilling mud waste for this type of application.

2. BACKGROUND

2.1 Drilling Muds and Regulatory Requirements

As described by Wills (2000), drilling muds used in oil and gas exploration and production drilling serve a variety of purposes. Drill muds are usually a mixture of bentonite clay, water and a variety of organic and inorganic additives. These additives vary with drill mud supplier and the intended use of the mud. Due to the highly competitive nature of the oil and gas industry, the exact constituents of the muds often remain confidential. They provide lubrication to the drill bit as well as assisting in cleaning and cooling the drill bit during drilling operations. The muds also suspend drill cuttings generated during drilling operations and assist in preventing well blow-outs (by using weighting agents such as barite to counteract the fluid pressure in the formation). In addition, the drill fluids assist in maintaining wellbore stability during drilling. Waste management issues also play a role in mud type selection (Antle et al, 2003).

From a regulatory perspective, the province of Nova Scotia identifies drill muds into four different classes (CNSOPB, 2004): water-based muds (WBMs), synthetic-based muds (SBMs), oil-based muds (OBMs) and enhanced mineral-based oil muds (EMOBMs). The last three groupings are sometimes generally referred to as organic-phase drilling fluids (Wills, 2000). WBMs are often the preferred drill fluid from an environmental perspective (Sadiq et al, 2004). However, OBMs often provide superior drilling performance. In many cases, drilling conditions are such that WBMs are not feasible and alternatives such as OBMs, SBMs, and EMOBMs become necessary. In Atlantic Canada, WBMs are often used to drill the upper hole sections, while SBMs and EMOBMs are used to drill the lower deviated hole sections into the reservoir. Waste management issues associated with OBMs in Atlantic Canada discourage OBMs.

During drilling operations, drilling fluids are re-circulated down the hole at which time they suspend formation cuttings (solids). Usually an effort is made to remove the majority of the solids (solids control) in order to recycle the muds, provided the mud properties satisfy the conditions of the drilling operation. As outlined in the Nova Scotia Best Management Practices for Drilling Waste (NSBMPDW) document (NSDEL, 2003), the regulations regarding the discharge of drilling waste solids vary in different international marine areas. Some areas of the North Sea regulate a maximum of 1 percent of oil per dry cuttings content for discharge which often means that technical limitations result in contaminated cuttings be re-injected or sent onshore for treatment. In the United States, a discharge limit of 6.9% to 9.4% oil on wet solids concentration is utilized to regulate discharge of SBM. OBM waste discharge is prohibited. The regulation of drilling mud wastes from offshore Nova Scotia falls under the National Energy Board and the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB). Currently CNSOPB limits SBM waste and EMOBM waste oil contents to less than 6.9 percent wet solids concentration, with no restrictions on discharges of water based muds.

During drilling, the muds also mix with formation fluids (oil, gas, water). The accumulation of fluids and cuttings in the mud is monitored by measuring various characteristics such as solids content, gel strength, viscosity, yield point, etc. When mud properties deviate from design parameters, the mud may be treated or "changed-out" which would then result in "clean" fluids be utilized (Cline and Piper, 1994) to achieve desirable drilling mud properties. After change-out, the discarded drill waste muds are considered useless for any further drilling activity and are disposed of using a variety of disposal techniques. Onshore disposal of this product then becomes a waste management issue. An indication of the general composition of the "waste" SBMs and EMOBMs is shown in Table1.

Table 1. Typical composition of SBMs and EMOBMs, after drilling.

40-60% Solids	Bentonite Clay Rock Cuttings Barium Sulphate
20-30% Water	Emulsified Water and Brine Water
20-30% Oil	Synthetic or Mineral Oil

(Envirosoil, 2003)

Land disposal in Nova Scotia is regulated by the Department of Environment and Labor (NSDEL). The province outlines preferred best management practices of drilling wastes (NSDEL, 2003) such as waste reduction through pollution prevention, reuse of recovered product, recycling of waste into useful products, treatment, and disposal (in decreasing order of preference). In Nova Scotia, treatment can consist of thermal treatment or bioremediation.

With the focus of this paper being the re-use of thermally treated drill mud waste (TTDMW), an overview of two forms of thermal treatment (LTTD and ITR) are provided in the following sections.

2.2 Thermal Treatment of Drilling Mud Waste

2.2.1 Low Temperature Thermal Desorption (LTTD) - (Blending and Oil Destruction)

Low Temperature Thermal Desorption (LTTD) is the process of contaminant removal by transferring petroleum hydrocarbons from liquid to gas phase (Troxler et al, 1993). Usually the system targets an operational temperature, which is slightly greater than the highest boiling point of the compound to be treated, but less than the auto-ignition temperatures of the compounds. As the soil is heated to this temperature, the contaminants reach their respective boiling points at which time the compounds volatilize and become part of the gas stream. These gases are then removed by negative pressure and routed into a secondary combustion chamber where they are heated above the auto-ignition temperatures of the specific compounds. The result of this process is a transformation of organic compounds into carbon dioxide and steam (water) that enters an evaporative cooling chamber, where the gases are cooled prior to final exhaust gas treatment (in the "baghouse"). The majority of particulate matter in the treated gas stream is intercepted in the baghouse and returned to the soil discharge system. Gases are then discharged from the baghouse stack, which is continuously monitored for air quality. The soil fraction, which has been treated to non-detectable limits for total petroleum hydrocarbons (TPHs), is discharged (Envirosoil, 2004).

The LTTD unit previously discussed in this paper is capable of treating soils containing petroleum hydrocarbons of up to 2.5 percent to 3.0 percent at production rates of 30 to 40 tonnes per hour; Polycyclic Aromatic Hydrocarbons (PAHs) and Perchloroethylene at production rates of 20 to 30 tonnes per hour (Envirosoil, 2004). As was shown in Table 1, hydrocarbon concentrations in drill mud waste can be as high as 30 percent which means that the material must first be blended with soil (from other hydrocarbon remediation projects), in order to achieve the required consistent 2.5 percent to 3.0 percent hydrocarbon concentration in the "feed" material.

2.2.2 Indirect Thermal Recovery (ITR) – (No Blending and Oil Recovery)

In terms of thermally treating drill mud waste, the ITR process is best described as a thermal phase separation process resulting in the production of the following end products (Antle et al, 2003):

- Oil
- Water
- Treated (Dry) Solids

As with the LTTD process, the ITR system is based on the concept of thermal desorption. However, unlike the LTTD process, the ITR system can potentially treat drilling mud waste without blending with other soils.

Since ITR maintains a separation of the heat source combustion products from the drilling mud waste, there is no restriction on hydrocarbon concentration. The indirect heated thermal desorption unit is coupled with an externally fired burner system, which provides heat for the thermal processor (Envirosoil, 2004). The “off-gases” from the processor contain moisture and vaporized hydrocarbons, which were originally present in the drilling mud waste. As with the LTTD method, the ITR system is operated by targeting an operational temperature based on the boiling point range of the compounds under treatment and lower than the auto-ignition temperatures of these products. The gases produced are then removed by negative pressure and routed into the off-gas treatment system where they are cooled, scrubbed, and then chilled to promote condensation for removal of hydrocarbons and also for capture of particulate matter. Finally, the treated gases are routed released through a carbon filter scrubber, which is monitored to ensure emissions meet regulatory requirements.

The general composition of a thermally treated SBM drill waste using ITR is presented in Table 2. After the ITR process, the majority of the petroleum hydrocarbons and water are removed from the solids, leaving sand, silt and clay sized particles (from both muds and cuttings) and the weighting agent, barium sulphate. Some moisture is then added to the treated solids, mainly as a dust inhibitor.

Table 2. General composition of thermally treated drilling mud waste, after ITR treatment.

85-90%	Solids	Silt and Clay Rock cuttings Barium Sulphate
10-15%	Water	Added to control particulate dust
0.1-0.2%	Oil	Synthetic or Mineral Oil

(Envirosoil Ltd, 2003)

3. GEO-ENVIRONMENTAL PROPERTIES OF A TTDMW

The unblended thermally treated solid material (i.e. Table 2) generated by the ITR process may have potential for re-use in waste containment applications. The TTDMW is essentially considered a waste product, although there are many potential uses for the soil such as topsoil amendment, landfill cover soil, concrete additive quarry restoration material, etc. (Page et al 2003). These applications do not necessarily provide “added-value” to the products currently used in these applications. Considering that drill mud waste contains a mixture of bentonite, organic additives and minerals, there may be potential value-added uses for the treated drill mud waste as an additive to landfill liner systems. The purpose of clayey barrier systems in waste containment applications is to mitigate contaminant transport (i.e. advection and diffusion), while promoting sorption of various contaminants. Hence any application of reuse of TTDMW in this regard would have to improve upon one or more of these transport mechanisms relative to current clayey liner systems.

The potential for re-use of a TTDMW will depend on many factors. From a preliminary assessment standpoint, it is important to understand its basic geoenvironmental and geotechnical properties. To facilitate this understanding, ITR processed TTDMW from Aberdeen, Scotland, was obtained. Unfortunately, very little technical information is known about the characteristics of the original drill mud waste except that it was generally considered SBM waste. A description of some preliminary test results for general chemical, mineralogical and geotechnical properties are provided below.

3.1 Chemical Testing

As shown in Table 3, the TTDMW contains 2.1 percent organic carbon which is approximately 4 to 5 times higher than most natural clayey barriers. This relatively high amount of total organic carbon is probably a reflection of some of the organically modified clays used in the original muds as well as residual carbon from the ITR treatment method. Table 3 also shows relatively high levels of chloride and barium. Chloride is found in the drilling mud waste from its use as an additive to prevent shale swelling during drilling to assist in maintaining hole integrity. The high concentration of barium reported in Table 3 is due to the barite sulphate weighting agent added to the drill muds. Some residual levels of TPH and negligible concentrations of BTEX remain after ITR treatment.

Table 3. Results of chemical analysis performed on ITR TTDMW.

Total Organic Carbon (%)	2.1
Chloride (mg/kg)	13,500
Barium (mg/kg)	16,900
>C6-C10 Hydrocarbons (mg/kg)	Not Detected
>C10-C21 Hydrocarbons (mg/kg)	375
>C10-C21 Hydrocarbons (mg/kg)	253
BTEX	Not Detected

(Envirosoil Ltd, 2003)

3.2 Mineralogical Testing

To ascertain mineralogical characteristics of the TTDMW, a powder pattern X-Ray Diffraction (XRD) analysis was performed on the <0.074mm air-dried fraction to establish the identity of major non-clay minerals present. X-ray analyses were performed with a PW3710 BASED diffractometer, generating copper radiation from a rotating anode source (Department of Earth Sciences, Dalhousie University). The diffractometer was operated at 40 kV and 40 mA with a scan rate of 0.6 degrees/min. The powder pattern scan was performed from 2θ angles of 5 to 65 degrees. Based on the results of this analysis, the primary non-clay minerals appear to be barite and quartz. Other non-clay minerals identified from the powder pattern included calcite, dolomite, and to a lesser extent, Na-feldspars and K-feldspars. The large variety of non-clay minerals is not surprising since the drilling process would have encountered a large variety of geological units. The continual recycling of the muds during drilling would also result in a mixing of the various geological units encountered. It is expected that the non-clay mineral content would be variable in any TTDMW due to the many different geological units that could be encountered. In terms of potential re-use of the treated drill mud waste, the non-clay mineral component, although variable, may have an positive influence on potential inorganic sorption processes of various anions and cations to mineral surfaces.

The clay mineral composition will also provide some indication on whether the product has potential for re-use in containment applications. Preferred orientation XRD slides were prepared of the clay fraction (<2μm) of the material. XRD test conditions were similar to that described previously. Three subsamples of the TTDMW were prepared; an untreated sample, a magnesium saturated sample and a potassium saturated sample. Methods outlined in SSSA (1986) were generally followed to prepare these clay fractions of the material for XRD. XRD results for air-dried, ethylene glycol saturated and heat-treatment (550°C) for the untreated sample are shown in Figure 2.

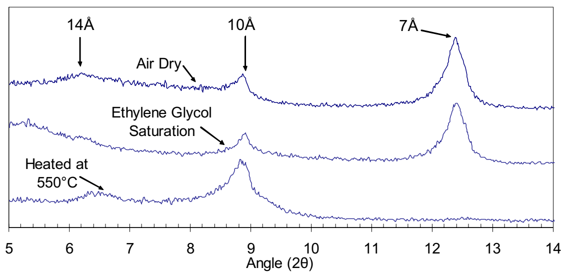

Figure 2. X-Ray Diffraction on the clay fraction (<2μm) of the TTDMW (Preferred Orientation)

Bentonite is a common ingredient in many drilling fluids and hence the general presence of smectites near 14Å-15Å is not surprising as shown from the air-dried trace in Figure 2. Swelling of the 14Å peak upon glycolation and the increase in intensity of the 10 Å after heating the sample to 550°C also seems to confirm the presence of smectite. Mg saturation of the clay fraction sample (not shown) produced an even sharper 14Å peak confirming the presence of smectite. Kaolinite in the TTDMW is suggested by the presence of the 7Å peak of the air-dried sample which disappears upon heating to 550°C. Illite is identified in the sample by its basal reflection at 10Å. Additional XRD analyses performed with potassium saturated samples confirmed minor amounts of vermiculite and chlorite in the clay fraction. Mineralogical analysis is in the preliminary stages and hence quantitative mineralogy in combination with other testing will assist in confirming the above observations.

To establish the engineering significance of the smectite component found in the clay fraction of the TTDMW sample, free swell testing (ASTM D5890, 2004) was performed. Four types of samples were prepared to establish swelling characteristics: bulk sample (unwashed); minus 2μm fraction sample (unwashed); bulk sample (washed repeatedly to remove residual salt content); and minus 2 μm fraction sample (washed repeatedly to remove residual salt content). Each of the subsamples was immersed in both distilled water and methanol for swell testing. As can be seen from distilled water results in Table 4, negligible swelling took place for any of the samples. The bulk samples submerged in methanol also exhibited negligible swelling while the minus 2μm fraction appeared to swell slightly upon addition of methanol.

Table 4. Free swell test results of TTDMW.

	Final volume (mL), water	Final volume (mL), methanol
Bulk sample, unwashed	3	3
Bulk sample, washed	3	3
<2um fraction, unwashed	3	4
<2um fraction, washed	3	5

These results suggest that even though there appears to be some smectite present in the sample, the small amounts are most likely organic in nature and do not swell significantly with water. Further indications of this are provided in the following section when discussing hydraulic conductivity testing performed on the bulk sample.

3.3 Geotechnical Testing

As can be seen from the results of grain size analyses performed on the TTDMW in Figure 3, the TTDMW in this paper is predominately fine-grained. It would be reasonable to expect that the grain-size distribution of TTDMWs would be variable with respect to the sand and silt size fractions since this size fraction will largely depend on the type of geological unit which is being drilled as well as the initial properties of the drill fluid (Tuncan et al., 1997). When combined with Atterberg Limit test results shown in Table 5, the TTDWM examined in this study is classified by ASTM D2487

2004) as a sandy silt soil. It should be noted that the soil is a borderline silt, with the plasticity index of 9 plotting just below the A-line on the plasticity chart. Generally speaking, the geotechnical properties shown in Table 5 are most likely a reflection of the drill mud as well as the drill cuttings. The high specific gravity of the TTDMW is mainly due to barite added to the drill mud which was previously identified in the sample from XRD analysis.

Table 6 presents the results of hydraulic conductivity tests preformed using both a fixed wall, falling head test and a flexible wall, constant head test (ASTM D5084, 2004). Bulk samples of the TTDMW tested for each of these methods were compacted to the dry unit weights and densities noted in Table 6 using standard compaction energy. As shown in Table 6, these hydraulic conductivities are borderline with respect to typical hydraulic conductivity specifications for clayey barrier systems of 1×10^{-9} cm/s.

Table 5. Selected Geotechnical Properties of TTDMW

Specific Gravity (-)	3.0
Water Content (%)	10
Maximum Dry Unit Weight	17 kN/m^3
Optimum Water Content	20%
Plastic limit (%)	26
Liquid limit (%)	34
Plasticity index (%)	8
Activity	0.8

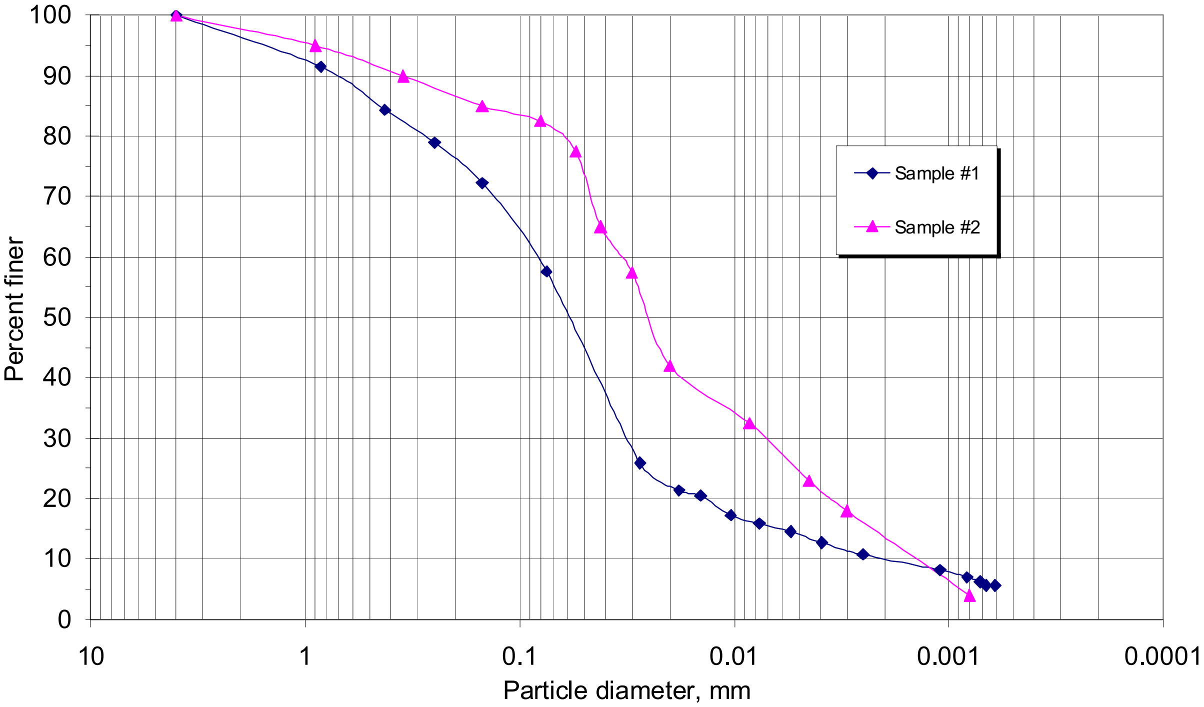

Figure 3. Grain size distributions of TTDMW

Table 6. Results of hydraulic conductivity tests performed on treated drilling muds.

Test Parameters	Hydraulic conductivity* (m/s)
Fixed wall γ_d=16.1 kN/m^3 , w =24%	8×10^{-10}
Flexible wall γ_d=16.4 kN/m^3 , w=22.9%	2×10^{-9}

*Note
[1] all samples permeated with water
[2] flexible wall testing was performed at effective confining stresses of 100 kPa

4. SUMMARY AND CONCLUSIONS

Waste management issues associated with drill mud waste can be a significant consideration in oil and gas exploration and production. Nova Scotia regulations result in approximately 1000 to 6000 tonnes per year of drill mud waste currently being received for LTTD treatment. The current process of blending drill mud waste prior to LTTD results in negligible value-added potential for the TTDMW, while ITR offers potential for value-added use of the TTDMW for waste containment applications. A sample of SBM waste subjected to the ITR treatment process has been classified as a sandy silt with some clayey characteristics. XRD analyses of the drill mud waste identified a wide variety of non-clay and clay minerals with barite and smectite appearing to be prevalent. Hydraulic conductivity testing showed the material to be marginal with respect to water permeation compared to typical clayey liner specifications of $1x10^{-9}$ m/s. Although these preliminary results seem to suggest that the TTDMW tested is "marginal" with respect to hydraulic conductivity, further testing with respect to other contaminant migration properties is in progress to assess the TTDMW as a waste containment liner system.

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