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Static and Dynamic Properties of Controlled Low-Strength Materials Incorporating Treated Oil Sands Waste

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ABSTRACT

Controlled Low-Strength Materials (CLSM) is a self-compacted self-leveling cementitious material with compressive strength of 8.3 MPa or less. It is used as an alternative of soil backfill materials in geotechnical and infrastructure applications. This study investigates the effects of incorporating treated oil sand wastes (TOSW) as a partial replacement of sand or fly ash on fresh and hardened properties of CLSM. In addition, the environmental impact of the proposed new mixtures was evaluated. The results show that CLSM mixtures incorporating TOSW had satisfied the limits and requirements of ACI committee 229 for CLSM with no environmental hazards. The incorporation of TOSW has increased the flowability of all mixtures and consequently reduced the water demand to reach the required flowability which consequently increased the compressive strength of mixtures containing TOSW and fly ash. Replacing fly ash with TOSW on the other hand, reduced the strength of CLSM slightly, but the strength remains within CLSM acceptable range of strength. In addition, this produced a more re-excavatable mixture, adequate for applications that may require future re-excavation. To investigate the effects of incorporating TOSW in CLSM as a replacement of fly ash and partial replacement of sand on its dynamic properties, shear wave velocity and geo-mechanical properties were evaluated. The piezoelectric ring actuator (PRA) technique was employed for measuring Vs of CLSM and an empirical equation was suggested to estimate Vs based on mixture proportions of CLSM. The results suggest that the shear wave velocity was affected primarily by the cement content, while TOSW had minimal impact on it. However, TOSW improved the flowability of the mixture and could totally replace fly ash for that function. It is concluded that TOSW can be successfully incorporated in CLSM mixtures, offering an application to reduce the landfill disposals of oil sands waste while reducing the demand on natural resources.

Co-Authorship Statement

This thesis has been prepared in a format of integrated-article in accordance with the regulations stipulated by the Faculty of Graduate Studies at The University of Western Ontario. Substantial parts of this theses were either published, submitted, or will be submitted for publication to peer-reviewed technical journals and in an international conference. All the laboratory testing, interpretation of results and writing of the draft and the final thesis and the initial versions of other publications, were carried out by the candidate himself, under the supervision of Dr. M. Hesham El Naggar. The contribution of the supervisor and other co-authors, consisted of either providing advice, and/or helping in the development of the final versions of publications. Following is a list of the publications:

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Chapter 1

INTRODUCTION

1.1. General Overview

The advancements and technologies of various aspects of modern life have increased the demands for energy and construction, which can negatively affect the task of maintaining and preserving the environment a difficult mission. As the number of by-products of different energy recourses increases, an immense pressure rises on the society to reduce, recycle and reuse these by-products.

Hydrocarbons is anticipated to remain a primary source of energy through the year of 2050 and beyond. Correspondingly, the demand for unconventional sources of hydrocarbons such as oil sands continues to increase as new oil extraction technologies advance. Canada's oil sands, a Bitumen-soaked sand deposit encompassing more than 149,000 square kilometers of Alberta, is one of the major contributors to the Canadian economy providing a secure, reliable source of energy to all North America (Carson, 2011). The extraction process of oil from oil sands produces large amounts of oil sands tailings that are dumped in tailing ponds, which poses a significant threat to the environment. Continuing efforts are made to develop innovative ways to treat the oil sands waste for landfill disposal. However, the cost of treatment and the tipping fee for disposal at landfills add unnecessary cost to the extracted oil.

The utilization of the treated oil sand waste in geotechnical and construction applications offer an attractive alternative towards making this important energy resource greener and more sustainable. One potential application of treated oil sand in construction is incorporating it in controlled low-strength materials (CLSM), which is used for backfilling around pipelines, foundations, and and pavement bases among other applications.

Controlled low-strength material is a flowable self-levelling cementitious material; it is widely used as a replacement for soil-cement materials in many geotechnical applications such as structural backfill, pipeline beddings, void fill, pavement bases and bridge approaches. Because of its low strength requirements, CLSM can be a perfect host for many waste and by-products given that these materials have been proven environmentally safe (Remond *et al.*, 2002), (Katz & Kovler, 2004). Many studies have evaluated the effect of incorporating different by-products, such as spent foundry sand, cement kiln dust, wood ash, scrap tire rubber and coal combustion by-products on the properties of CLSM (Siddique, 2009).

The main properties for CLSM performance are flowability, density, and compressive strength. However, other properties like shrinkage, bleeding, and subsidence may also be evaluated depending on the requirement of the application of CLSM. The upper limit of compressive strength of CLSM can be up to 8 MPa, however, maintaining a low strength is essential for projects where later excavation is required. CLSM with a compressive strength of 0.7 MPa and lower can be easily excavated manually if there is no high content of coarse aggregate in the mixture (ACI Committee 229R, 2013).

1.2. Objectives

The objective of this research is to investigate incorporating treated oil sand wastes (TOSW) as a filler material in CLSM and to evaluate the effects of TOSW on the static and dynamic properties of CLSM aiming to recycle the waste and reduce the use of expensive fly ash in the

CLSM mixture. New CLSM design mixture proportions are proposed incorporating TOSW. The properties of the new mixtures are evaluated to facilitate its use an alternative of compacted soils for different geotechnical applications.

1.3. Methodology

Eighteen different CLSM mixtures were prepared by varying three main ingredients (cement, fly ash and TOSW) in order to evaluate the effect of incorporating TOSW on the properties and performance of the CLSM. The testing program was divided into two phases:

- Phase I: Design and characterisation of CLSM mixtures incorporating TOSW and evaluation of the fresh and mechanical properties of the mixtures. In addition, the effect of TOSW on leaching of metals of mixtures with the highest concentration of TOSW was assessed. Tests of this phase included: flowability, fresh density, bleeding, drying shrinkage, unconfined compressive strength, removability modulus, elastic modulus and leaching tests.
- Phase II: Evaluation of the effects TOSW on the dynamic properties of hardened CLSM samples. The dynamic properties were estimated by measuring the shear wave velocity using a piezoelectric ring actuator (PRA) device designed and fabricated at the University of Western Ontario. The shear modulus and damping ratio of CLSM were obtained using the results of the shear wave measurements.

1.4. Thesis Organization

This thesis is divided into five chapters, the content of each chapter is briefly described in this section.

Chapter 1

Chapter 1 is a general overview of the current environmental challenges of oil sand industry and waste production in addition to a brief definition of controlled low strength material. The objectives and methodology of the research are also stated in this chapter.

Chapter 2 reviews the existing literature on CLSM mixtures using different waste products, in addition to a general overview of the oil sand industry in Canada, historical background of oil sands and techniques of treating oil sand tailings.

Chapter 3 investigates effects of incorporating treated oil sand waste in CLSM mixtures on the fresh and mechanical properties of CLSM in addition to an environmental evaluation of the mixtures containing waste.

Chapter 4 reports on the measurements of the shear wave and compression wave velocities of the hardened CLSM samples incorporating TOSW using the PRA device. The measurements were analyzed to establish very low strain shear modulus and damping ratio. The damping ratio, static and dynamic moduli of the CLSM were evaluated and some empirical equations are provided for their estimation.

Chapter 5 summarises the research results and conclusions in addition to recommendations for future work.

Appendix A Charts and tables for the laboratory raw data used for analysis in this research.

Appendix B Analysis report done by Newalta Corporation showing mono-aromatic hydrocarbon concentrations in Treated Oil Sands Waste .

The

1.5. References

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Chapter 2

LITERATURE REVIEW

2.1. Introduction

2.1.1. Backfill Materials

Infrastructure projects and repairs include excavations and backfilling. The backfills can either be the same natural soil excavated or, if the natural soil is not suitable for backfilling, a borrow material with better properties are used for backfilling. Inferior backfilling has been the leading cause of settlements of trenches, roads and foundations, especially if no proper compaction was applied. CLSM was developed to address this concern, eliminating the settlement problem of infrastructure works (Shah, Controlled low strength material (CLSM) produced from limestone fines and other by-products, 2012).

2.1.2. Controlled Low-Strength Materials

Controlled low-strength materials are a self-compacted self-leveled mix usually composed of cement, water, fly ash and aggregate, which is used as a replacement of compacted soil backfill. CLSM shares the characteristics of concrete and backfill materials and can be considered as a hybrid of both. Therefore, many tests designed mainly for concrete can also be performed on CLSM. CLSM mixtures generally have better properties in terms of strength and settlement compared to backfill soils, and can be applied to the work site in less time with no compaction required, hence reducing construction time and cost. These advantages rendered the use of CLSM very popular recently in a wide range of construction practices such as pipeline beddings, void filling, and structural backfill, bridge reclamation and pavement bases (ACI Committee 229R, 2013).

2.2. History and Background of CLSM

2.2.1. First Recorded Use of CLSM

The first known use of CLSM was documented in 1964 by the U.S. Bureau of Reclamation where CLSM was used as a bedding material for a 476-km pipeline in the Canadian River Aqueduct Project in Texas (Howard & Hitch, 1998). In the 1970's, the use of CLSM became more prominent and documented standards and guidelines have become essential for the development of the material in construction. Therefore, the American Concrete Institute (ACI) started the committee 229 on Controlled Low Strength Material in 1984. After about ten years, the committee has published its first report in the year 1994 marking the actual starting point of the use of CLSM in the industry, and the report was later revised in 2013. The ACI 229-13 report defines CLSM as a material that has a compressive strength of 8.3 MPa or less. Most applications require a compressive strength of not more than 2.1 MPa. This low strength is necessary for future excavation with a backhoe. For excavation with hand tools, the report recommends a strength of 0.7 MPa or lower.

CLSM is not as durable as concrete, and that is not a drawback because it is used to replace the conventional backfill material giving a bearing capacity higher than soil backfills. Also, CLSM is not designed to resist freezing and thawing, abrasion or aggressive chemicals. However, because CLSM is used as backfill, it is buried in the ground or confined; therefore, even if CLSM deteriorates, it will still preform effectively as backfill material (Smith, 1991).

2.2.2. Development of CLSM

The use of fly ash in concrete to produce what is known as low strength concrete was investigated in the early 1970's (Torrey, 1978) (Naik & Ramme, 1995). Meanwhile, the settlement and compaction problems of the conventional backfilling techniques was the main motivation to investigate the ability of the new low strength material to replace the conventional backfills (Brewer, 1994). The need for a low-cost, high-quality backfill material led to the development of controlled low strength materials. The low cost of CLSM is mainly due to the reduced labor and equipment costs for placement and removal. Since the material is flowable, self-leveled and self-compacted, it does not require densification effort after application. The ease of removal of CLSM depends on the application and can be controlled by maintaining a low compressive strength (Ayers, *et al.*, 1994).

The use and practice of CLSM were not standardized until 1994 when ACI committee 229 released its first report, which documented the ranges and limits of fresh and hardened properties of CLSM. The report also documented mixtures with their properties used by different departments of transportation in the United States. The American Society for Testing and Materials (ASTM) later published the book “The Design and Application of Controlled Low-Strength Materials (Flowable Fill) in 1998 including several publications about CLSM testing, ingredients, practical notes, specification, and standards.

2.3. Advantages of CLSM

CLSM has many advantages over the traditional backfilling materials. The main advantages of CLSM can be listed as follows (ACI Committee 229R, 2013):

- CLSM mixtures can be designed using locally available materials producing CLSM that satisfies the needs of most projects.
- Easy to deliver using truck mixers to the site.

- The mechanical and physical properties of CLSM are controlled and adjustable to meet deferent needs.
- High bearing capacity and more erosion resistant compared to compacted fill.
- Quick placement and application allows fast return to traffic in pavement repair projects.
- No settlement or rut under loading.
- Reduced excavation costs due to its ability of flowing in narrow trenches without the need for compaction, which also saves the costs of compaction tests and inspections.
- Improved safety as the workers do not need to enter the trench during application.
- Makes use of deferent by-products, hence facilitates recycling and sustainability.

2.4. Manufacturing Technology of CLSM

2.4.1. Mixing and Batching

CLSM is usually mixed like concrete mixtures. It can be mixed in pugmills, turbine mixers or central-mix concrete plant. Because of the large amount of fine materials in CLSM mixtures, it is important to stir the mixture thoroughly in order to avoid any cement clumps that may occur, especially if there were no coarse aggregates in the mixture.

2.4.2. Materials

CLSM mixtures can include a broad range of materials compared to concrete mixtures due to its low strength requirements. This makes CLSM a perfect choice for recycling various industrial by-products, producing a low cost and environmentally friendly construction material. CLSM is mainly composed of binder material (usually cement), water, and a filler material.

2.4.2.1. Water

Water affects both flowability and compressive strength of CLSM mixture; adequate amount of water is needed to achieve a homogenous mixture and to achieve target flowability. Unlike concrete mixtures, the main parameter controlling the amount of water required in CLSM is the flowability of the mixture. The adequate amount of water should be determined during the mixing procedure by measuring the flowability of the mix until it reaches the desired value. There are no specific regulations for water quality to be used in CLSM. Generally, the water that is acceptable for concrete can be used in CSLM mix.

2.4.2.2. Binder

A binder element is necessary to provide cohesion and strength control for the mixture. While Portland cement is the most common binder element in CLSM mixes, other pozzolanic and self-cementing materials such as fly ash and gypsum can also be used with or without cement. Halmen and Shah (2015) tested CLSM mixtures using only by-products as binder elements including class C fly ash, limestone quarry fines, and synthetic gypsum. Their results showed that CLSM could be designed using only by-products as binder elements for a wide range of compressive strength (between 237.4 kPa and 9932 kPa) (Halmen & Shah, 2015).

Fly ash is the most widely used by-product in CLSM mixtures due to its many unique advantages and pozzolanic properties. Owing to its fine particles, fly ash increases the flowability and consistency of CLSM and reduces segregation, bleeding, and shrinkage. Meanwhile, its pozzolanic properties increase the CLSM strength when used along with Portland cement. Fly ash is electrostatically collected in the exhaust stack of coal combustion chambers used in power generation plants. The fly ash used in Portland cement concrete usually complies with (ASTM C618, 2005), and the same specification can be applicable to CLSM mixtures. Non-standard

ASTM fly ash can also be used in CLSM after testing to ensure its acceptability (Brewer, 1994). The majority of CLSM research was performed on Class F fly ash, which has lower Lime (CaO) content compared to Class C fly ash. Higher content of lime in fly ash containing can result in higher compressive strength due to its self-cementing properties (ACI Committee 229R, 2013).

The cement kiln dust (CKD) is another by-product that is used as a binder. Its potential usage in CLSM has been investigated recently. Its low cementing capacity can be an advantage in CLSM when low strength is a priority for future excavation. However, increasing the amount of CKD results in large shrinkage and wide cracks (Katz & Kovler, 2004).

2.4.2.3. Filler

The most common filler material for CLSM is fine aggregate, which usually occupies more than 70% of the mix. Coarse aggregate is sometimes used also along with fine aggregate in the mix. The type and source of the aggregate were found to be significant factors affecting the water demand of the mix, which directly affects the compressive strength (Du, *et al.*, 2002). All fine Aggregates that are suitable for concrete and comply with ASTM Standard Specification for Concrete Aggregates (ASTM C33/C33M , 2016) are generally used in CLSM mixtures; however, granular excavation materials which are lower quality aggregates should also be considered in CLSM (ACI Committee 229R, 2013). The aggregates particle’s angularity is an important aspect when choosing a material as a filler, sharp-edged aggregates will result in poor flow characteristics in CLSM and should, therefore, be avoided (Brewer, 1994). Other non-standard materials, coal combustion by-products and natural soils can be used in CLSM after being tested to determine its acceptability based on the requirements of the desired application of CSLM.

Recently, and due to the increased need for recycling industrial by-products, many researchers have successfully used and tested by-products as a filler material such as scrap tire rubber, spent foundry sand, coal bottom ash and quarry waste (Siddique, 2009). CLSM offers a great opportunity for recycling by-products and non-standard materials not meeting (ASTM C33) for its filler aggregates. Non-standard materials like stone quarry may contain granular materials which do not satisfy the graduation requirements for ASTM C33; this material can be used in CLSM as a filler occupying the major portion of the mixture. All new materials should be tested in CLSM to see if it has any undesirable effects on the different properties of CLSM mixtures. Using non-standard materials have greatly reduced the cost of CLSM mixture making it a very cost-effective compared to conventional backfill materials.

2.4.3. Incorporation of Non-Standard Materials in CLSM

CLSM can be mixed from a wide range of non-standard materials, on-site soils. Waste, and industrial by-products, therefore attracting many researches in the field of waste recycling and environmental sustainability to study the feasibility of recycling waste materials in CLSM mixtures.

Using on-site materials in CLSM can save huge costs in large scale projects compared to high quality compacted fill materials. For example, the construction of Denver International Airpot in 1993 utilized more than 53500 cubic meters of CLSM for a concrete pipe drainage system; in this project, on-site sand from a borrow pit located on the airport site was used in CLSM although it violated the specification of the project regarding the maximum amount of fine materials (having 18% of materials passing #200 sieve violating the maximum of 10% for this project). However, the flowability and the 28-day compressive strength can be designed to be equal to that of CLSM made with concrete sand and aggregate. The usage of on-site materials had a significant effect on cost and time in this project (Clem, *et al.*, 1994).

Bassani *et al.* (2017) investigated the effect of a wide range of waste and by-products on the properties of CLSM, the study included testing on mixtures mixed with cement kiln dust, cement by-pass dust combined with powdered incinerator bottom ash and aggregates (saw-mill silt, concrete demolition waste, and incinerator bottom ash sand). This study concluded that CLSM made with CKD instead of cement, requires longer time toset, hence would not be prefareable for pavement aplications where trafic disruptoin should be minimized.

The study also showed that usage of incinerator bottom ash as an aggregate cause craking and swlling hariming the mechannical performance of CLSM; while using the same material as binder mixed with cement by-pass dust led to CLSM mixtures with strenght and stiffness similar to the control CLSM mixtures.

Bassani *et al.* (2017) also invistigated the reusage of sand derived from excavatable CLSM and reported performance simmilar to the orgenal material. The recylced sand reduced the setting time significantly, the study recommended a maxumim of 50% subtitution of natural sand to produce CLSM with setting time similar to the standard mixures.

Le *et al.* (2016) presneted a study on fresh and hardend properties of CLSM containing stainless steel slag (SSRS) as a cementeions material replacing cement by rates up to 30% by weight. An improvement of the flowability was was reported as the percentage of the SSRS replacing cement increased. The reported comprissive strength of the mixtures ranged from 0.3 to 1.63 MPa mathcing the requiremnt for supporting uper structhre and excavatability. SSRS mixtures showd a decrease in elastic modulus ranging for 32 to 41% as reported by the study. The over all performance of CLSM incorporating up to 30% SSRS was acceptable as reported by this study.

Another study by Naganathan *et al.* (2012) evaluated the properties of CLSM mixed using industrial waste inceneration bottom ash and quarry dust. The compressive strength of CLSM in this study ranged from 0.22 to 11.42 MPa, which is sligtly higer than the reccomended value of 8.1 MPa. Addition of quarry dust was noted to enhance the properties of CLSM made with bottom ash in many aspects as follwos: It increased the fresh and hardened density with hardend density ranging from 1414 to 2123 kg/m^3; increased the CBR value, reduced the bleeding making CLSM more stable, and increased the compressive strength.

2.5. Oil Sands Waste

2.5.1. History and Background

Oil sands are natural deposits of clay, sand, water, and bitumen in north-eastern Alberta underlying approximately 149,000 square kilometers of boreal forest **(Figure.2.1)**, which is around 23% of the area of the province. The sand particles are surrounded by a layer of water and a film of heavy and very viscous bitumen, which cannot flow easily making its extraction from the sand difficult and must be processed and upgraded to crude oil. Even though the efforts to access this source of oil started in the early 20th century, the commercial development of oil sands began in 1976 when Great Canadian Oil Sands Company started the first open pit surface mines in the Athabasca deposit. The development of modern technologies and the reduction of production costs led to huge increase in production in the last 25 years. The production goal of reaching 1 million barrels per day by the year 2020, which was set in 2004, (Woynillowicz, *et al.*, 2005) has already been well exceeded today.

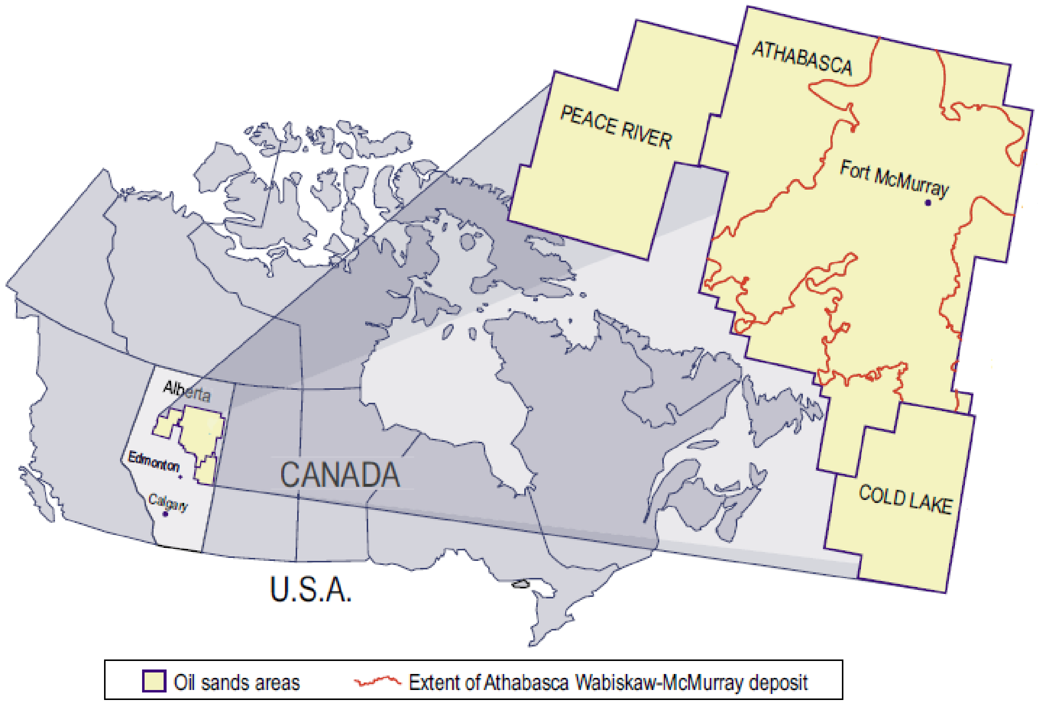

Figure 2.1 Alberta's oil sands deposits (AER, 2015)

With 13% of the world's proven oil reserves, Canada has the third largest oil reserves in the world, 98% of which are in oil sand. The total in-place oil sand resources in Alberta are estimated at 1.7 to 2.5 trillion barrels of bitumen, which is larger than all the oil that has been produced in the entire world to date (Alberta oil sands industry, 2017).

The estimated crude oil production from Alberta's oil sand reached 2.5 million barrels per day in 2016. This poses a great environmental challenge to deal with considering the amount of tailing ponds and waste landfilled. The oil sand industry is still growing and the government of Alberta has set a new goal of reaching 5 million barrels of bitumen production per day in 2030, which means more oil sand wastes challenges that should be urgently addressed.

Extraction of oil sands by surface mining requires the construction of dykes and dams to receive the disposed waste that resulted from the mining process forming tailing ponds. The tailings are a mixture of water, sand, silt, clay, residual bitumen and other contaminants. These ponds are the most challenging environmental problem of the oil sands industry as they cover an area of approximately 170 square kilometers (Woynillowicz, *et al.*, 2005), (Iglesias, 2014).

Oil is produced by separation of bitumen from the sand grain as shown in **Figure 2.2**. This requires the liquefication of the heavy bitumen by thermal, mechanical or chemical energy. Oil Sands contain 8% to 14% bitumen and 3% to 5% water by weight, the remaining components are around 83% to 88% minerals, mainly silt, clay and sand which are the main components of oil sand tailings (Gosselin, et al., 2010).

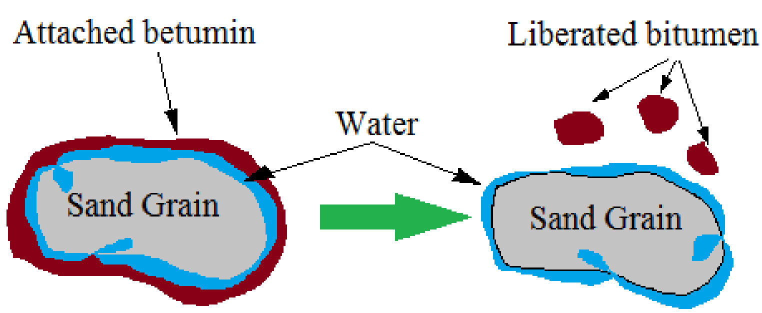

Figure 2.2 Bitumen separation from oil sand grain scheme (Gosselin, et al., 2010).

The resulting oil sand tailing should be treated further before it can be used in cementitious materials after the initial treatment to separate the residual oil and water from the solid sand grain, which will be referred herein as treated oil sad waste (TOSW).

2.5.2. Environmental Impact of Oil Sand Tailings

Tailing ponds are essential part in conventional oil sand surface mining. During this process, the fluid fine tailings and oil sand process water (OSPW) are discharged and stored in ponds surrounded by dykes usually constructed from permeable sand tailings. Since the dykes are permeable, OSPW can migrate from the pond to the ground water or to a nearby natural surface water, causing a contamination risk to the natural water resources and to the aquatic life due to the high toxicity of the components of the fresh OSPW (Gosselin, et al., 2010).

A research study by (MacKinnon, *et al.*, 2005) investigated the migration of OSPW through dykes at the Mildred Lake Settling Basing at the Syncrude mine. Water samples were collected at a potential migration path demonstrated that OSPW reached the natural water that flows along the edge of the dyke.

Another study by (Frank, *et al.*, 2014) traced the OSPW seepage from tailing ponds to the groundwater and to the Athabasca River in Northern Alberta by analysing groundwater samples for the components and acids of OSPW. Water samples were collected from near-field interceptor and monitoring wells near tailing ponds and from points along the bank of the Athabasca River within 200 meters of a tailing containment. Analysis performed on these samples indicated that it contains a mixture of OSPW and groundwater-derived naphthenic acids.

In addition to leakage of OSPW to ground and surface waters, tailing ponds can be a deadly trap to migrating birds that land on the surface of the ponds mistaking it for a freshwater lake. Landing on the pond can be deadly for a bird by soaking in oil or by ingesting toxic chemical. In April 2008, more than 1,600 ducks died by landing on a tailing pond run by Syncrude Company; the company was prosecuted and fined a penalty of $3 Million. In October 2010, an additional 400 ducks died again after being forced to land on a tailing pond by a winter storm. These two incidents highlight the importance of developing a wildlife mitigation plans by oil companies to minimize the environmental footprint of oil sand tailings.

2.5.3. Treatment of Oil Sand Tailings

The process of extraction of bitumen using hot or warm water produces a slurry waste that is transported to tailing ponds for storage. The large particles of sand in the tailings are quickly naturally settled and segregated from the slurry at the edge of the ponds, while the finer particles accumulate in the middle of the ponds forming what is known as mature fine tailings (MFT). MFT consists of about 86% water (Chalaturnyk *et al.*, 2002) and separation of water from MTF is one of the major operational challenges facing oil sands mining; therefore, various techniques have been developed over the past 40 years for efficiently separating water and hydrocarbons form MFT. (BGC Engineering Inc., 2010). Following is a brief description of some of the existing treatment methods:

2.5.3.1. Incineration

This technique involves combustion of organic components of the waste using rotary kilns. The waste is treated with temperature of between 1200 and 1500 degree Celsius resulting in a less harmful material (Ifeadi *et al.*, 2004). This method is considered as a very energy intensive treatment for the amount of heat needed for incineration. Moreover, it is not suitable for treating inorganic components of the waste which will only oxidize and turn into ash or vapor.

2.5.3.2. Thermal Desorption

In this method, oil-free solids are achieved by distillation process in two major stages. First, free oil and oil-water emulsions are evaporated and additional energy is applied to remove the interstitial oil bound by molecular forces and surface tension (Stephenson *et al.*, 2004). The evaporated fluids are then condensed to separate water and oil using different desorption mechanisms:

- The Drum type unit: A rotating drum heated by burners.
- The Screw type unit: A hollow screw heated by circulating hot fluids.

These desorption techniques require high energy to heat the units as they use indirect heating. Which means that the temperature of the heat source needs to be higher than the required temperature of the process (Kleppe *et al.*, 2009).

2.5.3.3. Biodegradation

Hydrocarbons are known to be biodegradable, therefore, bioremediation can be used to clean the contaminated soil with bacteria. Nutrients should be added to the waste to create a perfect environment to enable proper growth of microorganisms (Chaineau, *et al.*, 2002).

This method has the following drawbacks:

- Sensitive to external factors like temperature.
- Requires a huge area of land.
- The energy contained in the waste is not recovered.

2.5.3.4. Dispersion by Chemical Reaction (DCR)

This method uses a dispersant agent like hydrophobized Calcium Oxide to treat the waste resulting in dry solids that can be used as construction materials. The advantage of this method is that it immobilizes the organic content and the heavy metals form the cuttings which protects the environment (Ifeadi *et al.*, 2004).

2.5.3.5. Thermomechanical Cutting Cleaner (TCC)

The Thermomechanical Cutting Cleaner (TCC) is technology developed recently for oil sand tailing treatment. In this technique, the tailings are heated to a temperature enough to separate water and oil from the solid grains by evaporation. Unlike other thermal desorption techniques, heat is generated by friction between the waste particles; therefore, less energy is needed for the process. The evaporated water and oil are then condensed separately and discharged for recycling or re-usage. The remaining solids are very fine inert quartz powder material rich in silica. The treated solids leave the chamber at a temperature of 350 °C, typically containing less than 1,000 mg/kg of hydrocarbons and can be used in different construction materials (Thermtech, 2010). The schematic diagram of TCC technology is shown in **Figure 2.3.**

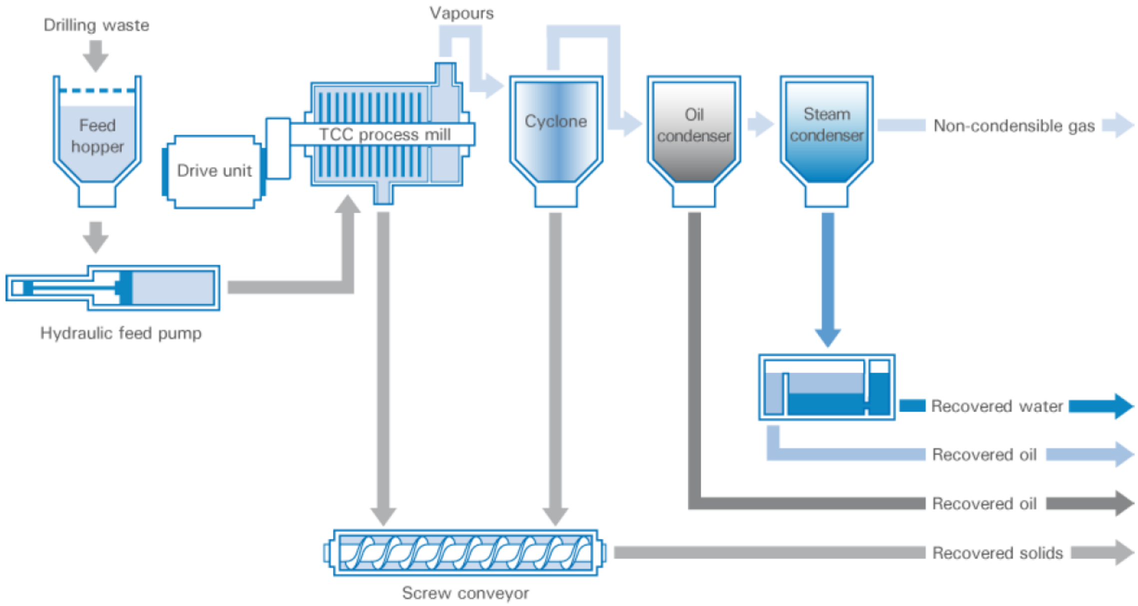

Figure 2.3 Schematic diagram of TCC technology (Thermtech, 2010)

TCC has the following advantages over the previously mentioned techniques (Thermtech, 2010):

- The recovered oil is clean and very similar to the original oil and proven to be re-usable.
- Clean water and solids. The solids contain between 0.3% and 1% oil by weight and can be used in construction materials.
- No large areas of lands required
- Homogeneous lump-free output mixture.
- Less process time and no heat media is required, and lower temperature is needed compared to indirectly-heated units which have the risk of local overheating and require more processing time.

2.5.4. Waste Recycling and Disposal

2.5.4.1. Waste Disposal

During the past decade, the concerns on managing oil sand waste has been growing internationally to eliminate the negative impacts of these wastes on the environment. Effective and responsible waste management systems are required for all working companies in oil sands industry. The priorities of all waste management plans are to reduce the waste production, reuse the material required in the production process, recycle waste materials to make new products, recover energy and metals from waste, and finally the least preferred option is the safe disposal of the waste to landfill (Sharif *et al.*, 2017).

In landfill disposal, the treated or untreated cuttings are placed in a landfill facility designed to contain the waste. The landfill unit should be designed to ensure long-term containment of the waste which depends on the materials used in the containment, the quality of the design, and the underlying geological conditions (Sharif *et al.*, 2017).

2.5.4.2. TOSW in Construction Materials

Despite the harmful consequences of waste land fill, most of the drilling wastes are managed to be disposed. Therefore, to reduce the disposal and landfilling of the waste materials, the cutting wastes are used for other beneficial purposes after ensuring that the hydrocarbon fluid content, salinity and clay content are suitable for the intended use. Two of the most common usage of drilling wastes are road spreading and construction materials. Cutting wastes are also used in roofing tiles materials, soil reconditioning, restoration of wetlands, and as fuel for energy production (Sharif *et al.*, 2017).

Research studies proved that incorporating oil contaminated waste in construction materials can in fact enhance some of the engineering properties.

A study done by Abousnina *et al.* (2015) investigated the effect of oil contamination on the mechanical properties of sand and it's concrete. Crude oil was added up to 20% by weight of dry sand. Abousnina reported a significant increase of cohesion of sand with up to 1% of oil contamination; while the cohesion decreased as the percentage of contamination increased. Moreover, a higher compressive strength was achieved with mortar with 4% contamination compared with uncontaminated samples. The properties of the mortar mixed with oil contaminated sand were found to be suitable for some engineering purposes.

Another study by Mosavi *et al.* (2015) investigated the feasibility of incorporating drill cutting waste in concrete as a replacement of cement. The results showed that replacing 5%, 20% and 35% of cement by drill cutting reduced the compressive strengths by 10%, 22%, and 63% consecutively. The research also reported that the compressive strength reduction can be compensated by adding different amounts of fly ash to mixtures containing 20% of waste achieving a maximum of 33% increase in strength by adding 20% fly ash by weight of cement.

Similar observations were reported by Aboutabikh *et al*. (2016). This study investigated the incorporation of treated oil sand waste in grout mixtures by replacing up to 20% of cement by weight with TOSW. The properties of grout mixtures were not adversely affected by TOSW; however, a reduction of less than 30% were observed when no more than 20% of TOSW were used. It was also noticed that TOSW induced higher shrinkage of the mixture; the use of shrinkage control admixtures were recommended. On the other hand, TOSW increased the grout flowability due to its small particle size which enhanced packing density of the mixture and reduced interstitial voids.

Tuncan *et al.* (2000) used petroleum contaminated soil to construct road sub-base material. A significant increase in unconfined compressive strength and California bearing ratio of the sub-base were observed using waste materials stabilized by 5% cement, 10% fly ash and 20% lime.

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Chapter 3

ENGINEERING PROPERTIES OF CONTROLLED LOW-STRENGTH MATERIALS CONTAINING TREATED OIL SAND WASTE

3.1. Introduction

With the increasing demand for energy, new technologies are developed for oil extraction from oil sands. Consequently, oil sand industry became an important source for hydrocarbons with large reserves in western Canada (Carson, 2011). This has led to more challenges regarding waste management due to the large amount of waste in the form of oil sand tailings that need to be landfilled. Many technologies have been developed to treat these tailings and reduce the amount of waste directed to landfill. One of the recent technologies is Thermo-Mechanical Cuttings Cleaner (TCC), which separates water and oil from the oil sand solid waste (Ormeloh, 2014) (Aboutabikh *et al.*, 2015). The remaining part of the tailing is fine particles, mainly quartz crystals, which is referred herein as Treated Oil Sand Waste (TOSW) (Kassem *et al.,* 2015) (Mansour *et al*., 2016).

The effect of using petroleum-contaminated drilling waste as sub-base material for road construction was investigated by Tuncan *et al. (*2000). The petroleum waste used in this study was stabilized by mixing it with pozzolanic fly ash, lime, and cement. Physical, mechanical, and chemical properties of the new mixtures were studied and found to have better properties compared to the commonly used sub-base materials. The potential uses of petroleum contaminated soil (PCS) in highway construction were also investigated by Hassan *et al.* (2004).

Their investigation included the stabilization of the tested soil with cement and crushed stone aggregates. The new mixtures were used as replacement for fine aggregates in asphalt concrete mixtures. A toxicity characteristic leaching procedure (TCLP) was conducted on the tested soil specimens and found to be non-hazardous. The unconfined compressive strength for cement-stabilized contaminated soil at a percentage of 5% remained relatively constant with increasing the cement content. An adverse effect on the cement hydration caused by the addition of waste was also noticed. However, the tested waste was still deemed a good potential for use in road construction. Moreover, Hassan *et al.* (2008) investigated the permeability and leaching of asphalt concrete mixtures containing oil-contaminated soils (OCS) as a partial replacement of fine aggregates with percentages up to 40% by weight. A reduction in the tested asphalt permeability was observed with increasing the OCS percentage. This reduction was significant for OCS up to 30%.

The effect of using oil drill cuttings in road construction was also investigated (Misra *et al.*, 2011). Their results showed that drill cuttings waste can provide a stable and strong sub-grade for roads with minimal amount of heavy/toxic metals, which makes it suitable to be safely used in road construction. The potential use of mine tailings wastes as a base material for unpaved roads had been studied (Mahmood & Mulligan 2010). Physical characteristics and unconfined compressive tests were performed on different types of tailings wastes brought from several mines in eastern Canada. The results revealed that all tested samples have exceeded the minimum strength requirements, hence, this type of waste could be used as a base material for unpaved temporary access roads.

The main objective of this phase of testing is to investigate the potential of incorporating TOSW in CSLM as a fine filler material in order to produce green CLSM. This will be an important contribution to the efforts of reducing the footprint of oil sands industry by recycling TOSW and reducing the amount of natural sand used in CLSM. Using TOSW as a fine filler will alter the properties of CLSM either chemically or physically; therefore, it is important to evaluate the properties of the new CLSM to maintain the performance within the requirements of ACI committee 229 for deferent geotechnical applications.

3.2. Experimental program

3.2.1. Materials

Type 10 Ordinary Portland Cement (OPC) with Blaine fineness of 360 m^2/kg and specific gravity of 3.15 and Class F fly ash according to ASTM C618 were used as binding material in CLSM mixtures. It contained 61% Tricalcium Silicate (C_3S), 11% Dicalcium Silicate (C_2S), 9% Tricalcium Aluminate (C_3A), 7% Tetracalcium Aluminoferrite (C_4AF), 0.82% equivalent alkalis and 5% limestone. Treated Oil Sand Waste (TOSW) was used as a silicate base fine filler material with a Blaine fineness of 1440 m^2/kg and specific gravity of 2.23. The chemical composition and the physical properties of the cement, fly ash and TOSW are shown in **Table 3.2** The particle size distribution of TOSW and OPC are shown in **Figure 3.1** (Aboutabikh *et al.*, 2016).

The TOSW was obtained from TCC process through Newalta Corporation an environmental waste management specialized firm. The TOSW was analyzed by the source company to evaluate the amount of hydrocarbons in the material. The results show that mono-aromatic hydrocarbons leachate concentrations were less than 0.01 mg/L which is below the limits of Class II landfill requirements of Alberta’s standards for landfills (Environment Alberta, 2010). A copy of the analysis report is presented in Appendix B.

Kassem (2017) performed a leaching test on the raw TOSW sample. The concentrations of metals were below the CCME standard guideline limits and were further reduced significantly after incorporating TOSW in cementitious materials. The results of this analysis are shown in **Table 3.1.**

Three groups of mixtures were prepared and tested in the current study as shown in **Figure 3.2**: Group 1 included control mixtures prepared based on proportion guidelines reported by ACI committee 229. All mixtures were mixed with natural river bed sand with a specific gravity of 2.65. Group 2 included six mixtures where TOSW was added as a partial replacement of sand by volume at rates of 5%, 10%, and 15%. Group 3 was comprised of nine mixtures prepared with TOSW as a replacement of 100% of the fly ash along with partial replacement of sand by volume at rates 5%, 10% and 15%. Mixture proportions are shown in **Table 3.3**.

Table 3.1 Measured metals in TOSW by leaching test (Kassem, 2017)

Element	Symbo l	CCME guideline (mg/l)	Raw TOSW leaching (mg/l)
Silver	Ag	N.A.	0.005
Aluminum	Al	5.000[b]	1.656
Arsenic	As	0.005[a]	0.012
Barium	Ba	N.A.	1.113
Cadmium	Cd	N.A.	0.066
Cobalt	Co	0.050[b]	0.001
Copper	Cu	0.004[a]	0.012
Iron	Fe	0.300[a]	0.451
Manganese	Mn	0.200[b]	0.011
Molybdenum	Mo	0.073[a]	0.056
Nickel	Ni	0.150[a]	0.017
Vanadium	V	0.100[b]	0.038
Zinc	Zn	0.030[a]	0.001
Lithium	Li	2.500[b]	0.013
Lead	Pb	0.006[a]	0.004

[a] CCME (Canadian Council of Ministers of Environment) guide lines for protection of fresh water
[b] CCME guide lines for protection of agriculture (irrigation)

Table 3.2 Chemical composition and physical properties of cementitious materials. After (Aboutabikh *et al*., 2016)

Chemical Composition	OPC	TOSW	Fly ash
SiO_2	21.60	61.24	43.39
AI_2O_3	6.00	8.73	22.08
Fe_2O_3	3.10	3.00	7.74
CaO	61.41	5.55	15.63
MgO	3.40	0.92	-
K_2O	0.83	1.60	-
Na_2O	0.20	0.85	1.01
P_2O_5	0.11	0.15	-
SO_3	1.76	3.00	1.72
TiO_2	-	0.46	-
Loss on Ignition	0.81	12.6	
Physical properties			
Surface area (m^2/kg)	360	1440	280
Specific gravity	3.15	2.23	2.5

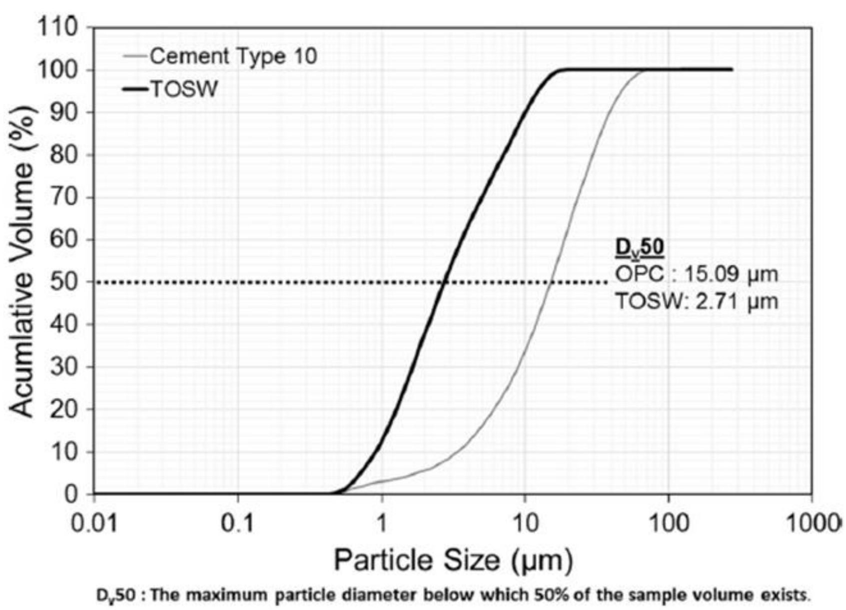


Figure 3.1 Particle size distribution of OPC and TOSW (Aboutabikh *et al*., 2016).

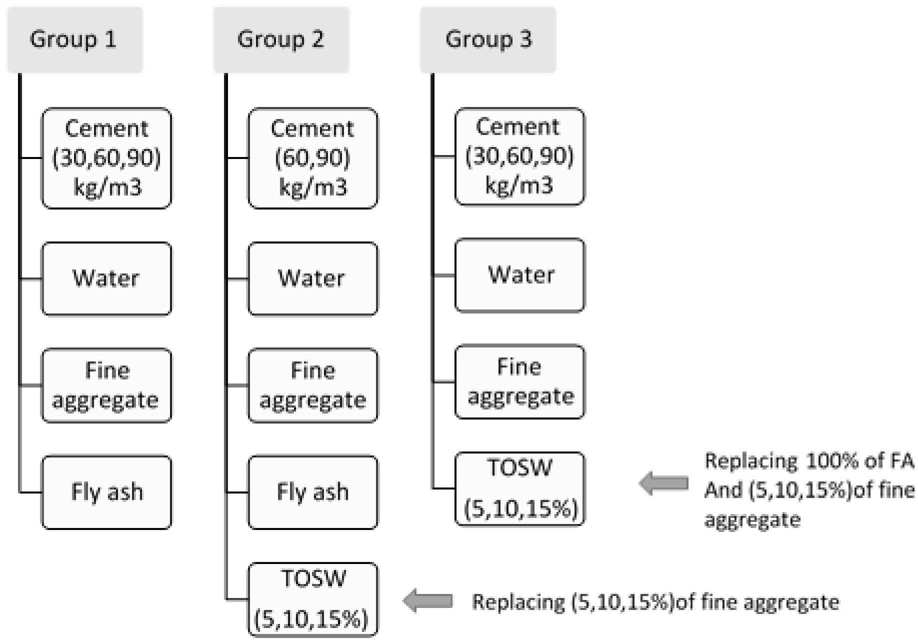


Figure 3.2 Mixture groups diagram

Table 3.3. Mixtures proportions per one cubic meter of CLSM

Mixture Groups	Mix Code	Cement (kg)	Fly ash	Aggregate (kg)	TOSW (kg)	Water (kg)	W/Powder[1] (kg)
(Group 1)	G130	30	148	1727	0	297	4.3
Control	G160	60	148	1691	0	297	3.8
Mixtures	G190	90	148	1655	0	297	3.4
(Group 2)	G260W	60	148	1606	84	221	1.9
	G260W	60	148	1522	168	226	1.5
TOSW	G260W	60	148	1437	253	221	1.2
replacing	G290W	90	148	1572	82	270	2.2
aggregate	G290W	90	148	1490	165	245	1.5
	G290W	90	148	1407	247	244	1.13
	G330W	30	0	1641	205	209	2.1
(Group 3)	G330W	30	0	1554	277	177	1.3
	G330W	30	0	1468	350	165	1.0
TOSW	G360W	60	0	1606	205	246	2.2
replacing	G360W	60	0	1522	274	227	1.6
fly ash and	G360W	60	0	1437	341	232	1.3
aggregate	G390W	90	0	1572	205	224	1.9
	G390W	90	0	1490	274	212	1.4
	G390W	90	0	1407	341	213	1.2

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

3.2.2. Mixing Procedure

Dry mixture components (i.e. cement, fly ash and TOSW) were mixed for 1 minute without addition of water to ensure a homogeneous distribution. About half of the mixing water was then added gradually to the mixture and mixed for 1 more minute and the rest of the mixing water was then added and mixed for another minute. The mixture was allowed to rest for 1 minute after adding the water and then mixed for another 2 minutes before sampling (Lachemi *et al.,* 2007). No special admixtures were needed to adjust the properties of the mixture. The flowability of the mixture was continuously measured during the addition of water to reach the desired normal flowability range of 150 mm to 200 mm as recommended by (ACI Committee 229R, 2013).

3.2.3. Testing

3.2.3.1. Flowability

Flowability of the fresh CLSM mixtures was evaluated in accordance with ASTM standards ASTM D6023-07 (Flow Consistency of Controlled Low Strength Material). The test was performed using a D100 mm × 200 mm open-end slump cylinder. The CLSM mixture was filled to the top edge of the cylinder placed on a levelled glass plate and then quickly lifted to allowing the fresh mixture flow freely on the plate. The diameter of the circular section formed by the fresh CLSM was measured as the flow value of the CLSM as shown in **Figure 3.3.**

Figure 3.3 Measurement of flowability value of a fresh CLSM mixture

3.2.3.2. Density

The fresh density of CLSM was measured as per ASTM D6023-07 (Density, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material). A steel cylindrical measure was filled by fresh CLSM mixture. The mass of the CLSM was then determined and divided by the volume of the measure to obtain the density.

Hardened density was determined by accurately calculating the volume of the hardened cylindrical sample, measuring the mass of the sample, and dividing the mass by the volume to obtain the hardened density.

3.2.3.3. Bleeding

Following the ASTM test method C232 (Standard Test Method for Bleeding of Concrete), a known volume of fresh CSLM mixture was carefully filled in a 1000 ml graduated cylinder. The cylinder was then covered to prevent evaporation of water and placed on a leveled surface of bleed water. The bleed water level was observed until no further change in the level (Usually after 4 hours of testing). The bleed water was then collected in a separate graduated measure.

The bleeding value is calculated as the percentage ratio of volume of bleed water to the volume of the test CLSM sample.

3.2.3.4. Drying Shrinkage

To assess the effect of mixing materials on drying shrinkage, a drying shrinkage test was conducted following the ASTM test method C490-11 (Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete). Four 25 mm × 25 mm × 280 mm prismatic samples were prepared for each mixture. The prisms were kept in plastic bags for 7 days to reduce evaporation of water. The samples were then demolded and the initial readings were taken before wrapping the samples in plastic bags and storing them in an ambient temperature (20ºC) until testing age. The readings were taken daily using a length comparator with a digital indicator **(Figure 3.4.b)** until no change was recorded.

a. CLSM prismatic samples b. Length Comparator with sample

Figure 3.4 Samples and device used for drying shrinkage measurements

3.2.3.5. Compressive Strength and Elastic Modulus

The compressive strength was determined as per ASTM test method D4832-10 (ASTM D 4832-10, 2010) (Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders). Due to the weak early age strength of CLSM mixtures, samples were matured in their uncovered molds inside a 98% relative humidity curing room until testing age. Compressive tests were conducted after 7, 14 and 28 days of mixing using a strain controlled unconfined compressive strength machine. The compressive loading was applied at a strain rate of 1.14 mm/min, which ensured that failure of the tested sample would not occur in less than 2 minutes (ASTM D 4832-10, 2010). The stress-strain curve was plotted and the secant elastic modulus was calculated as the slope of the line from origin to the point of 50% of maximum stress (Nataraja & Nalanda, 2008). The CLSM specimens were also tested for splitting tensile strength at age of 28 days following ASTM standards C496/C496M (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens).

a. Unconfined compressive strength test

b. Split tensile strength test

Figure 3.5 Unconfined compressive strength and split tensile strength tests setup.

3.2.3.6. Removability Modulus (RE)

The need for future excavation after the CLSM was applied is the main reason behind the low strength requirements of the CLSM. The removability modulus (RE) can be used to assess the excavatability of a CLSM mixture based on its strength and dry density (Eq.3.1).

$$RE = \frac{W^{1.5} \times 0.619 \times C^{0.5}}{10^6} \qquad [3.1]$$

Where W is the dry density of the mixture in (kg/m^3), C is the compressive strength at 28 days in (kPa). The CLSM mixture is considered easily removable if RE is less than 1 (ACI Committee 229R, 2013).

3.2.3.7. Leaching

The environmental assessment of incorporating TOSW in CLSM mixtures was done by investigating leaching of metals from the hardened CLSM samples while immersed in distilled water. As aforementioned, three different replacement rates (5%, 10%, and 15%) of TOSW were used; however, environmental assessment was conducted only on samples having the highest content of TOSW, which is 15%, to represent the most critical impact of using TOSW as a fine material in CLSM mixtures. The results were compared with the groundwater standards of the Canadian Council of Ministers of Environment (CCME, 2004). In addition, tests were conducted on the raw TOSW separately in order to evaluate its leaching properties. Cubic samples of 50 × 50 × 50 (mm) were used following the procedure of method 1315 of the US Environmental Protection Agency (EPA, 2013) (Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure). Leachates samples were collected after 2, 7 and 28 days of immersion in distilled water and analyzed using coupled plasma mass spectrometry (ICP-MS).

3.3. Results and discussion

3.3.1. Flowability

Flowability of CLSM mixtures is generally controlled by the amount of water used to achieve the targeted flow of 150 to 200 mm (6 to 8 in). Results show that changing the cement content while maintaining the same fly ash content has an insignificant effect on the flowability of CLSM, in agreement with previous work (Qian *et al.,* 2015). **Figure 3.6** presents the results of the flowability for tested CLSM mixtures. The flowability of CLSM control mixtures ranged from 185 to 250 mm, which falls within the normal to high flowability category according to the ACI committee 229R report. The incorporation of TOSW reduced the amount of water required to achieve the same flowability range of control mixtures of about 25%. It can be seen from **Figure 3.6** that mixtures containing TOSW required considerably lower water/powder ratios while maintaining a normal flowability. Incorporating very fine material, such as TOSW, increases the surface area of the particles in the mix, which leads to a higher water demand. On the other hand, the fine particle size in TOSW helped enhance the powder packing and released the water entrapped between cement particles making it available for lubrication and hence increasing the flowability of the mix. A similar behavior of TOSW was observed in previous works (Mneina *et al.,* 2016), (Aboutabikh *et al.,* 2016) and (Mansour *et al.,* 2016). In addition to filling voids between coarser particles, the very fine TOSW acts as a "lubricant" between them, reducing the particle interference and consequently the viscosity. This was confirmed in Group 3 mixtures at which fly ash was replaced by TOSW. TOSW addition was more efficient in increasing flowability than fly ash **(Figure 3.6).**

3.3.2. Density

Density of the fresh and hardened CLSM samples were measured at different ages up to 28 days of curing. **Table 3.4** presents the fresh and hardened density of the different tested mixtures. The fresh density of the control mixtures ranged from 2190 to 2195 kg/m^3. It can be noticed from **Table 3.4** that the density of Group 2 ranged from 1816 to 1901 kg/m^3. This represents a reduction of density up to 17% compared to that of the control mixtures but the density still lies within the range of normal CLSM reported by ACI Committee 229. The reduction in density can be attributed to the low specific gravity of TOSW compared with aggregate. For Group 3 mixtures, in which fly ash was replaced by TOSW, the fresh density increased up to 6% for G390 and G360 mixtures, then it started to decrease 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 is also within the range of normal CLSM.

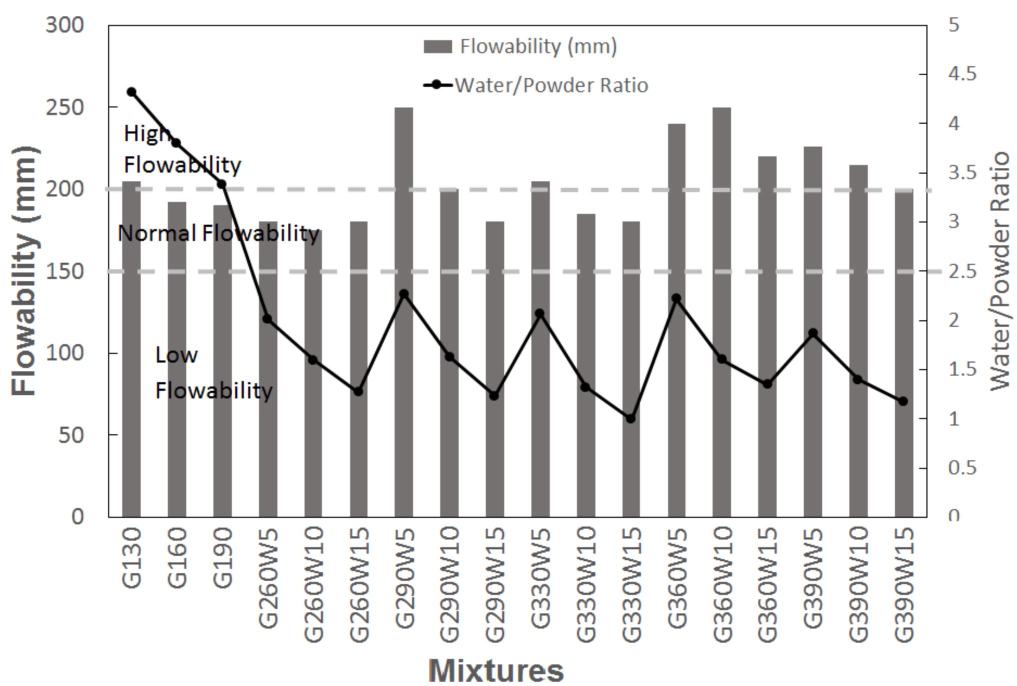


Figure 3.6 Followability and Water/Powder ratio chart

Table 3.4 Fresh and hardened densities of CLSM mixtures

Mixture Groups	Mix Code	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)		
			7 days	14 days	28 days
(Group 1) ACI-229R Control	G130	2195	2201	2231	2226
	G160	2190	2244	2218	2207
	G190	2192	2217	2201	2207
(Group 2) TOSW replacing aggregate	G260W5	1939	1872	1900	1897
	G260W10	1901	1849	1846	1860
	G260W15	1928	1932	1935	1918
	G290W5	1942	1963	1955	1935
	G290W10	1816	1930	1913	1988
	G290W15	1939	1935	1932	1952
(Group 3) TOSW replacing fly ash and aggregate	G330W5	2087	1765	1774	1774
	G330W10	2067	1677	1761	1761
	G330W15	2134	1785	1796	1796
	G360W5	2325	1977	1977	2002
	G360W10	2214	1915	1930	1938
	G360W15	2308	1990	1962	1968
	G390W5	2249	1897	1927	1914
	G390W10	2313	1946	1948	1947
	G390W15	2302	1919	1934	1949

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) and (Dickson *et al.*, 2014). 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 3.7**. 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 & Kovler, 2004). Bleeding values of all mixtures, however, were well below the maximum of 5% for stable CLSM (Yan *et al.*, 2014) and (Dickson *et al.*, 2014).

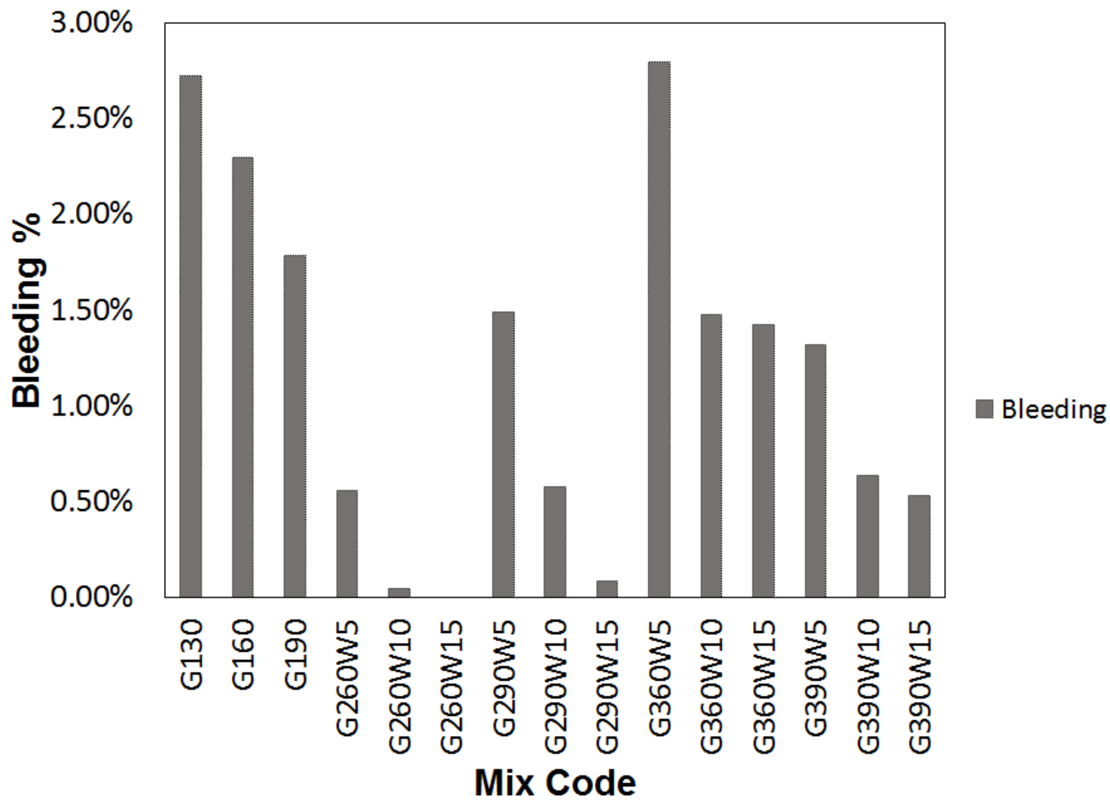


Figure 3.7 Bleeding results as percentage of volume

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 & 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 & 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 does not affect the performance of CSLM (ACI Committee 229R, 2013).

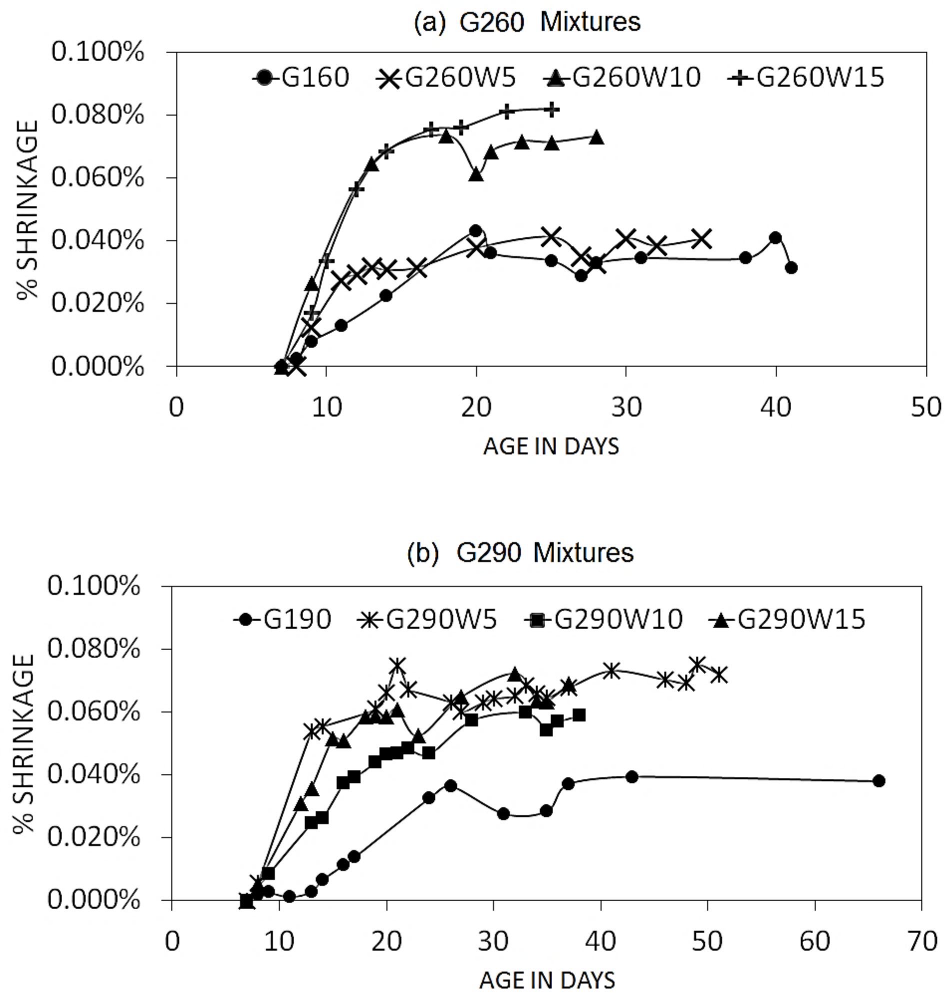


Figure 3.8 Drying shrinkage for G260 and G290 mixtures

3.3.5. Leaching

Table 3.5, Figure 3.9 and **Figure 3.10** show the results of the conducted (ICP-MS) analysis on the leachates. It is noticed from **Figure 3.9** 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, 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. From **Figure 3.10**, we notice 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).

Table 3.5 : Results of (ICP-MS) analysis of leachate

Mixtures	Age	Lithium (Li)	Chromium (Cr)	Arsenic (As)	Strontium (Sr)	Cadmium (Cd)	Barium (Ba)
Mix code	(days)	Conc. (μg/L)	Conc. (μg/L)	Conc. (μg/L)	Conc. (μg/L)	Conc. (μg/L)	Conc. (μg/L)
G260W15	2	5.29	6.43	1.55	179.45	ND	153.45
G260W15	7	7.70	11.09	1.94	455.31	ND	146.11
G260W15	28	21.97	30.29	1.67	1148.03	ND	118.08
G290W15	2	5.29	3.03	0.93	81.40	ND	131.21
G290W15	7	12.32	9.38	0.64	480.47	ND	180.43
G290W15	28	38.03	21.32	1.11	977.09	ND	320.43
G360W15	28	16.86	12.10	1.31	3887.84	<0.05	874.63
G390W15	28	12.58	9.07	0.98	3699.30	<0.05	792.48
Raw G2 TOSW	2	<5.29	<0.26	13.20	1040.43	0.34	394.81
Raw G2 TOSW	7	<5.29	0.32	16.74	1201.91	0.21	381.74
Raw G2 TOSW	28	<5.29	<0.26	13.93	1485.15	0.33	477.06
Raw G3 TOSW	28	12.85	0.38	23.09	1920.81	0.27	371.45

ND=lower than method detection limit

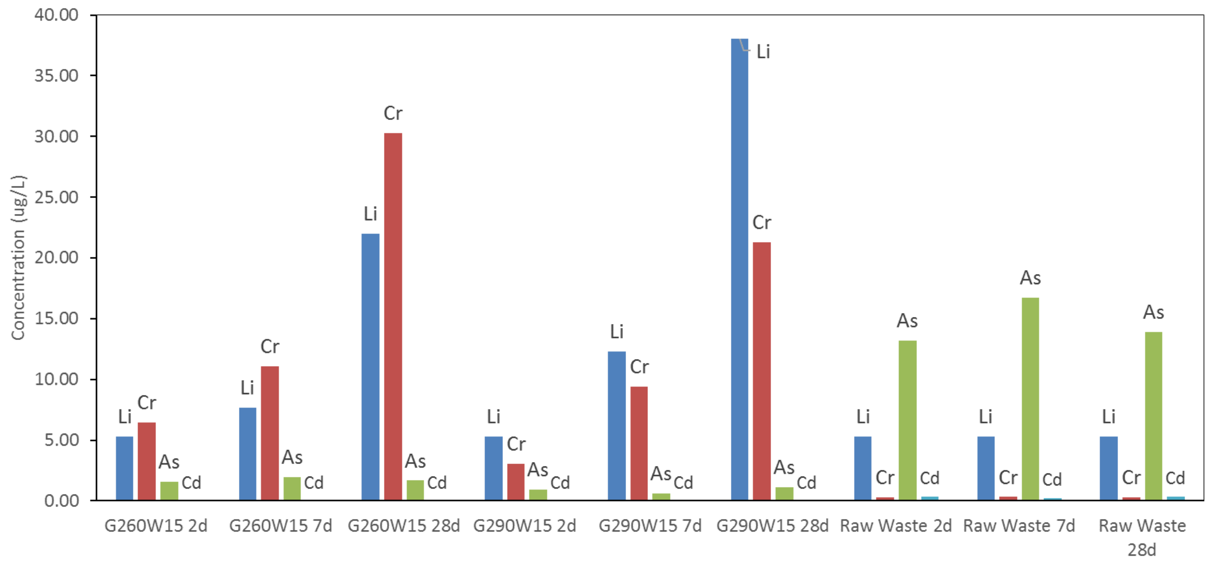


Figure 3.9 Results of ICP-MS analysis showing effect of curing days on Group 2 leachates samples.

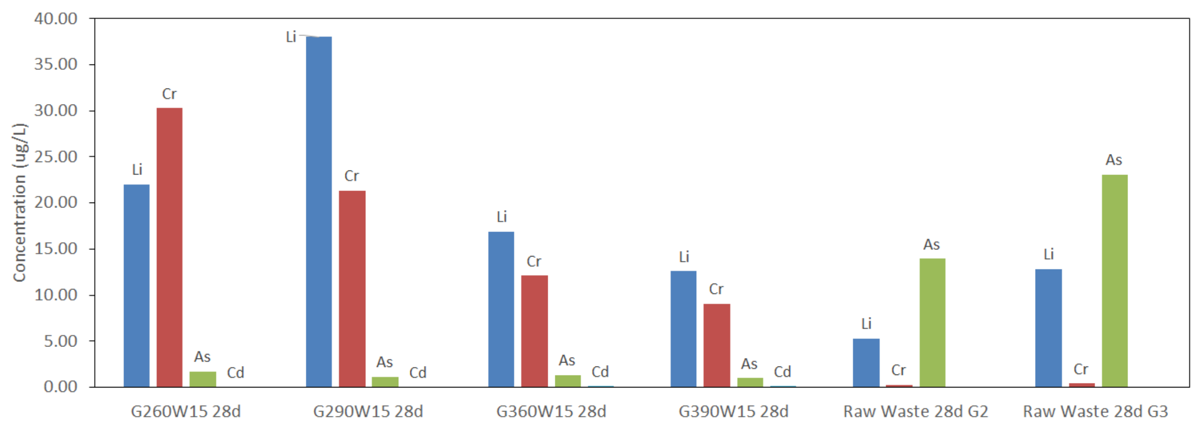


Figure 3.10 ICP-MS analysis showing results of 28 days of curing on Group 2 and Group 3 mixtures

3.3.6. Compressive strength

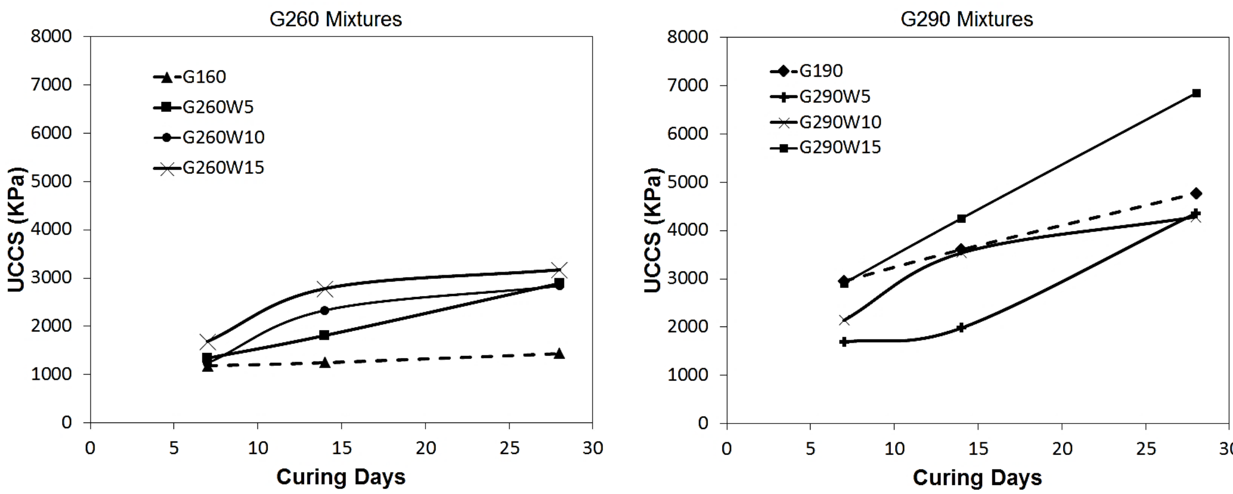
The compressive strength was investigated for the 3 control mixtures of CLSM and 15 mixtures with different cement, TOSW and fly ash contents, CLSM samples were tested after 7, 14 and 28 days of curing. The compressive strength values of the tested mixtures are presented in **Table**

3.6 and **Figure 3.11**. 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). This can be explained as follows: the class F fly ash used in these mixtures has no cementitious properties and needs cement in order for the pozzolanic reaction to take place; 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).

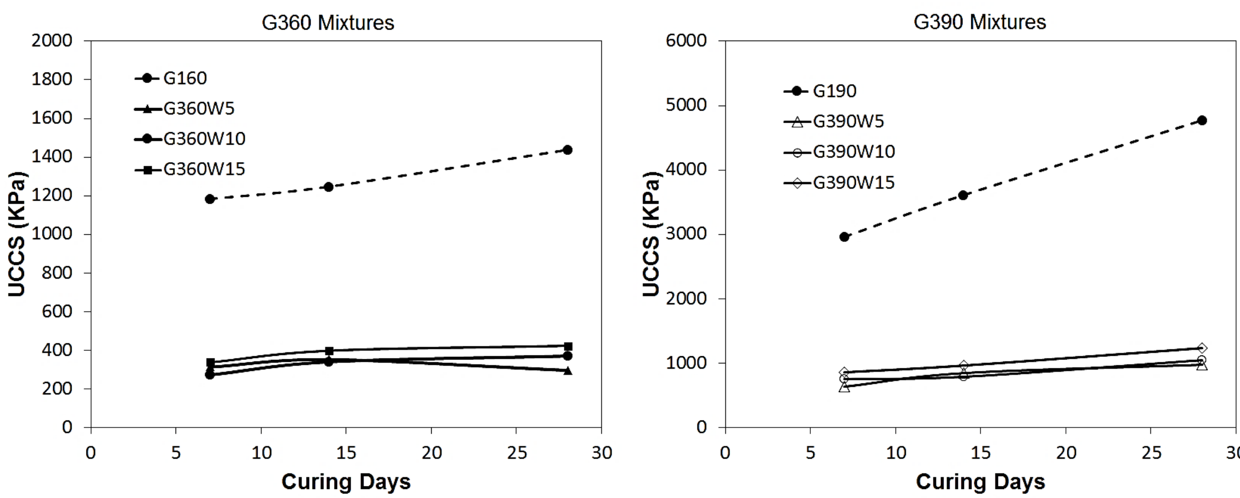
For mixtures incorporating TOSW, the compressive strength depends mainly on the water/powder ratio. By referring to **Figures 3.5** and **3.10.a**, the strength of G290 mixtures increased with the decrease of water/powder ratio regardless of the waste content. However, in Group 2 mixtures, the ability of the TOSW to enhance flowability reduced the amount of water needed for the mixture, which led to an increase in strength when the same flowability was maintained as noticed for G260 mixtures. On the other hand, replacing fly ash with TOSW in Group 3 mixtures resulted in a significant reduction in strength. This is attributed to reduced bonding between particles due to the lack of the pozzolanic activity of fly ash that was available in Group 2 mixtures. However, this reduced strength 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 (ACI Committee 229R, 2013).

CLSM cylinders were also tested for tensile strength according to ASTM test method C496/C496M (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete

Specimens). **Figure 3.12** shows a good linear relationship between the tensile strength and the compressive strength of the tested CLSM samples. The tensile strength ranged from 7% to 17% of the compressive strength and this range is very close to the normal range of Portland cement concrete, which is 8% to 14% (Qian *et al.*, 2015).



(a) Unconfined compressive strength for Group 2 mixtures



(b) Unconfined compressive strength for Group 3 mixtures

Figure 3.11 Development of compressive strength with age of Group 2 and Group 3 selected mixtures.

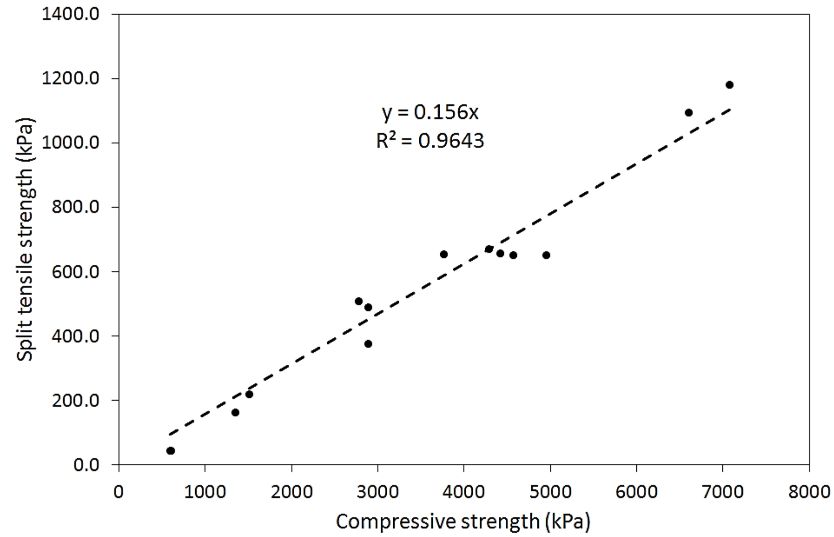


Figure 3.12 Relationship between split tensile strength and compressive strength

To assess the excavatability of the mixtures, the removability modulus is calculated according to (Eq.1) based on the results of the compressive strength and density of the samples. The requirements and limits of RE vary with the application of CSLM, CLSM is considered easily removable by hand tools if RE is equal or less than 1, Replacing fly ash with TOSW lowered the RE producing more easily removable CLSM while maintaining the other properties of CLSM within ACI specifications. The results of removability modulus calculations are shown in **Table 3.6.**

3.3.7. Elastic Modulus

The secant elastic modulus (E_S) was calculated based on the stress-strain curve obtained from the unconfined compressive strength test at 50% of the maximum strength at 28 days (Nataraja and Nalanda 2008 and Kim and Kang 2011) (Nataraja & Nalanda, 2008), (Kim & Kang, 2011). The obtained results demonstrated that the secant elastic modulus increased as the compressive strength increased, as shown in **Table 3.6**. The secant elastic modulus was found to be 54 to 395 times the corresponding compressive strength which is within the range reported in the literature for CLSM. Tsuchida (2004) (Tsuchida, 2004) investigated mixing light-weight soils in CLSM and reported E/UCCS values ranging from 40-260. Chittoori (2013) (Chittoori, Puppala, & Raa, 2013) investigated mechanical properties of CLSM and observed a similar range of E/UCCS ranging from 54 to 240.

Table 3.6 Compressive strength, elastic modulus and removability modulus at age of 28 days

Mixture Groups	Mix code	(E) Modulus of Elasticity (KPa)	(UCCS) Compressive strength (KPa)	E/UCCS	RE
(Group 1) ACI-229R Control Mixtures	G130	73324	595	122	1.59
	G160	203050	1436	141	2.43
	G190	578012	4771	121	4.43
(Group 2) TOSW replacing aggregate	G260W5	181647	2894	63	2.75
	G260W10	360617	2840	127	2.65
	G260W15	322350	3172	101	2.93
	G290W5	625374	4364	143	3.48
	G290W10	529035	4281	124	3.59
	G290W15	567013	6848	83	4.42
(Group 3) TOSW replacing fly ash and aggregate	G330W5	3154	72	54	0.39
	G330W10	20174	158	128	0.57
	G330W15	26749	184	146	0.64
	G360W5	50106	298	168	0.96
	G360W10	81043	370	219	1.02
	G360W15	167004	423	395	1.11
	G390W5	242029	972	249	1.62
	G390W10	177013	1043	170	1.72
	G390W15	237031	1233	192	1.87

3.4. Conclusions

The results of this study demonstrate that TOSW can be used as a filler material and as a replacement of fly ash in CLSM producing a sustainable and environmentally safe CLSM that satisfies fresh and hardened properties. Moreover, some of the CLSM properties were enhanced after incorporating TOSW. The conclusion of this study can be listed in the points below:

- The incorporation of TOSW has increased the flowability of the mixtures, which reduced the water demand to reach a specific flowability value, which in turn 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 of the mixtures can also 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.
- Mixtures with TOSW showed higher drying shrinkage as the content of TOSW increases), therefore it is recommended to use shrinkage control admixtures for applications where shrinkage control is required.
- Incorporating TOSW in CLSM mixtures has significantly reduced bleed water.
- Incorporating TOSW in CLSM mixtures lowered the pollutant potential of the TOSW in terms of leaching concentrations.
- The unconfined compressive strength at 28 days of the tested 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 content. Higher strength values were achieved for mixtures with higher TOSW content within the same group.

Replacing fly ash with TOSW in Group 3 mixtures lowered the strength and elastic modulus of the mixtures compared to the control mixtures, which may be beneficial in some applications of CLSM where low strength is required for future excavation. Higher cement content can compensate for the reduced strength due to elimination of fly ash. Increasing cement content from 60 kg/m3 to 90 kg/m3 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.

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Chapter 4

DYNAMIC PROPERTIES OF CONTROLLED LOW-STRENGTH MATERIALS INCORPORATING TREATED OIL SAND WASTE

4.1. Introduction

Controlled low strength material (CLSM) is a flowable cementitious material used as an alternative to conventional backfill materials. It is a mixture of cement, sand, water, and other supplementary materials such as fly ash, resulting in a material with high flowability and enhanced mechanical properties. These desired properties render CLSM superior to the conventional compacted granular materials, especially as a backfill of foundations subjected to dynamic loading (Byun *et al.,* 2016). In addition, CLSM provides excellent solution for many geotechnical applications such as trench backfilling, structural fills for uniform level surface and great bearing capacity compared to normal fills, pavement repairs and pipeline beddings (ACI Committee 229R, 2013)

Evaluating the effect of each component of the CLSM mixture on its static and dynamic properties is important for designing the mixture with acceptable properties for different geotechnical applications. Various types of wastes and by-products have been incorporated in CLSM mixtures and the properties of their mixtures are reported in the literature. By-products such as cement kiln dust, wood ash, limestone fines and scrap tire rubber were investigated for use in CLSM. In most of these studies, the investigation of the characteristics of produced CLSM focussed mostly on its fresh and static mechanical properties. The dynamic properties of hardened CLSM are not well covered in the literature. Dynamic properties such as the shear wave velocity, shear modulus and damping ratio are important inputs for foundation design and the effect of CLSM mix proportions on its properties should be evaluated.

The shear wave velocity (Vs) of backfill materials is an important design parameter for embedded foundations subjected to dynamic loading. Several methods are available to measure the shear wave velocity of soil samples in the laboratory with high accuracy. The most commonly used test methods to measure Vs in the laboratory are the Bender Element (BE) (Dyvik, 1985) and the Resonance Column (RC). The RC test provides reliable and accurate measurements of the shear wave velocity and damping ratio. However, the test requires expensive equipment and processing its results is complicated (Cai *et al.,* 2015). On the other hand, the bender element offers a cheap testing option that involves simple data processing to measure the shear wave velocity; nonetheless, it has its own limitations. For example, the bender elements must penetrate the sample, which may cause sample disturbance; and in cemented samples, it may be necessary to drill a hole to facilitate penetration and the hole is then filled with epoxy material that may fail causing short-circuit and/or signal loss. Moreover, high voltages are required for samples with long travel distance to attain clear signals, and the small thickness of the bender element makes it venerable to depolarization under high voltages (Ismail, 2005).

A new technique originated in University of Sherbrook by (Gamal El-Dean, 2007) and later was modified and developed further at Western University (Ahmed *et al*. 2016) employing a device incorporating piezoelectric ring actuators (PRA) that sends and receives signals on the surface of the sample without the need to penetrate the soil **(Figure 4.1)**. Employing the developed PRA device incorporated into an oedometer setup, (Ahmed, 2016) measured the shear wave velocity of both sands and cohesive soils. The received signals were clear with distinguished waves and low noise to signal ratio. The measured shear wave velocity employing the PRA were in good agreement with the reported values in the literature that was measured using resonant column testing, which verified the performance of the fabricated PRA device. Ahmed *et al*. (2015) utilized the developed device to measure the properties of manufactured clay used in dynamic centrifuge tests**.** Since no sample penetration is needed, the new PRA device is ideal for measuring the shear wave velocity of hard samples like hard clay, soft rock and controlled low strength materials (CLSM).

Figure 4.1 PRA device for measuring shear wave velocity

The development of shear wave velocity at early stages of the fresh CLSM mixture was examined by (Byun *et al*., 2016) to monitor the hydration process. The measurements were made using two different piezoelectric transducers techniques: a piezoelectric disk element (PDE); and a bender element (BE) embedded in the fresh mix to measure the compressional waves (P-wave) and shear waves (S-wave) of the samples. They suggested employing an input sinusoidal pulse wave with a frequency equal to the measured resonance frequency of the sample to reduce the interference of compressional waves and to enhance the response of the shear waves. They reported that the measured shear wave velocity decreased as the fine content of the CLSM increased, especially in the very early ages of the hydration process. (Yang & Liu, 2016) reported similar observations on the effect of fines content on shear wave velocity of sand mixed with crushed silica fines as an additive. They tested mixtures with a range of fines from 0 to 30% and reported that Vs decreased as the fines content increased. The results of both studies emphasise the role of fines on the shear wave velocity of the mixture. In case of lightly cemented samples, the fines content would have more significant influence on the shear wave velocity and the dynamic shear modulus of the mixture.

Saxena (1988) studied the very small strain shear modulus and damping ratio of artificially cemented sands using resonant column apparatus. He reported increases in the dynamic shear modulus and damping ratio with the increase of cement content up to a certain level after which the modulus continued to increase while the damping ratio started to decrease. The unexpected behaviour of damping ratio was explained as follows. At lower cement content, the cement formed a layer of coating on the clean sand particles, which increased the energy needed to rearrange the particles after dynamic loading hence increasing the damping ratio. Meanwhile, at this low level of cement, the cement was not enough to form bonds between the coated particles. Increasing the cement content to a level that particle-coating is not the governing mechanism reduced the damping ratio as the strong cementing bonds increased. A similar increase in damping was reported by (Chiang & Chae, 1972) when the amount of additives (such as lime and fly ash) was increased in the mixture; however, no explanation was provided for the observed behaviour.

In this research, mixtures of CLSM composed of cement, sand, water, fly ash and treated oil sand wastes (TOSW) with varying proportions were prepared and their dynamic properties were measured to explore replacing the sand and/or fly ash with TOSW in CSLM material. The PRA device was employed to measure the shear wave velocity of the hardened CLSM samples at different ages to monitor the effect of TOSW on the dynamic properties of CLSM.

This work is part of a comprehensive program to incorporate TOSW in grout manufacture and CLSM for geotechnical application (Aboutabikh *et al.*, 2015; Mansour, *et al*,. 2016; Kassem, *et al*., 2015). Aboutabikh *et al*., (2015) tested grout mixtures replacing up to 20% of cement with TOSW and reported that the properties of the grout were not adversely affected. TOSW was successfully used in CSLM mixtures in a companion study (Mneina *et al*., 2016). The main objective of this research is to evaluate the dynamic properties of CLSM incorporating TOSW as a replacement material of sand and fly ash.

4.2. Experimental Program

4.2.1. Materials

All mixtures were manufactured using Type 10 Portland cement (OPC) with Blaine fineness of 360 m^2/kg and specific gravity of 3.15. The cement contained 61% Tricalcium Silicate (C3S), 11% Dicalcium Silicate (C2S), 9% Tricalcium Aluminate (C3A), 7% Tetracalcium Aluminoferrite (C4AF), 0.82% equivalent alkalis and 5% limestone. The Class F fly ash used in the tests had a surface area of 280 m^2/kg and a specific gravity of 2.5. Treated oil sand waste (TOSW) was used as a replacement of fly ash and as a partial replacement of sand in some mixtures. The TOSW was silicate based with Blaine fineness of 1440 m^2/kg and specific gravity of 2.23. The chemical composition and the physical properties of the cement, fly ash and TOSW are shown in **Table 3.2**.

Twelve different CLSM mixtures were prepared with different cement and TOSW contents and were categorized into three groups. Group 1 was the control group with no TOSW, and with cement contents of 60 and 90 kg/m^3. Group 1 mixtures were designed based on the proportion guidelines reported by ACI committee 229 for CLSM. Group 2 mixtures incorporated fly ash and TOSW that was used as a partial replacement of sand by rates of 10% and 15% by volume. Group 3 mixtures incorporated TOSW as a total replacement of fly ash (i.e. 100%) and as partial replacement of sand by rates of 5%, 10% and 15%. All mixtures were manufactured using natural river bed sand with specific gravity of 2.65. Mix proportions are presented in **Table 3.4**.

4.2.2. Preparation of Mixtures

The specified proportions of each mixture (i.e. sand, cement, fly ash and TOSW) were placed in the mixer and were stirred for 1 minute without addition of water to ensure a homogeneous distribution. Half of the mixing water was then added gradually to the mixture and was mixed for one minute and the rest of the mixing water was then added and mixed for another minute. The mixture was then allowed to rest for 1 minute and then was mixed for 2 more minutes before sampling (Lachemi *et al*., 2007). No special admixtures were added to the mixture. 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 Committee 229R, 2013).

4.2.3. Tests and Analysis Methods

The freshly mixed CLSM was poured into 50 mm cubic metal molds while taping the outside walls of the molds to remove any air voids and to make sure that the molds are filled completely.

The test samples were then cured inside a curing room with a constant temperature of 23 ± 2°C and relative humidity of 100%, until testing. For each mixture, three samples were cast and tested to determine its shear wave velocity. The shear wave velocity for each mixture was taken as the average of the measurements of the three samples.

The samples were allowed to cure for the target time before testing in the PRA device to measure V_s. The cubes were tested using the PRA with an applied pressure varying from 190 to 375 kPa (but no lateral confinement) to ensure good contact between the PRA and the sample surface. The test is non-destructive and same samples could be used for testing at different ages. A high voltage sinusoidal wave was triggered through the sample with frequencies ranging from 24 to 65 kHz and the resulting signals were received and recorded via a data acquisition system. The arrangement of the test setup is shown in **Figures 4.2 and 4.3.** The shear wave arrival time was determined using time domain and frequency domain analysis methods (Viggiani, 1995). However, due to the uncertainty of these methods, visual picking of arrival time considering the first zero-crossing point was also adopted for measuring the shear wave velocity (Ahmed, 2016). The arrival time obtained from different methods was evaluated.

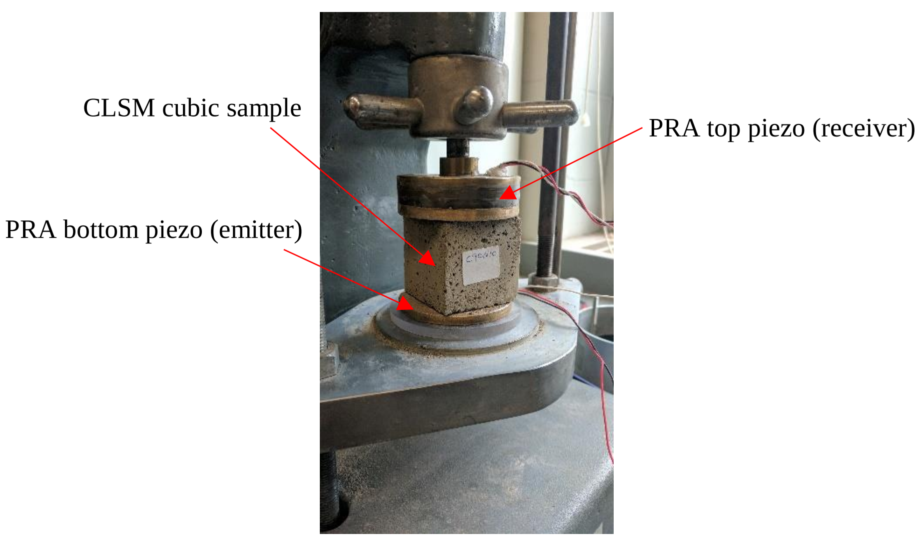

Figure 4.2 Measuring shear wave velocity using PRA device setup in an odometer.

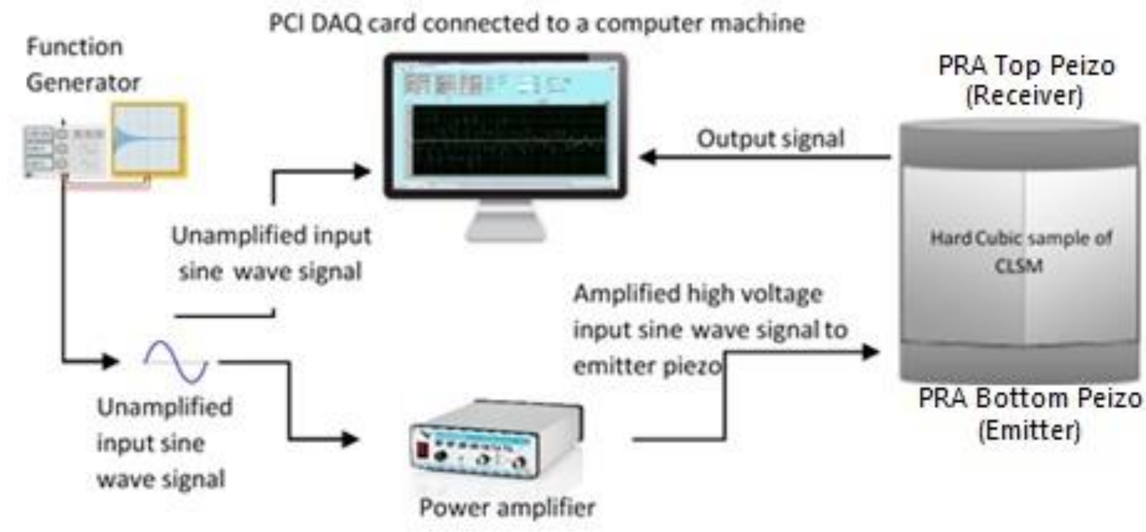

Figure 4.3 Schematic diagram of PRA setup

Measurements of compression wave velocity (V_p) were also made during shear wave measurement. The results were used to calculate the dynamic Poisson's ratio.

The fresh and hardened densities as well as the unconfined compressive strength of the mixtures were measured in accordance to ASTM D6023-07 (Density, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material) and ASTM test method D4832-10 (Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders). The secant elastic modulus (E_s) was calculated based on the stress-strain curve obtained from the unconfined compressive strength test at 50% of the maximum strength at 28 days (Nataraja & Nalanda, 2008; Kim & Kang, 2011).

The measured shear wave velocity and mixture density were used to calculate the low-strain shear modulus G_0 , i.e.:

$$G_0 = \rho(V_s)^2 \qquad [4.1]$$

Where: ρ is the density of the sample.

To study the relationship between the static and dynamic moduli (large-strain and small-strain shear modulus), the static shear modulus was calculated using the obtained static elastic modulus and Poisson's ratio as follows:

$G_{static} = E_s/[2(1+\upsilon_s)]$ [4.2]

Where: E_s is the secant (static) elastic modulus and υ_s is the static Poisson's ratio.

The static Poisson's ratio was measured using a compressometer and an extensometer attached to a cylindrical CLSM sample to measure the longitudinal and transverse strains during a strain controlled unconfined loading (**Figure 4.4)**. Poisson's ratio was then calculated as the ratio of transverse strain to longitudinal strain as per ASTM C469/C469M – 10 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression).

Figure 4.4 Determining static Poisson's ratio using a compressometer

The dynamic modulus of elasticity (E_{dyn}) of the CLSM mixtures may be calculated knowing the dynamic shear modulus and the dynamic Poisson's ratio, i.e.

$$E_{dyn} = G_0[2(1+\upsilon_d)] \qquad [4.3]$$

Where E_{dyn} is the dynamic elastic modulus and υ_d is the dynamic Poisson's ratio.

The compressional wave velocity and dynamic Poisson's ratio of the different CLSM mixtures tested herein were evaluated from the wave propagation measurements using the PRA device as will be described later.

The damping ratio (D) of the CLSM samples was evaluated using the half-power bandwidth method of the frequency spectrum (Lutz *et al.*, 2008) and (Amaral *et al.*, 2011). The response spectrum of the received signal is acquired by applying the Fast Fourier Transform function to the received amplitude values, and the damping ratio associated with the spectral peak can be calculated as:

$$D = \frac{f_2 - f_1}{f_2 + f_1} \qquad [4.4]$$

Were f_1 and f_2 are lower and upper frequencies at an amplitude value equal to $1/\sqrt{2}$ of the maximum amplitude of the frequency spectrum (A_{max}). **Figure 4.5** shows an example of applying the half-power bandwidth method on the frequency response spectrum to calculate the damping ratio of a hardened CLSM sample.

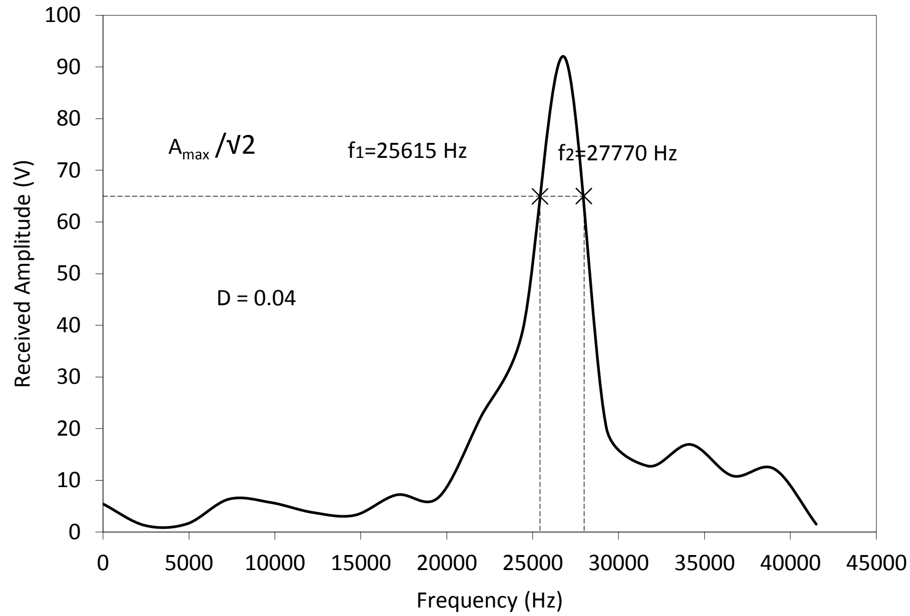

Figure 4.5 Example of calculating the damping ratio from the frequency response spectrum (sample G360W15)

4.3. Results and Discussion

4.3.1. Shear Wave Velocity Measurements

The interpretation of the received signal of the bender element and, similarly, the PRA requires care in signal analysis. That is because the received signal may contain components other than the shear wave such the nearfield effect and compression wave. Distinguishing the shear wave among these components has been the focus of Bender element signal interpolation studies such as (Brignoli *et al*. 1996) (Dyvik, 1985) (Lee & Santamarina, 2005) (Viggiani, 1995). In particular, evaluating the travel time of shear wave is influenced by the selection of which point represents the first shear wave arrival. Numerous studies compared different first arrivals of the received signal at different potential points (e.g., Dyvik and Madshus 1985; Jamiolkowski *et al.* 1995; Viggiani and Atkinson 1995). Generally, there is no universal agreement on the detection of the first arrival of the received signal. Four critical points are considered as the beginning of the received signal (Karray *et al.*, 2015): ((i) first deflection; (ii) first inflection; (iii) first zero after inflection; and (iv) second inflection or major peak.

For this reason, a range of different input excitation frequencies were applied to all the tested samples in this work to monitor the nature of the received signal. The compression wave is affected by the input frequency in a manner different than the shear wave of the same sample. Thus, different input frequencies were used while monitoring the signal until a clear shear wave arrival was achieved. The point of shear wave arrival was identified by the first significant excursion in the signal with the proper positive polarity (Brignoli *et al*., 1996). **Figure 4.6** illustrates a typical received signal and shear wave arrival identification methods, including visual inspection, cross correlation and frequency domain analysis (Viggiani, 1995).

The near field component of the signal experienced a rapid decay with increasing the ratio L/λ (where L = sample height, λ = wavelength of input wave), which led to a clear shear wave signal. Viggiani and Atkinson (1995) recommended $L/\lambda \geq 3$-4 for a reliable measurement of shear wave velocity. Keeping this value higher than 3 ensured an adequate number of wave lengths traveling through the sample. Higher values of L/λ were achieved by increasing the frequency of the input signal. The frequency was increased until a constant shear wave measurement was achieved. It is noted that the shear wave velocity reached a constant reading at a frequency range of 50 to 65 kHz and L/λ ranging from 4 to 7. **Figure 4.7** shows the benefits of using higher frequencies on the quality of the signal minimizing the near field effect. Using 65 kHz signal showed clear shear wave arrival with $L/\lambda = 4.3$ in this particular example.

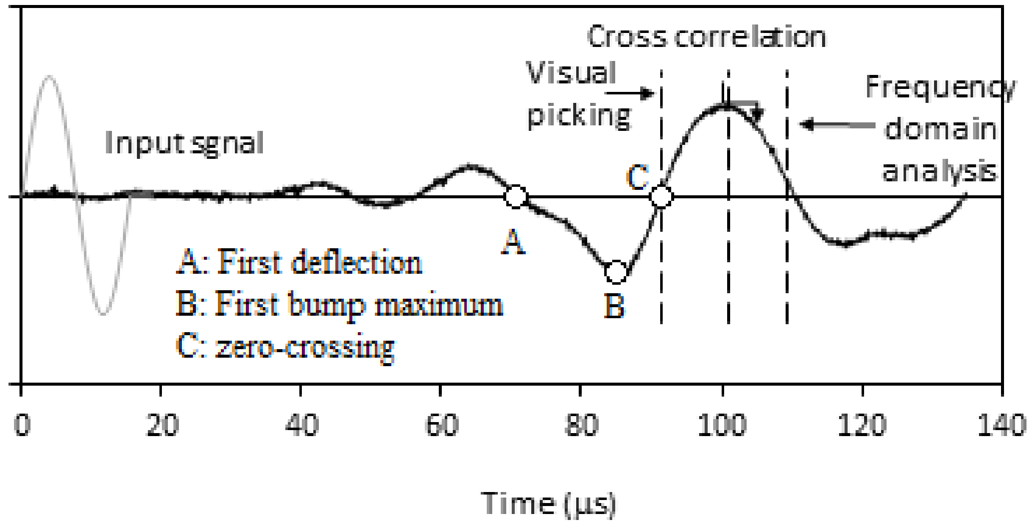

Figure 4.6 Determination of a typical shear wave arrival using different methods.

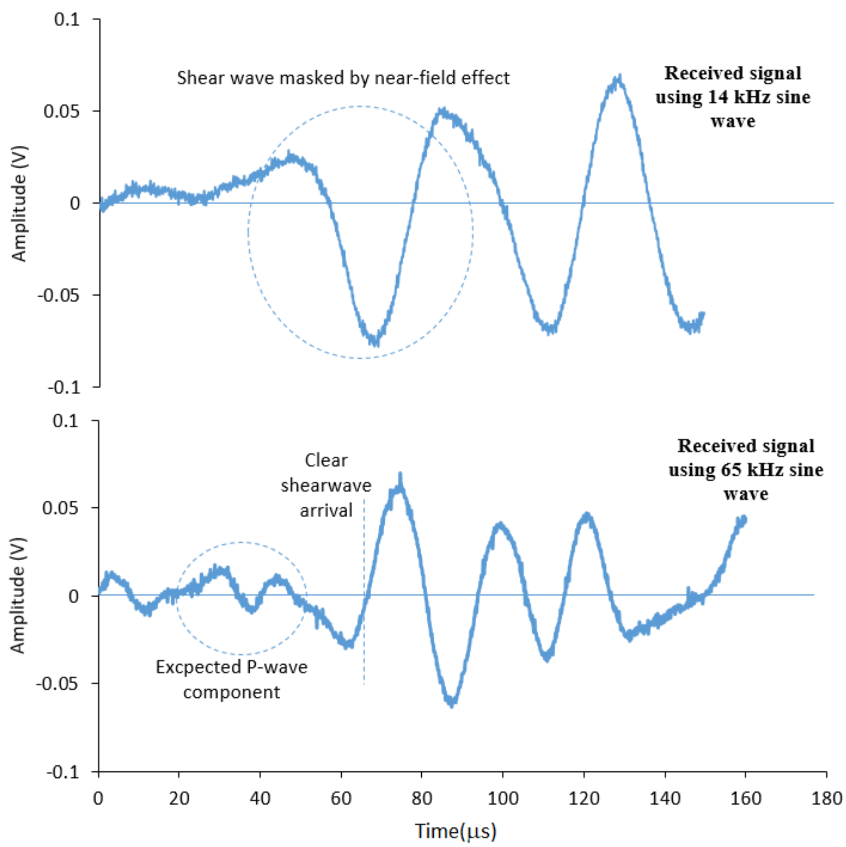

Figure 4.7 Effect of excitation frequency on the shear wave signal showing near-field effect (both signals were plotted to the same scale)

For each test specimen, several measurements of V_s were taken over a period of 50 days. **Figure 4.6** displays the variation of shear wave velocity with curing time for Groups 1 and 2 while **Figure 4.8** presents the variation of shear wave velocity of Group 3 with curing time.

As can be noted from **Figures 4.8** and **4.9**, the mixtures did not exhibit any appreciable change in Vs after the 15th day. It is also noted from **Figure 4.8** that the shear wave velocity was almost the same for mixtures with TOSW replacing 10% and 15% of sand. It is interesting to note that the addition of the TOSW had a positive effect on the shear wave velocity for the mixtures with 60 kg cement, while it slightly reduced Vs for the mixtures with 90 kg cement.

Figure 4.8 shows that for mixtures where TOSW replaced 100% of the fly ash, the addition of additional TOSW as partial replacement of sand has resulted in increased shear wave velocity for mixtures with 60 kg and 90 kg. Finally, comparing **Figures 4.8** and **4.9** demonstrates that replacing fly ash (which is a binder material) with TOSW has resulted in reduction of Vs by about 32%. However, this effect could be compensated for by increasing the cement proportion in the mixture to achieve the target V_s.

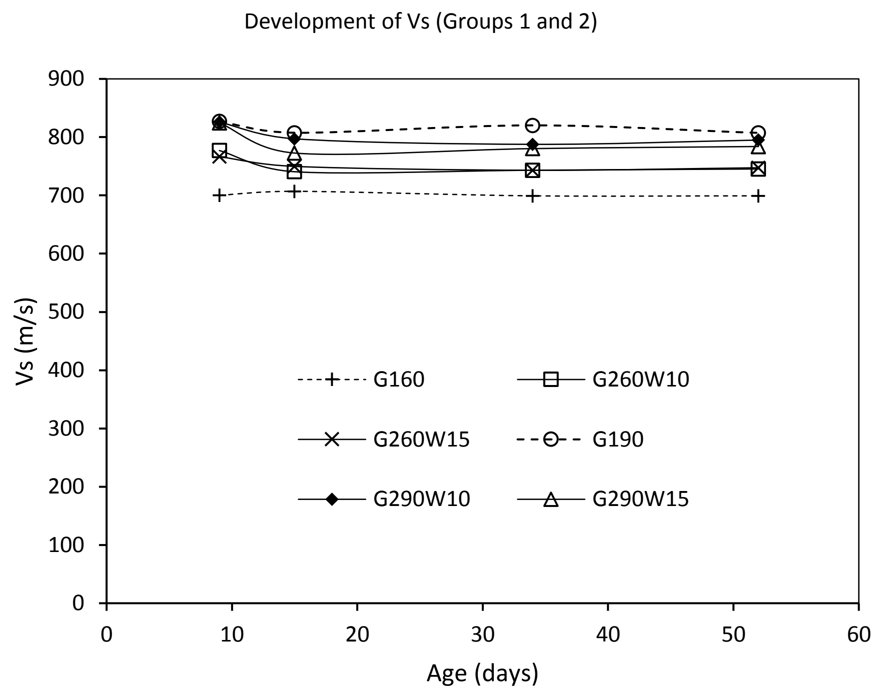

Figure 4.8 Development of shear wave velocity with age for Group1 and 2

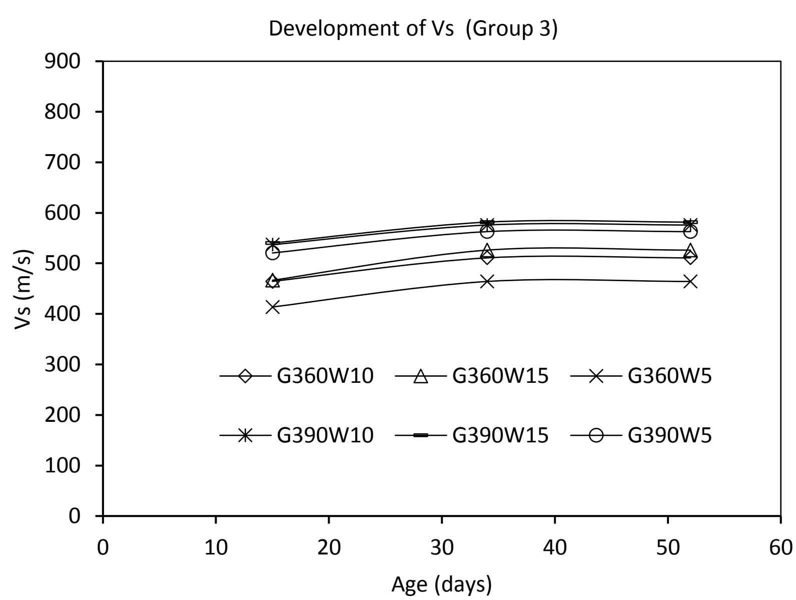

Figure 4.9 Development of shear wave velocity with age for Group 3

El Naggar *et al.* (2013) proposed an empirical equation to estimate the upper bound (UB) and lower bound (LB) values of shear wave velocity for cemented sand knowing the cement to aggregate ratio, i.e.

$$(Vs)_{UB} \text{ (m/s)} = 45.92 \text{ CC } (\%) + 426.1 \qquad [4.5]$$

$$(Vs)_{LB} \text{ (m/s)} = 46.92 \text{ CC } (\%) + 321.1 \qquad [4.6]$$

Where CC is cement content to sand ratio by weight.

The measured V_s values of samples of Group 3, which were devoid of fly ash, fell within the range of V_s values predicted using Eq. 4.5 and 4.6. However, the measured values for Groups 1 and 2 were higher than the values predicted by Eq. 4.5 due to the binding effect of the fly ash. In order to account for the effect of fly ash content on the shear wave velocity of the mixture, the measured shear wave velocities of mixtures of Groups 1 and 2 were curve fitted, producing the following correlation:

$$Vs = 85(CC\%) + 2500(FA\%) + 500 \qquad [4.7]$$

Where FA% is fly ash to sand ratio by weight.

Figure 4.10 compares the calculated Vs values using Eq. 4.7 with the measured values for different mixtures. The excellent agreement between the predicted and measured Vs values suggest that the proposed correlation (Eq. 4.7) is suitable for predicting the shear wave velocity of CLSM incorporating TOSW with and without fly ash. Given that incorporating TOSW had minimal impact on the shear wave velocity of the mixtures, it may be concluded that Eq. 4.7 can be used to predict shear wave velocity of CLSM materials without TOSW considering the range of cement content investigated in the current study.

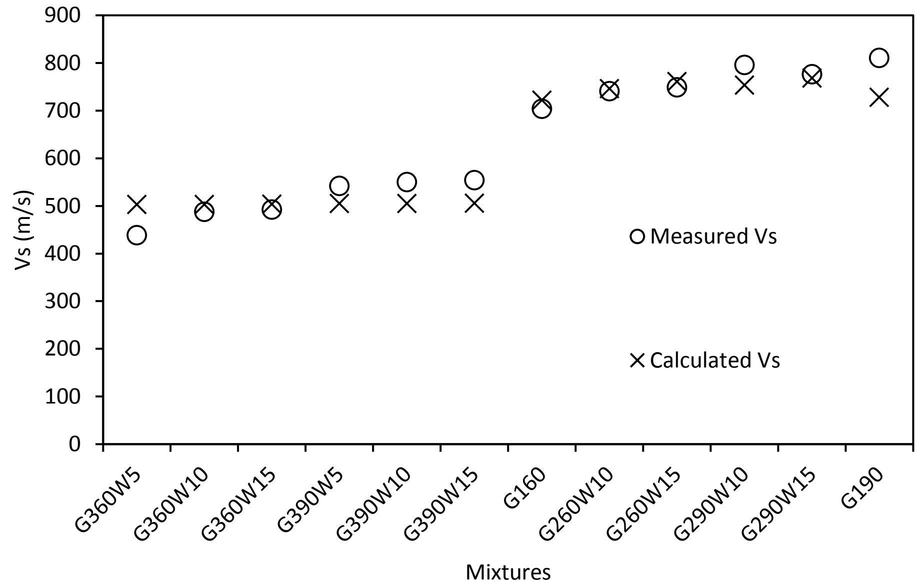

Figure 4.10 Measured and calculated Vs using Eq. 4.7

4.3.2. Compression Wave Velocity Measurements

The PRA deviance was designed mainly to measure shear waves; however, the received signal also contains a compression wave component (P-wave). Usually, the P-wave component received from bender elements are weak and very difficult to distinguish. But since the PRA device utilizes high voltage signal, the P-wave component is clear enough for measurements of compression wave velocity. Brignoli (1996) reported that the arrival of shear wave measured from shear plate transducer is proceeded with a P-wave with much lower intensity and with negative signal polarity. (Ahmed, 2016) has reported the same observation and suggested a method to determine the arrival time for P-wave. **Figure 4.11** shows a typical output signal with clear S-wave proceeded by a weaker P-wave signal.

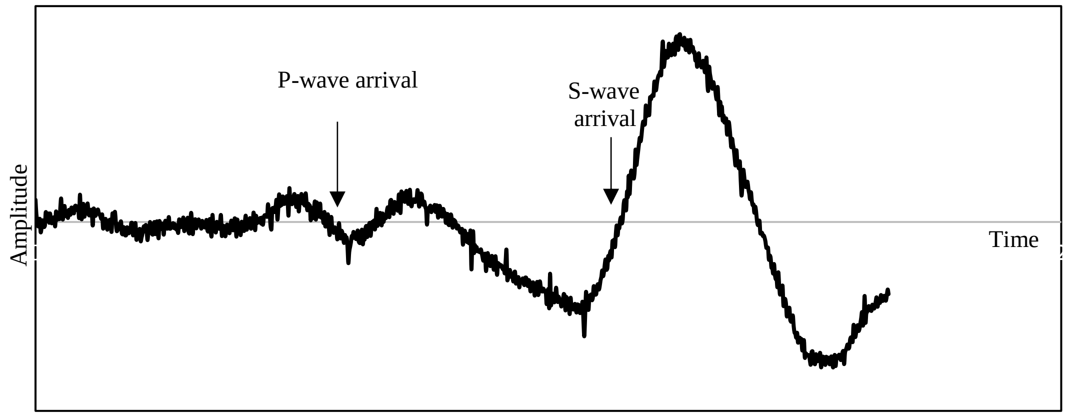

Figure 4.11 Typical signal showing S-wave and P-wave arrival points

The measured V_p ranged from 1.6 to 2.1 times V_s. **Figure 4.12** presents variation of V_s and V_p, which displays a linear correlation between them.

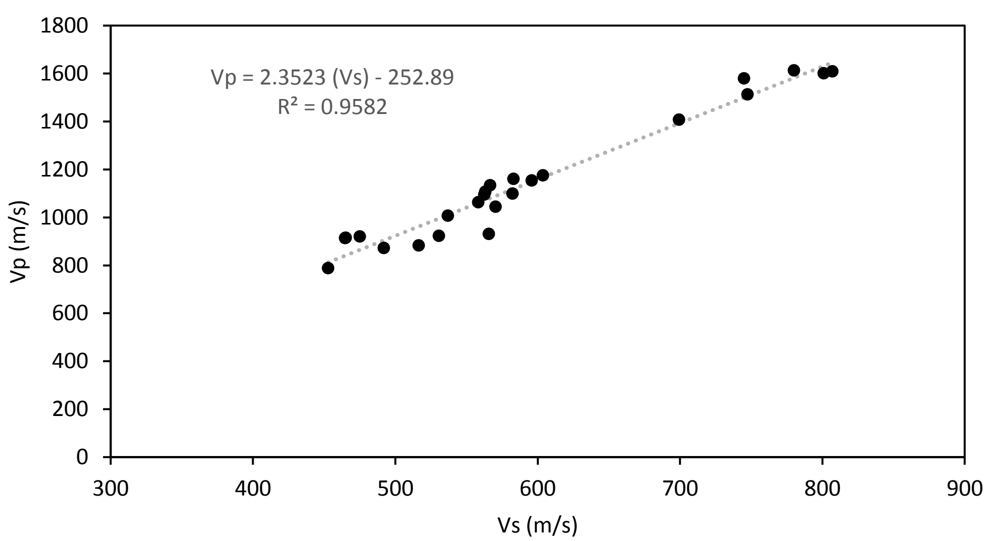

Figure 4.12 The relation between P-wave and S-wave velocities

The dynamic Poisson's ratio may be calculated from the measurements of S-wave and P-wave velocities, i.e.:

$$\upsilon_d = (V_p^2 - 2V_s^2)/2(V_p^2 - V_s^2) \quad [4.8]$$

The calculated dynamic Poisson's ratio using Eq. 4.8 ranged from 0.25 to 0.35, with an average value of 0.3, which was slightly larger than the average static poisons ratio of 0.29 measured using large strain static loading tests.

The unconfined axial compressive strength (UCCS) was compared with the measured shear wave velocity and plotted in **Figure 4.13**. The relationship between V_s and UCCS is exponential with a good correlation coefficient of 0.94. According to **Figure 4.13**, the shear wave velocity of CLSM mixtures increases with compressive strength and can be expressed as follows:

$$V_s = 168.98(UCCS)^{0.1823} \quad (m/s) \qquad [4.9]$$

Where (UCCS) is the unconfined compressive strength (kPa)

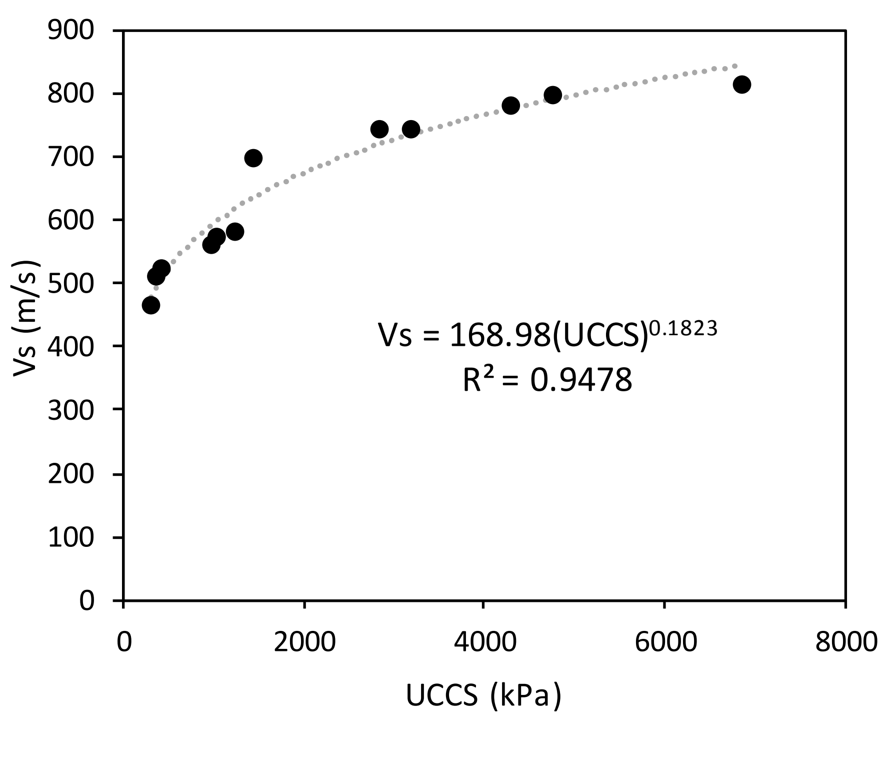

Figure 4.13 Unconfined compressive strength versus shear wave velocity

Using Eq. 4.9 and **Figure 4.13**, the small strain shear modulus, G_0, and the dynamic elastic modulus, E_d can be estimated knowing the unconfined compressive strength of the material using Eq. 4.1 and Eq. 4.3.

4.3.3. Damping Ratio

The damping ratio of the samples was evaluated using Eq. 4.4 and the obtained results are plotted in **Figure 4.14**. As can be noted from **Figure 4.14**, the damping ratio varied between 4 and 6% with an average of 5%. It can also be noticed that the TOSW had no appreciable effect on the damping ratio of the CLSM mixture. Also, the effect of the cement content on the damping ratio is not clear.

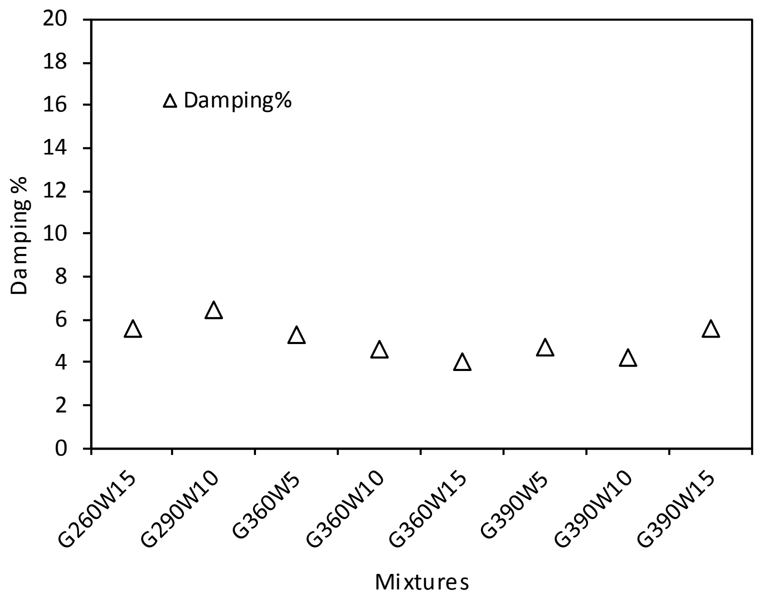

Figure 4.14 Damping ratio for different mixtures

4.3.4. Elastic Modulus

The elastic modulus was evaluated from the stress-strain curves of the unconfined compressive strength tests that were conducted on the test samples. **Figure 4.13** shows the variation of the elastic modulus with the shear wave velocity for the different mixtures tested in this study. As can be noted from **Figure 4.15**, as expected, the elastic modulus increased as the shear wave velocity measured form a separate test setup (PRA) increased. The TOSW content had insignificant effect on E_s and V_s values for the same group. However, for Group 3 in which TOSW replaced fly ash, V_s and E_s values decreased compared to Groups 1 and 2.

The shear wave velocity and the elastic modulus can be related employing a power function. **Figure 4.15** shows a correlation between Es and Vs with correlation coefficient of 0.84. The shear wave velocity can be related to the static elastic modulus as follows:

$V_s = 173.15\ E_s^{0.2392}$ where V_s is in (m/s) and E_s is in (MPa) [4.10]

The proposed function can be used as a reference for future work to estimate the shear wave velocity of similar CLSM mixtures knowing the elastic modulus.

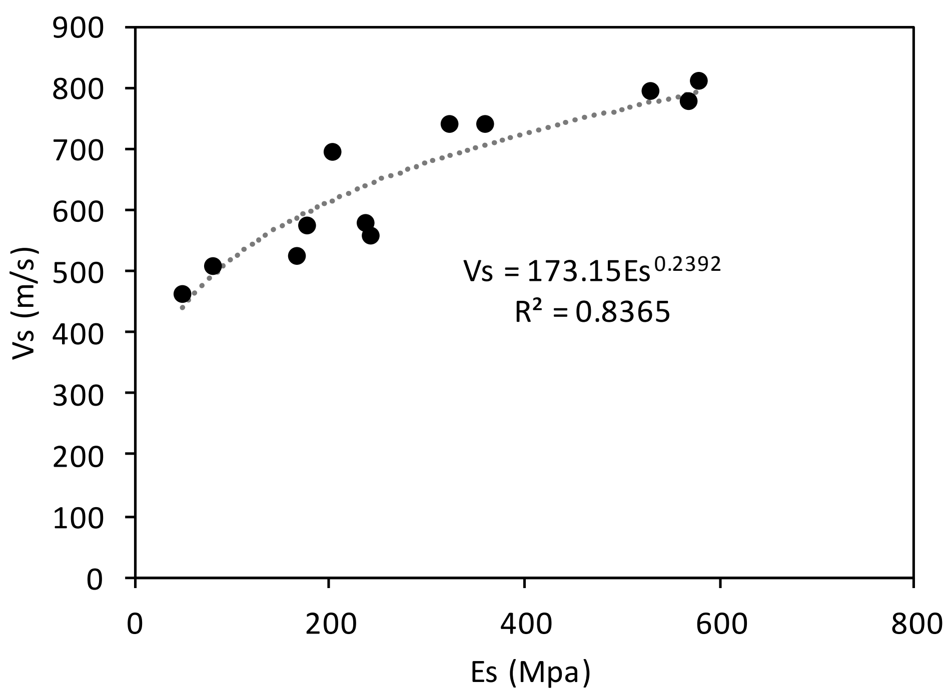

Figure 4.15 Variation of static elastic modulus with shear wave velocity

To further investigate the dynamic properties of CLSM mixtures, the dynamic elastic modulus was evaluated using the dynamic Poisson's ratio calculated from Eq. 4.8. The average value of the calculated dynamic Poisson's ratio was 0.3. The calculated Poisson's ratios were used to evaluate the dynamic elastic modulus using Eq. 4.3

Figure 4.16 shows the variation of the evaluated dynamic modulus with the static elastic modulus for different mixtures. It can be noticed that an increase of TOSW for mixtures with 60 kg/m^3 of cement increased the dynamic elastic modulus, and this increase was more apparent in mixtures containing no fly ash (Group 3-60). On the other hand, for mixtures containing fly ash, the effect of TOSW was less pronounced on $E_{dyn,}$ For mixtures with 90 kg/m^3 of cement, the observed effect of TOSW on both moduli was less significant; however for mixtures with fly ash (Group 3-90) the dynamic elastic modulus decreased by about 15%, while the static elastic modulus was not affected. This behavior is due to the advantage of TOSW to reduce the water needed for CLSM mixtures to reach the required flowability (Mneina *et al*,. 2016), which in turn increased the strength and stiffness relatively for low cement mixtures. However, increasing the fine content is known to reduce the shear wave velocity which was also observed by Byun, *et al*. (2016) and Yang and Liu (2016), and for mixtures with fly ash and higher cement content, this effect was more dominant, which explains the reduction in the dynamic modulus of Group 2-90.

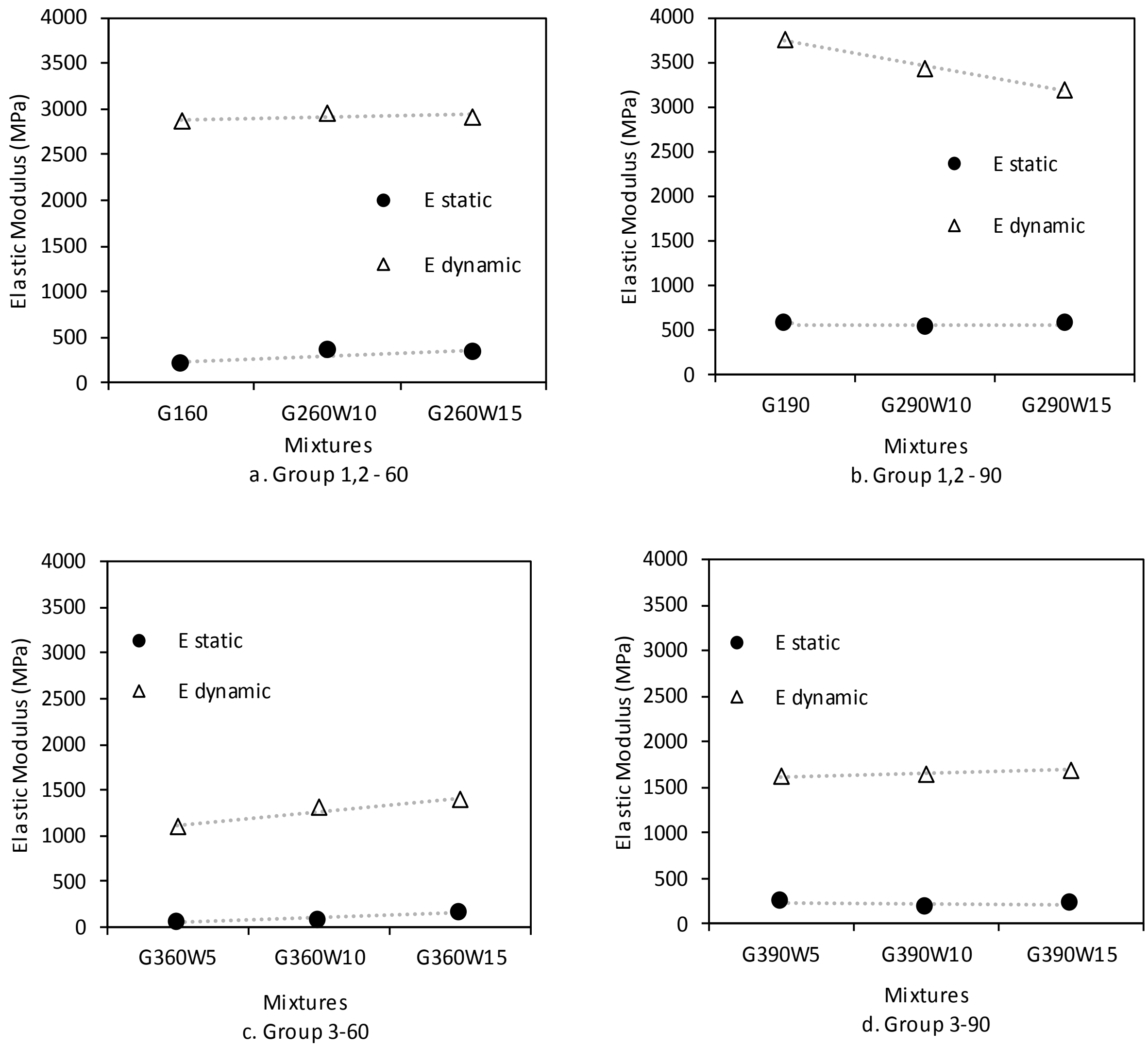

Figure 4.16 Static and dynamic elastic moduli for CLSM mixtures

4.3.5. Shear Modulus

The low-strain shear modulus (G_0), also referred to as "dynamic shear modulus G_0", was calculated using Eq. 4.1 and the results are summarized in **Table 4.1**. In addition, the static shear modulus (G_{static}) was calculated from the static modulus of elasticity (E_s) and static poison's ratio (υ) that were measured from unconfined compressive strength tests conducted on the CLSM mixtures. The average value of static poison's ratio (υ) was 0.29 and was used for calculating

G_{static} using Eq. 4.2, and the obtained values are also presented in **Table 4.1**. As can be noted from **Table 4.1**, G_0 ranged from 420 to 1275 MPa while G_{static} varied between 31 to 224 MPa for the tested mixtures. The results indicated an almost linear relationship between the dynamic and static shear moduli, with G_o being approximately 6 to 15 times G_{static}.

Table 4.1 Shear wave velocity and shear moduli of test mixtures.

Mixtures	TOSW% by volume	Vs (m/s)	Density (kg/m^3)	G_0 (MPa)	G_{static} (MPa)
G160	0.0%	699	2183	1068	79
G190	0.0%	814	2092	1386	224
G260W10	6.8%	744	1965	1089	140
G260W15	10.2%	745	1945	1078	125
G290W10	6.5%	798	2005	1277	205
G290W15	10.0%	782	1948	1192	220
G360W5	9.5%	464	1951	421	19
G360W10	13.0%	511	1915	502	31
G360W15	16.2%	526	1987	551	65
G390W5	9.8%	563	1902	603	94
G390W10	13.3%	576	1947	646	69
G390W15	16.5%	582	1898	642	92

The small strain to large strain modulus ratio (G_0/G_{static}) or (E_d/E_s) represents the change of shear modulus with the change of strain level. The dynamic shear modulus measured using shear wave measurements with strain of less than 0.001% (Lee *et al.*, 2014) while the static shear modulus was measured from static loading tests with strain of about 0.7 to 1%, therefore the results from both strain levels were significantly different. The difference however, depends largely on the strength of the material (Hammam & Eliwa, 2013).

The ratio (G_0/G_{static}) (which had the same value as (E_d/E_s)) was plotted against the unconfined compressive strength in **Figure 4.17**. The small to large strain modulus ratio was found to decrease with the increase of strength as can be noted from **Figure 4.17**. This suggests that the dynamic properties for stiffer samples are not largely affected by strain level as for weaker samples.

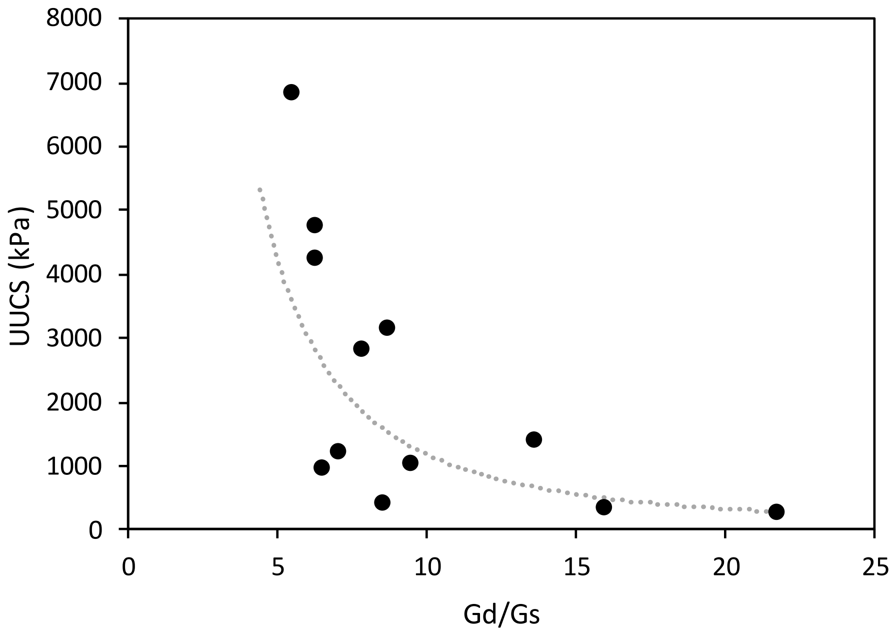

Figure 4.17 Unconfined compressive strength versus G0/Gstatic

4.4. Conclusions

TOSW was successfully incorporated in CSLM mixtures producing a sustainable CLSM with acceptable performance in terms of flowability and dynamic properties. The effect of incorporating TOSW on the geotechnical dynamic properties of CLSM was investigated and the following conclusions may be drawn:

- TOSW content has no significant effect on the measured shear wave velocity in the same mixture group.

- Replacing fly ash with TOSW has reduced the shear wave velocity by 32-34% due to the fine particle size of TOSW compared with fly ash.
- TOSW has no significant effect on the low-strain shear modulus, however increasing TOSW increased the stiffness within the mixture groups. Mixtures containing fly ash showed the highest values of G_0. The calculated G_0 ranged from 420 to 1275 MPa.
- The damping ratio decreased slightly as the TOSW content increased.
- An empirical equation was suggested to estimate the shear wave velocity of CLSM mixtures knowing the cement, fine aggregate and fly ash contents.
- The shear wave velocity of CLSM mixtures was correlated to the unconfined compressive strength and an equation was provided to estimate V_s form UCCS values.
- The shear wave velocity was also correlated to the static elastic modulus of CLSM and an equation is proposed for estimating V_s.
- The compression wave velocity was measured and compared with shear wave velocity. The correlation between both velocities was used to calculate the dynamic Poisson's ratio and the dynamic elastic modulus.
- The dynamic elastic modulus of the CLSM mixtures tested was found to be 6 to 15 times the static elastic modulus, and this ratio decreased as the strength of CLSM increased.

4.5. References

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Chapter 5

SUMMARY AND CONCLUSIONS

5.1. Summary

The main objective of this research was to investigate the effects of incorporating treated oil sand wastes in controlled low-strength materials. A total of 18 different CLSM mixtures were prepared and categorized into 3 groups. Group 1 is the control group with 3 mixtures with cement contents of 30,60, and 90 kg/m^3 and no waste was added to this group. Group 2 with nine mixtures that contained a constant fly ash content of 145 kg/m^3 and a variable TOSW content. The TOSW was added as a replacement of natural sand by rates of 5, 10 and 15% by volume of sand.

In Group 3, mixtures of group 2 were modified to completely replace the fly ash content with TOSW making another nine mixtures with high waste content up to 341 kg/m^3.

The testing program was divided into two stages. The first stage of testing was to investigate the fresh and hardened properties of CLSM incorporating TOSW. This stage included tests on fresh and hardened density, flowability, bleeding, compressive and tensile strength, elastic modulus, drying shrinkage and leaching.

The second stage was to evaluate the dynamic properties of the hardened CLSM mixtures incorporating TOSW by measuring the shear and compression wave velocity using a piezoelectric ring actuator (PRA) device. This stage included evaluation of the static and dynamic moduli, and static and dynamic Poisson's ratios. The results from the first stage were used to obtain relationships between the different static and dynamic parameters to characterize the newly designed CLSM mixture and to understand the effect of TOSW on the properties of CLSM.

5.2. Conclusions

5.2.1. Fresh and hardened properties of CLSM incorporating TOSW

From the tests and results of stage one of this research, the following conclusions were revealed:

- Incorporating TOSW in CLSM has indirectly increased the compressive strength within the same mix group. Replacing fly ash with TOSW lowered the strength and elastic modulus compared to control mixtures and mixtures with fly ash. This strength reduction maybe beneficial in applications where low-strength is required for future excavation. The compressive strength, however, can be controlled by increasing the cement content.
- TOSW has effectively increased the flowability of all mixtures, which reduced the amount of water required to reach the design flowability value. This reduction lead to higher compressive strength within the mix group. It was also noted that TOSW was even more effective than fly ash in regarding enhancing the flowability.
- The addition of TOSW lowered the dry density, and some of the mixtures can be classified as Class VII low-density CLSM according to ACI 229R.
- High shrinkage were observed on samples containing TOSW compared to control mixtures, therefore, it is recommended to use shrinkage control admixtures in certain applications if high shrinkage was not tolerated.
- Bleed water reduction was observed in mixtures containing TOSW
- Fly ash was successfully replaced by TOSW producing CLSM mixtures satisfying the limits and requirements of ACI committee 229 report.

5.2.2. Evaluation of Dynamic Properties of CLSM incorporating TOSW

By measuring and analysing the shear wave and compression wave velocity of hardened CLSM samples, the following was concluded:

- No significant effect of TOSW on shear wave velocity measurements was observed within the mix group.
- A reduction of 32-34% of shear wave velocity was noticed on samples containing TOSW and no fly ash compared to samples with TOSW and fly ash.
- Samples containing fly ash content showed he highest value of the low-strain shear modulus. While increasing TOSW content within the mixture group did not greatly affect G_0 value.
- A slight decrease in damping ratio was observed on mixtures containing TOSW.
- An empirical equation was proposed to estimate the shear wave velocity knowing the cement, fly ash, and fine aggregate content of the mixture.
- Various correlations were proposed to estimate the shear wave velocity from the unconfined compressive strength and the elastic modulus of CLSM.
- The dynamic elastic modulus was evaluated and found to be 6 to 15 times the static modulus.

5.3. Recommendations and Future Work.

The following are recommendations for further investigations needed on the effect of incorporating TOSW in CLSM mixtures.

- It is known that using CLSM as pipeline bedding may decrease the frost depth compared to the natural soil around the pipe, which causes unexpected freezing of pipelines. Therefore, the investigation on the effect of CLSM mixed with TOSW on the frost line is recommended.
- Using the shear wave and compression wave velocities data along with the static testing data, a finite element model can be proposed to predict the behaviour of CLSM bedding under different loading conditions and for different geotechnical applications.
- The damping ratio calculated by the half-power bandwidth ratio method using the frequency domain analysis of data obtained from the PRA device can be further validated using the resonant column method.
- For more extensive evaluations of the dynamic properties of CLSM incorporating TOSW mixtures, cyclic and monotonic triaxial tests can be performed on hardened samples to measure the response of the samples and validate the results using data from shear wave measurements.

APPENDIX A

TEST RESULT SAMPLES

A. 1. Particle Size Distribution of the Used Fine Aggregate

Sieve analysis was performed in accordance with ASTM C33/C33M (Standard Specification for Concrete Aggregates)

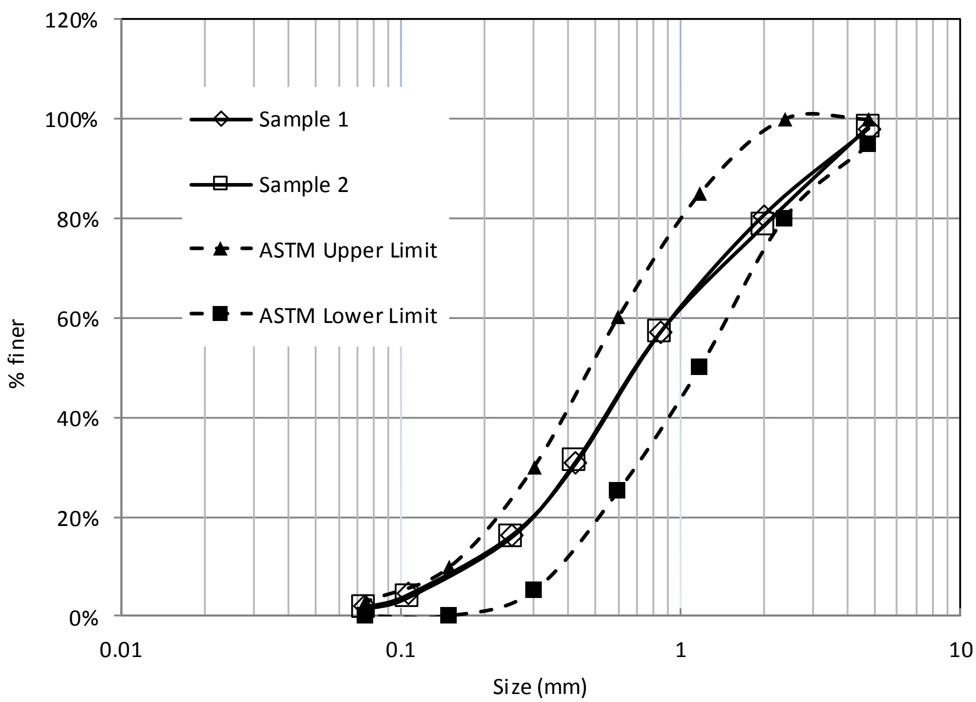

Figure A.1 Results of sieve analysis test of the used sand

The uniformity coefficient (C_u) was calculated as follows:

$$C_u = \frac{D_{60}}{D10} \qquad [A.1]$$

The coefficient of curvature (C_c) was calculated as follows:

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \qquad [A.2]$$

Where (D10, D30, D50 and D60) are the intercepts for 10%, 30%, 50% and 60% of the cumulative mass.

D10 = 0.17mm (effective size), D30 = 0.41 mm, D50 = 0.70 mm (average grain diameter)

, D60 = 0.93 mm.

Using Equations A.1 and A.2 the coefficients C_u and C_c were 5.47 and 1.06 consecutively.

A. 2. Samples of Stress Strain Curves

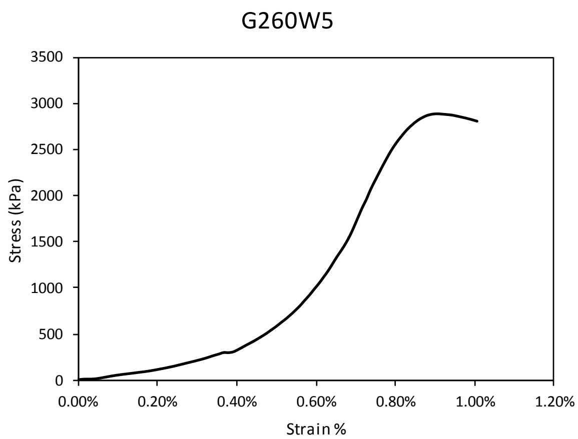

Figure A.2 Stress strain curve of sample G260W5

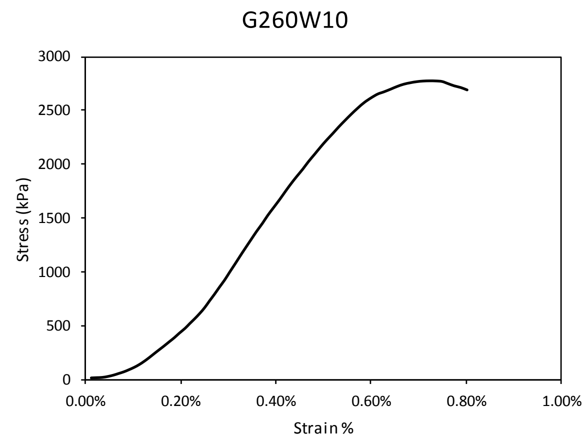

Figure A.3 Stress strain curve of sample G260W10

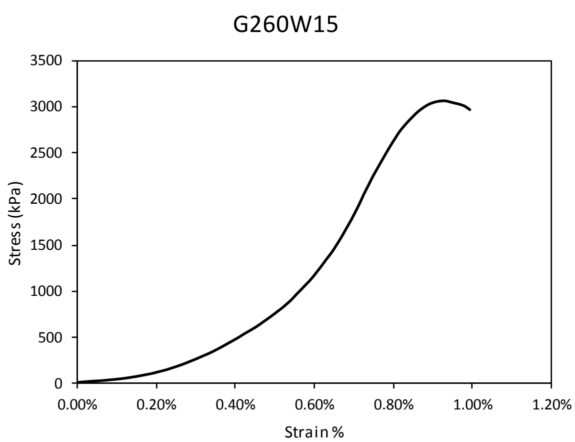

Figure A.4 Stress strain curve of sample G260W15

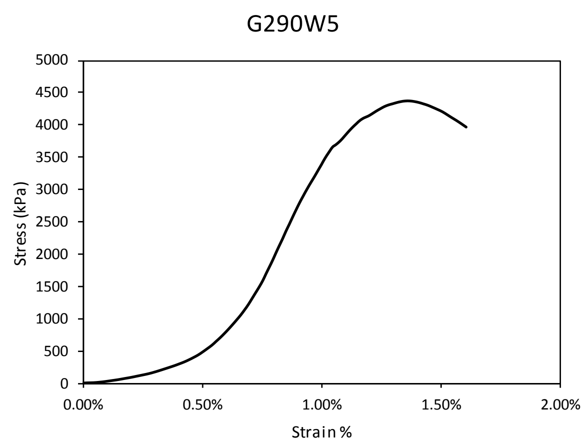

Figure A.5 Stress strain curve of sample G290W5

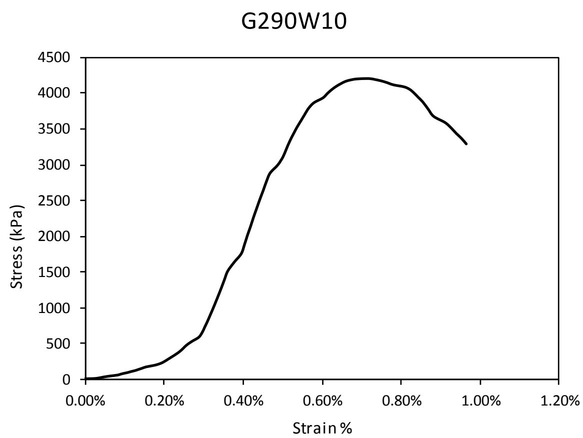

Figure A.6 Stress strain curve of sample G290W10

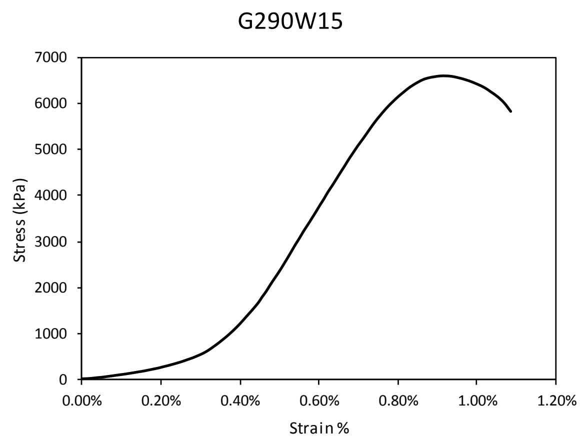

Figure A.7 Stress strain curve of sample G290W15

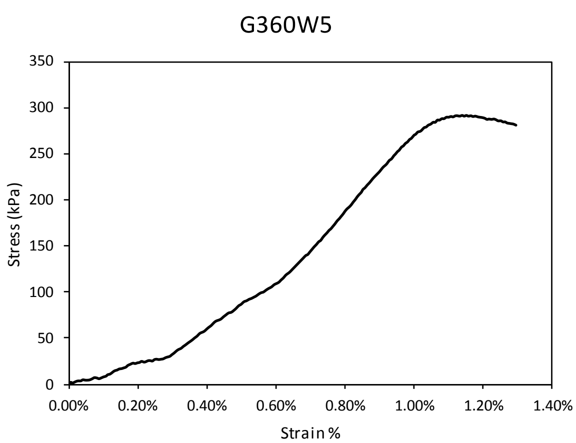

Figure A.8 Stress strain curve of sample G360W5

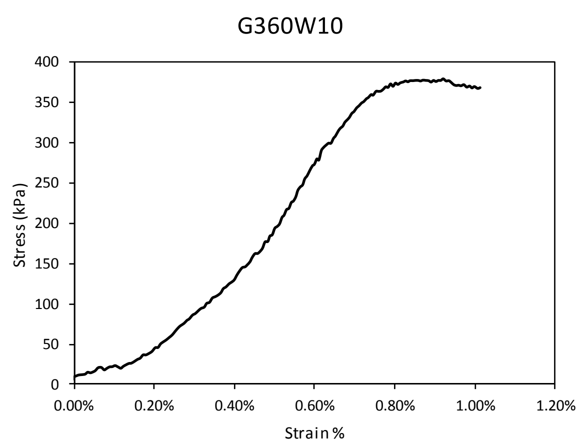

Figure A.9 Stress strain curve of sample G360W10

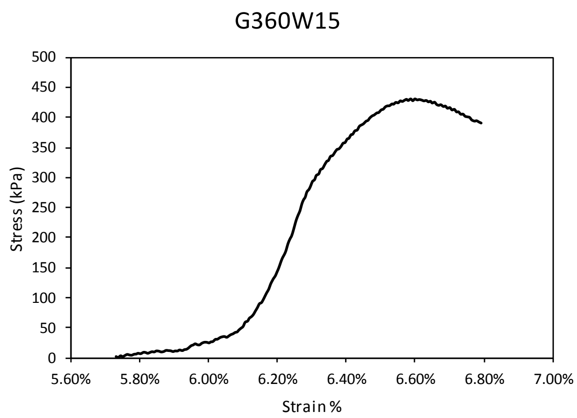

Figure A.10 Stress strain curve of sample G360W15

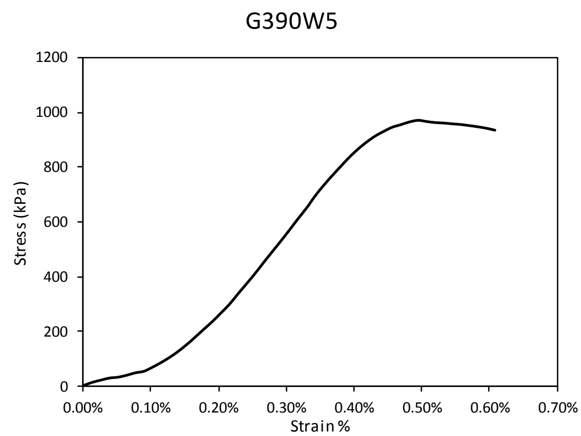

Figure A.11 Stress strain curve of sample G390W5

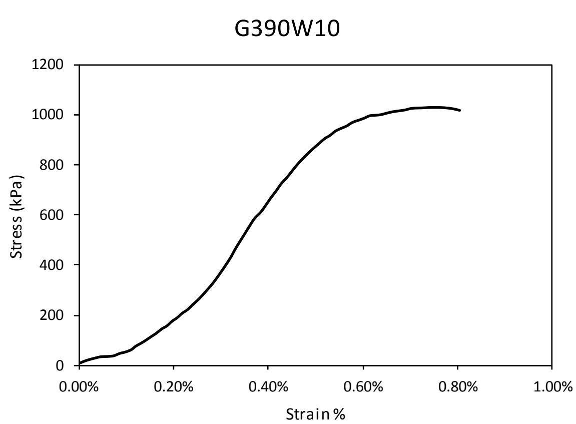

Figure A.12 Stress strain curve of sample G390W10

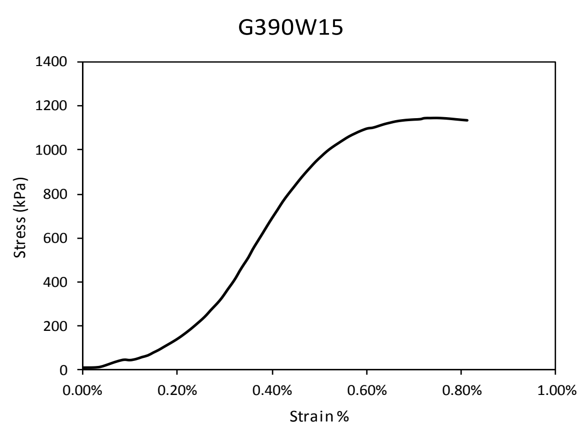

Figure A.13 Stress strain curve of sample G390W15

A. 3. Samples of Shear Wave Received Signals

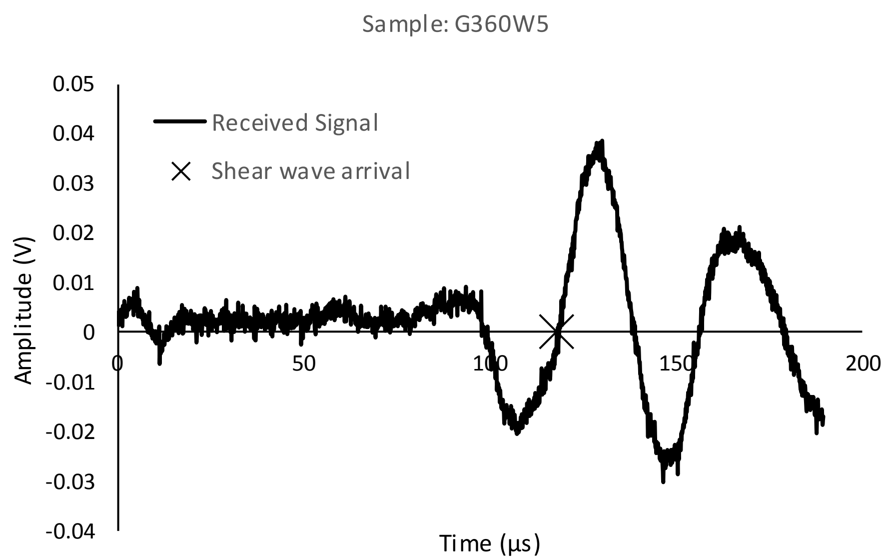

Figure A.14 Received shear wave signal of sample G360W5

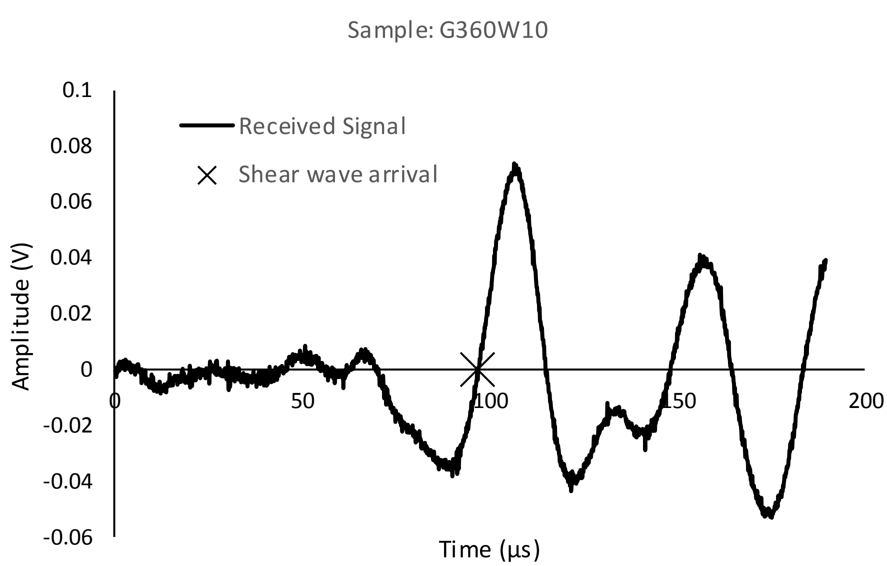

Figure A.15 Received shear wave signal of sample G360W10

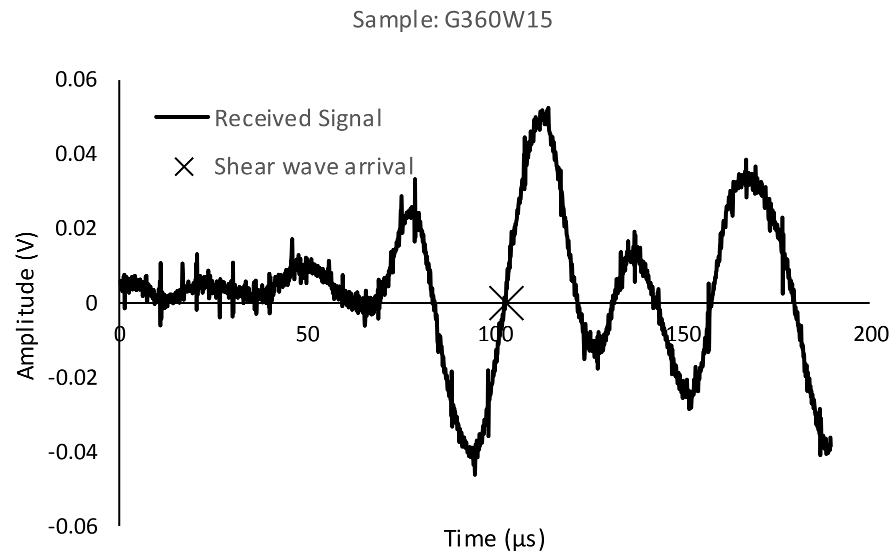

Figure A.16 Received shear wave signal of sample G360W15

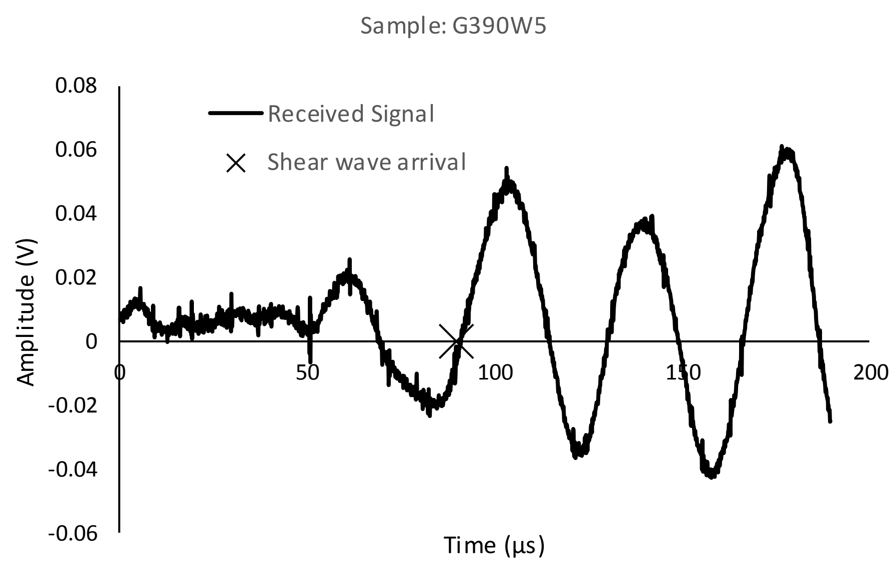

Figure A.17 Received shear wave signal of sample G390W5

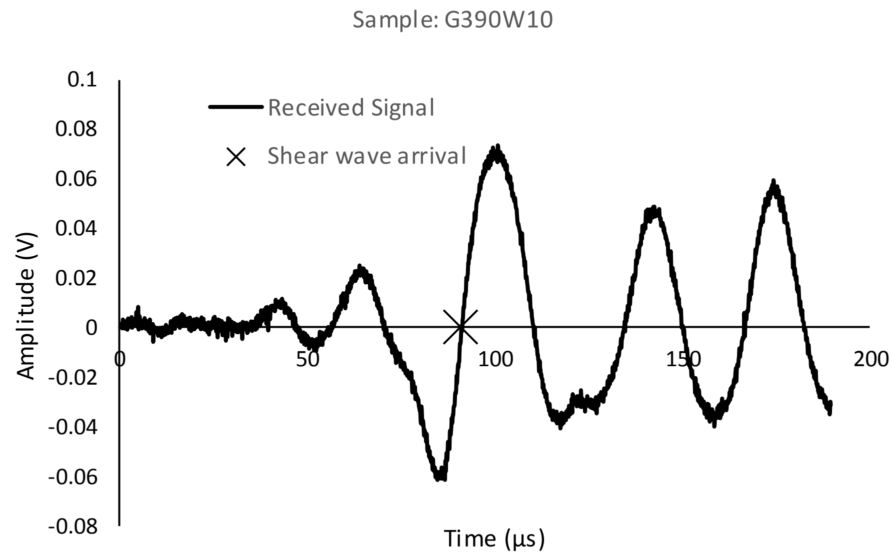

Figure A.18 Received shear wave signal of sample G390W10

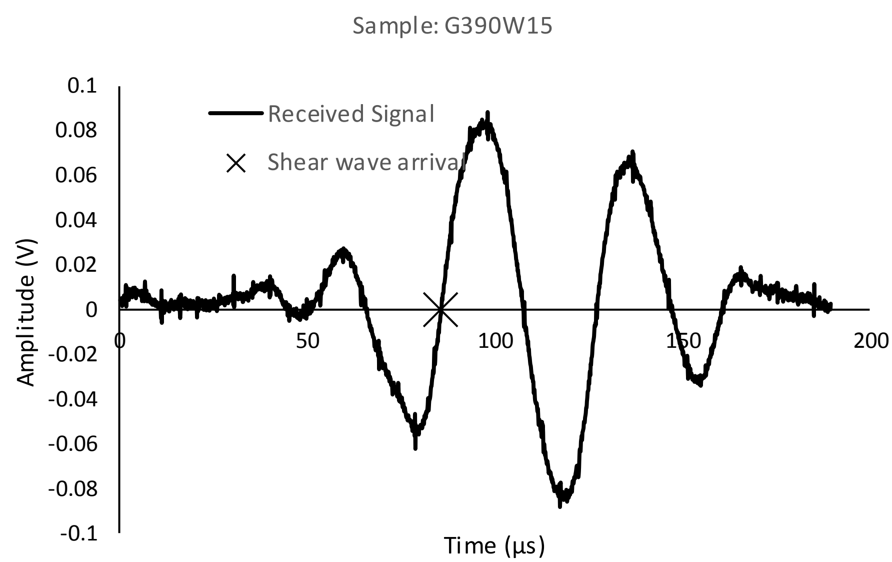

Figure A.19 Received shear wave signal of sample G390W15

A. 4. Effect of Input Frequency on Shear Wave Arrival

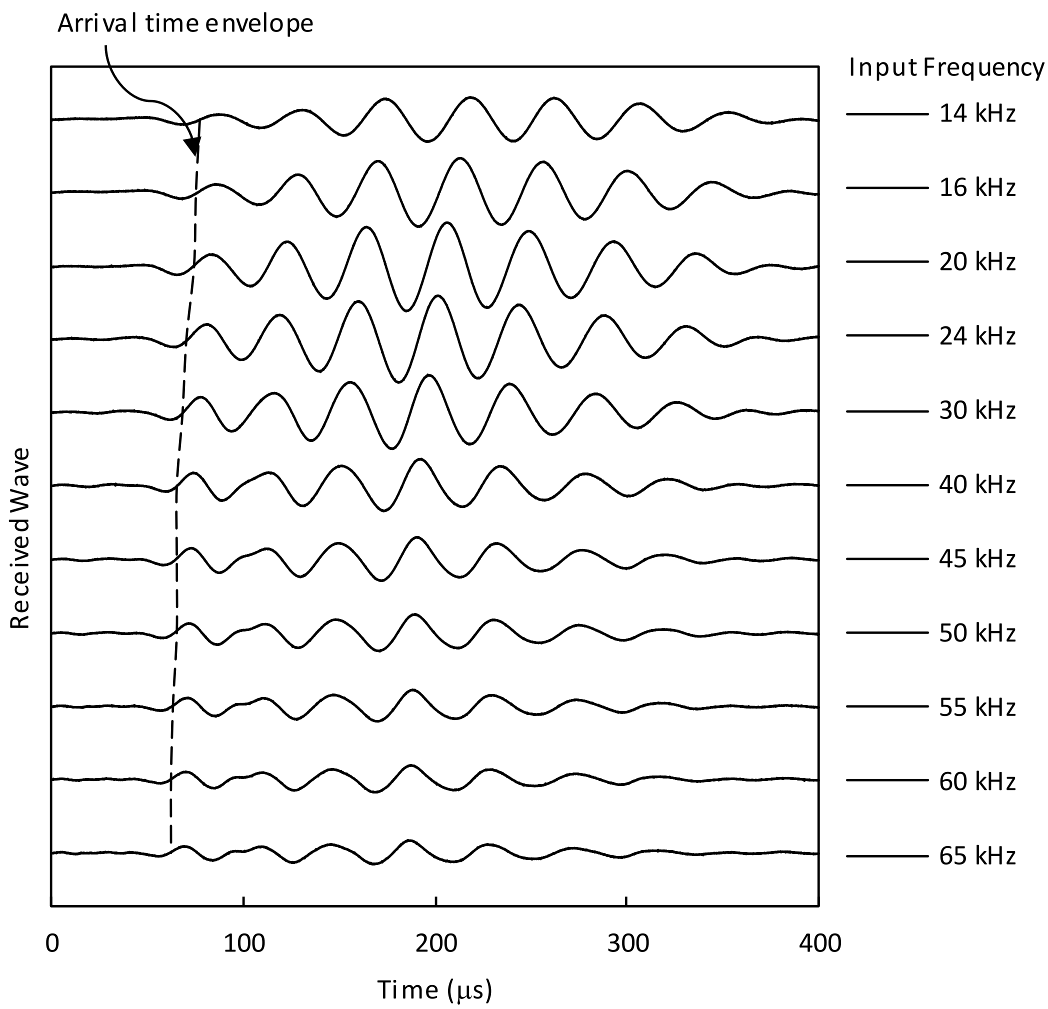

Figure A.20 Effect of excitation frequency on shear wave arrival of sample G190

A. 5. Shear wave velocity Raw Data Measurements

Table A.1 Shear wave velocity raw data measurements

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G160	1	51.0	9	570	14	94	543.1	1.3	2183.3	643.9	0
G160	1	51.0	9	570	16	90	567.2	1.4	2183.3	702.4	0
G160	1	51.0	9	570	20	88	580.1	1.8	2183.3	734.7	0
G160	1	51.0	9	570	24	85	600.6	2.0	2183.3	787.4	0
G160	1	51.0	9	570	30	82	622.5	2.5	2183.3	846.1	0
G160	1	51.0	9	570	40	79	646.2	3.2	2183.3	911.6	0
G160	1	51.0	9	570	45	78	654.5	3.5	2183.3	935.1	0
G160	1	51.0	9	570	50	75	680.6	3.8	2183.3	1011.4	0
G160	1	51.0	9	570	55	75	680.6	4.1	2183.3	1011.4	0
G160	1	51.0	9	570	60	74	689.8	4.4	2183.3	1038.9	0
G160	1	51.0	9	570	65	72.9	700.2	4.7	2183.3	1070.5	0
G160	1	51.0	15	114	24	85	600.6	2.0	2183.3	787.4	0
G160	1	51.0	15	190	24	85	600.6	2.0	2183.3	787.4	0
G160	1	51.0	15	380	24	82	622.5	2.0	2183.3	846.1	0
G160	1	51.0	15	570	24	82	622.5	2.0	2183.3	846.1	0
G160	1	51.0	15	114	65	75	680.6	4.9	2183.3	1011.4	0
G160	1	51.0	15	190	65	73	699.3	4.7	2183.3	1067.6	0
G160	1	51.0	15	380	65	71	719.0	4.6	2183.3	1128.6	0
G160	1	51.0	15	570	65	70	729.3	4.6	2183.3	1161.1	0
G160	1	51.0	34	380	24	83	615.0	2.0	2183.3	825.9	0
G160	1	51.0	34	380	40	78	654.5	3.1	2183.3	935.1	0
G160	1	51.0	34	380	65	73	699.3	4.7	2183.3	1067.6	0

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m^3)	G (MPa)	TOSW%
G160	1	51.0	52	380	24	83	615.0	2.0	2183.3	825.9	0
G160	1	51.0	52	380	40	78	654.5	3.1	2183.3	935.1	0
G160	1	51.0	52	380	65	73	699.3	4.7	2183.3	1067.6	0
G190	1	51.3	9	570	14	77	665.8	1.1	2092.3	927.5	0
G190	1	51.3	9	570	16	75	683.5	1.2	2092.3	977.6	0
G190	1	51.3	9	570	20	74	692.8	1.5	2092.3	1004.2	0
G190	1	51.3	9	570	24	70	732.4	1.7	2092.3	1122.2	0
G190	1	51.3	9	570	30	68	753.9	2.0	2092.3	1189.2	0
G190	1	51.3	9	570	40	65	788.7	2.6	2092.3	1301.5	0
G190	1	51.3	9	570	45	65	788.7	2.9	2092.3	1301.5	0
G190	1	51.3	9	570	50	65	788.7	3.3	2092.3	1301.5	0
G190	1	51.3	9	570	55	63	813.7	3.5	2092.3	1385.5	0
G190	1	51.3	9	570	60	62	826.9	3.7	2092.3	1430.5	0
G190	1	51.3	9	570	65	62	826.9	4.0	2092.3	1430.5	0
G190	1	51.3	15	114	24	75	683.5	1.8	2092.3	977.6	0
G190	1	51.3	15	190	24	74	692.8	1.8	2092.3	1004.2	0
G190	1	51.3	15	380	24	72.6	706.1	1.7	2092.3	1043.3	0
G190	1	51.3	15	570	24	71	722.0	1.7	2092.3	1090.8	0
G190	1	51.3	15	114	65	65	788.7	4.2	2092.3	1301.5	0
G190	1	51.3	15	190	65	64	801.0	4.2	2092.3	1342.5	0
G190	1	51.3	15	380	65	63	813.7	4.1	2092.3	1385.5	0
G190	1	51.3	15	570	65	62	826.9	4.0	2092.3	1430.5	0
G190	1	51.3	34	380	24	73.2	700.3	1.8	2092.3	1026.2	0

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m^3)	G (MPa)	TOSW%
G190	1	51.3	34	380	40	68	753.9	2.7	2092.3	1189.2	0
G190	1	51.3	34	380	65	62.5	820.2	4.1	2092.3	1407.7	0
G190	1	51.3	52	380	24	73.9	693.7	1.8	2092.3	1006.9	0
G190	1	51.3	52	380	65	63.5	807.3	4.1	2092.3	1363.7	0
G190	1	51.3	52	380	40	68.9	744.0	2.8	2092.3	1158.3	0
G260W10	1	51.3	15	114	24	82	625.4	2.0	1965.1	768.6	6.770%
G260W10	1	51.3	15	190	24	80	641.0	1.9	1965.1	807.5	6.770%
G260W10	1	51.3	9	570	14	85	603.3	1.2	1965.1	715.3	6.770%
G260W10	1	51.3	9	570	16	83	617.9	1.3	1965.1	750.2	6.770%
G260W10	1	51.3	9	570	20	80	641.0	1.6	1965.1	807.5	6.770%
G260W10	1	51.3	15	380	24	80	641.0	1.9	1965.1	807.5	6.770%
G260W10	1	51.3	15	570	24	80	641.0	1.9	1965.1	807.5	6.770%
G260W10	1	51.3	34	380	24	80	641.0	1.9	1965.1	807.5	6.770%
G260W10	1	51.3	52	380	24	80	641.0	1.9	1965.1	807.5	6.770%
G260W10	1	51.3	9	570	24	78	657.5	1.9	1965.1	849.4	6.770%
G260W10	1	51.3	9	570	30	74	693.0	2.2	1965.1	943.7	6.770%
G260W10	1	51.3	15	114	65	70	732.6	4.6	1965.1	1054.7	6.770%
G260W10	1	51.3	15	190	65	70	732.6	4.6	1965.1	1054.7	6.770%
G260W10	1	51.3	34	380	40	73	702.5	2.9	1965.1	969.8	6.770%
G260W10	1	51.3	52	380	40	73	702.5	2.9	1965.1	969.8	6.770%
G260W10	1	51.3	9	570	40	70	732.6	2.8	1965.1	1054.7	6.770%
G260W10	1	51.3	9	570	45	70	732.6	3.2	1965.1	1054.7	6.770%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G260W10	1	51.3	9	570	50	70	732.6	3.5	1965.1	1054.7	6.770%
G260W10	1	51.3	15	380	65	69	743.2	4.5	1965.1	1085.5	6.770%
G260W10	1	51.3	34	380	65	69	743.2	4.5	1965.1	1085.5	6.770%
G260W10	1	51.3	52	380	65	68.8	745.4	4.5	1965.1	1091.8	6.770%
G260W10	1	51.3	9	570	55	68	754.2	3.7	1965.1	1117.6	6.770%
G260W10	1	51.3	9	570	60	68	754.2	4.1	1965.1	1117.6	6.770%
G260W10	1	51.3	15	570	65	68	754.2	4.4	1965.1	1117.6	6.770%
G260W10	1	51.3	9	570	65	66	777.0	4.3	1965.1	1186.4	6.770%
G260W15	1	51.4	9	570	14	85	604.1	1.2	1944.5	709.7	10.210%
G260W15	1	51.4	9	570	16	83	618.7	1.3	1944.5	744.3	10.210%
G260W15	1	51.4	9	570	20	80	641.9	1.6	1944.5	801.2	10.210%
G260W15	1	51.4	34	380	24	79.1	649.2	1.9	1944.5	819.6	10.210%
G260W15	1	51.4	34	380	24	78.4	655.0	1.9	1944.5	834.3	10.210%
G260W15	1	51.4	52	380	24	78.4	655.0	1.9	1944.5	834.3	10.210%
G260W15	1	51.4	15	114	65	70	733.6	4.6	1944.5	1046.5	10.210%
G260W15	1	51.4	15	380	24	78	658.4	1.9	1944.5	842.8	10.210%
G260W15	1	51.4	9	570	24	77	666.9	1.8	1944.5	864.9	10.210%
G260W15	1	51.4	15	570	24	77	666.9	1.8	1944.5	864.9	10.210%
G260W15	1	51.4	9	570	30	74	694.0	2.2	1944.5	936.4	10.210%
G260W15	1	51.4	34	380	40	73.3	700.6	2.9	1944.5	954.4	10.210%
G260W15	1	51.4	52	380	40	72.3	710.3	2.9	1944.5	981.0	10.210%
G260W15	1	51.4	34	380	40	72.3	710.3	2.9	1944.5	981.0	10.210%
G260W15	1	51.4	9	570	40	70	733.6	2.8	1944.5	1046.5	10.210%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m^3)	G (MPa)	TOSW%
G260W15	1	51.4	9	570	45	70	733.6	3.2	1944.5	1046.5	10.210%
G260W15	1	51.4	34	380	65	69.5	738.9	4.5	1944.5	1061.6	10.210%
G260W15	1	51.4	9	570	50	69	744.2	3.5	1944.5	1077.0	10.210%
G260W15	1	51.4	15	114	24	80	641.9	1.9	1944.5	801.2	10.210%
G260W15	1	51.4	15	190	24	80	641.9	1.9	1944.5	801.2	10.210%
G260W15	1	51.4	9	570	55	69	744.2	3.8	1944.5	1077.0	10.210%
G260W15	1	51.4	52	380	65	68.7	747.5	4.5	1944.5	1086.5	10.210%
G260W15	1	51.4	15	190	65	68	755.2	4.4	1944.5	1109.0	10.210%
G260W15	1	51.4	34	380	65	68.7	747.5	4.5	1944.5	1086.5	10.210%
G260W15	1	51.4	15	380	65	68	755.2	4.4	1944.5	1109.0	10.210%
G260W15	1	51.4	15	570	65	68	755.2	4.4	1944.5	1109.0	10.210%
G260W15	1	51.4	9	570	60	67	766.5	4.0	1944.5	1142.3	10.210%
G260W15	1	51.4	9	570	65	67	766.5	4.4	1944.5	1142.3	10.210%
G290W10	1	51.2	15	114	65	66	775.7	4.3	2005.4	1206.7	6.527%
G290W10	1	51.2	9	570	14	78	656.4	1.1	2005.4	864.0	6.527%
G290W10	1	51.2	9	570	16	77	664.9	1.2	2005.4	886.6	6.527%
G290W10	1	51.2	9	570	20	75	682.6	1.5	2005.4	934.5	6.527%
G290W10	1	51.2	34	380	24	75	682.6	1.8	2005.4	934.5	6.527%
G290W10	1	51.2	52	380	24	74.3	689.1	1.8	2005.4	952.2	6.527%
G290W10	1	51.2	15	380	24	73	701.3	1.8	2005.4	986.4	6.527%
G290W10	1	51.2	15	190	65	65	787.7	4.2	2005.4	1244.2	6.527%
G290W10	1	51.2	9	570	24	72	711.1	1.7	2005.4	1014.0	6.527%
G290W10	1	51.2	15	570	24	72	711.1	1.7	2005.4	1014.0	6.527%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G290W10	1	51.2	9	570	30	70	731.4	2.1	2005.4	1072.8	6.527%
G290W10	1	51.2	34	380	40	69	742.0	2.8	2005.4	1104.1	6.527%
G290W10	1	51.2	52	380	40	68.7	745.2	2.7	2005.4	1113.7	6.527%
G290W10	1	51.2	9	570	40	66	775.7	2.6	2005.4	1206.7	6.527%
G290W10	1	51.2	9	570	45	65	787.7	2.9	2005.4	1244.2	6.527%
G290W10	1	51.2	52	380	65	64.4	795.0	4.2	2005.4	1267.4	6.527%
G290W10	1	51.2	9	570	50	64	800.0	3.2	2005.4	1283.3	6.527%
G290W10	1	51.2	34	380	65	63.9	801.2	4.2	2005.4	1287.4	6.527%
G290W10	1	51.2	15	380	65	63	812.7	4.1	2005.4	1324.4	6.527%
G290W10	1	51.2	15	570	65	63	812.7	4.1	2005.4	1324.4	6.527%
G290W10	1	51.2	9	570	55	63	812.7	3.5	2005.4	1324.4	6.527%
G290W10	1	51.2	9	570	60	62	825.8	3.7	2005.4	1367.5	6.527%
G290W10	1	51.2	9	570	65	62	825.8	4.0	2005.4	1367.5	6.527%
G290W10	1	51.2	15	114	24	75	682.6	1.8	2005.4	934.5	6.527%
G290W10	1	51.2	15	190	24	75	682.6	1.8	2005.4	934.5	6.527%
G390W15	1	51.1	9	570	14	80	638.9	1.1	1947.9	795.1	10.010%
G390W15	1	51.1	9	570	16	78	655.3	1.2	1947.9	836.4	10.010%
G390W15	1	51.1	9	570	20	75	681.5	1.5	1947.9	904.7	10.010%
G390W15	1	51.1	9	570	24	72	709.9	1.7	1947.9	981.6	10.010%
G390W15	1	51.1	9	570	30	70	730.2	2.1	1947.9	1038.5	10.010%
G390W15	1	51.1	9	570	40	68	751.7	2.7	1947.9	1100.5	10.010%
G390W15	1	51.1	9	570	45	67	762.9	3.0	1947.9	1133.6	10.010%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G390W15	1	51.1	9	570	50	65	786.3	3.3	1947.9	1204.4	10.010%
G390W15	1	51.1	9	570	55	65	786.3	3.6	1947.9	1204.4	10.010%
G390W15	1	51.1	9	570	60	63	811.3	3.8	1947.9	1282.1	10.010%
G390W15	1	51.1	9	570	65	62	824.4	4.0	1947.9	1323.8	10.010%
G390W15	1	51.1	15	114	24	78	655.3	1.9	1947.9	836.4	10.010%
G390W15	1	51.1	15	190	24	77	663.8	1.8	1947.9	858.3	10.010%
G390W15	1	51.1	15	380	24	75	681.5	1.8	1947.9	904.7	10.010%
G390W15	1	51.1	15	570	24	75	681.5	1.8	1947.9	904.7	10.010%
G390W15	1	51.1	15	114	65	68	751.7	4.4	1947.9	1100.5	10.010%
G390W15	1	51.1	15	190	65	68	751.7	4.4	1947.9	1100.5	10.010%
G390W15	1	51.1	15	380	65	64.8	788.8	4.2	1947.9	1211.9	10.010%
G390W15	1	51.1	15	570	65	64	798.6	4.2	1947.9	1242.4	10.010%
G390W15	1	51.1	34	380	24	76	672.5	1.8	1947.9	881.0	10.010%
G390W15	1	51.1	34	380	40	70	730.2	2.8	1947.9	1038.5	10.010%
G390W15	1	51.1	34	380	65	65.5	780.3	4.3	1947.9	1186.1	10.010%
G390W15	1	51.1	52	380	24	75.4	677.9	1.8	1947.9	895.1	10.010%
G390W15	1	51.1	52	380	40	68.9	741.8	2.8	1947.9	1072.0	10.010%
G390W15	1	51.1	52	380	65	65.2	783.9	4.2	1947.9	1197.1	10.010%
G360W5	1	51.1	34	190	24	124	411.9	3.0	1952.2	331.2	9.533%
G360W5	1	51.1	34	190	40	116.8	437.3	4.7	1952.2	373.3	9.533%
G360W5	1	51.1	15	190	24	130	392.9	3.1	1952.2	301.3	9.533%
G360W5	1	51.1	15	190		-	Unclear signal		1952.2	NA	9.533%
G360W5	1	51.1	15	190	65	120	425.6	7.8	1952.2	353.6	9.533%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G360W5	1	51.1	34	190	65	112.8	452.8	7.3	1952.2	400.2	9.533%
G360W5	2	51.1	15	190	24	140	364.8	3.4	1949.1	259.4	9.533%
G360W5	2	51.1	15	190	40	130	392.9	5.2	1949.1	300.8	9.533%
G360W5	2	51.1	15	190	65	128	399.0	8.3	1949.1	310.3	9.533%
G360W5	2	51.1	34	190	65	109.9	464.7	7.1	1949.1	420.9	9.533%
G360W5	2	51.1	34	190	40	113.8	448.8	4.6	1949.1	392.6	9.533%
G360W5	2	51.1	34	190	24	122.9	415.6	2.9	1949.1	336.6	9.533%
G360W5	3	51.2	34	190	40	112.4	455.7	4.5	1951.0	405.1	9.533%
G360W5	3	51.2	34	190	24	113.8	450.1	2.7	1951.0	395.2	9.533%
G360W5	3	51.2	15	190	24	125	409.8	3.0	1951.0	327.6	9.533%
G360W5	3	51.2	15	190	40	125	409.8	5.0	1951.0	327.6	9.533%
G360W5	3	51.2	15	190	65	123	416.4	8.0	1951.0	338.3	9.533%
G360W5	3	51.2	34	190	65	107.8	475.1	7.0	1951.0	440.5	9.533%
G360W10	1	51.1	34	190	65	95.2	536.9	6.2	1904.5	548.9	13.035%
G360W10	1	51.1	34	190	24	107.5	475.4	2.6	1904.5	430.5	13.035%
G360W10	1	51.1	34	190	40	100	511.1	4.0	1904.5	497.5	13.035%
G360W10	1	51.1	15	190	24	123	415.5	3.0	1904.5	328.8	13.035%
G360W10	1	51.1	15	190	40	120	425.9	4.8	1904.5	345.5	13.035%
G360W10	1	51.1	15	190	65	115	444.4	7.5	1904.5	376.2	13.035%
G360W10	2	51.2	15	190	24	118	433.6	2.8	1882.4	354.0	13.035%
G360W10	2	51.2	15	190	40	112	456.9	4.5	1882.4	392.9	13.035%
G360W10	2	51.2	15	190	65	108	473.8	7.0	1882.4	422.6	13.035%
G360W10	2	51.2	34	190	24	118.2	432.9	2.8	1882.4	352.8	13.035%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G360W10	2	51.2	34	190	40	113.2	452.0	4.5	1882.4	384.6	13.035%
G360W10	2	51.2	34	190	65	110	465.2	7.2	1882.4	407.3	13.035%
G360W10	3	51.3	15	190	24	120	427.6	2.9	1957.4	357.9	13.035%
G360W10	3	51.3	15	190	40	113	454.1	4.5	1957.4	403.6	13.035%
G360W10	3	51.3	15	190	65	108	475.1	7.0	1957.4	441.8	13.035%
G360W10	3	51.3	34	190	65	96.7	530.6	6.3	1957.4	551.1	13.035%
G360W10	3	51.3	34	190	40	100.9	508.5	4.0	1957.4	506.2	13.035%
G360W10	3	51.3	34	190	24	106.9	480.0	2.6	1957.4	451.0	13.035%
G360W15	1	50.7	15	190	24	130	389.7	3.1	2036.5	309.3	16.157%
G360W15	1	50.7	15	190	40	125	405.3	5.0	2036.5	334.5	16.157%
G360W15	1	50.7	15	190	65	120	422.2	7.8	2036.5	362.9	16.157%
G360W15	1	50.7	34	190	24	116.6	434.5	2.8	2036.5	384.4	16.157%
G360W15	1	50.7	34	190	40	108.2	468.2	4.3	2036.5	446.4	16.157%
G360W15	1	50.7	34	190	65	103	491.8	6.7	2036.5	492.6	16.157%
G360W15	2	50.1	15	190	24	140	357.8	3.4	1987.8	254.5	16.157%
G360W15	2	50.1	15	190	40	135	371.0	5.4	1987.8	273.7	16.157%
G360W15	2	50.1	15	190	65	130	385.3	8.5	1987.8	295.1	16.157%
G360W15	2	50.1	34	190	65	97	516.4	6.3	1987.8	530.1	16.157%
G360W15	2	50.1	34	190	40	102	491.1	4.1	1987.8	479.4	16.157%
G360W15	2	50.1	34	190	24	117.7	425.6	2.8	1987.8	360.0	16.157%
G360W15	3	50.5	34	190	65	88.6	570.4	5.8	1935.7	629.9	16.157%
G360W15	3	50.5	34	190	40	93.6	540.0	3.7	1935.7	564.4	16.157%
G360W15	3	50.5	34	190	24	102.3	494.0	2.5	1935.7	472.4	16.157%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G360W15	3	50.5	15	190	24	108	468.0	2.6	1935.7	423.9	16.157%
G360W15	3	50.5	15	190	40	100	505.4	4.0	1935.7	494.4	16.157%
G360W15	3	50.5	15	190	65	97	521.0	6.3	1935.7	525.5	16.157%
G360W15	3	50.5	15	380	24	110	459.5	2.6	1935.7	408.6	16.157%
G360W15	3	50.5	15	380	40	100	505.4	4.0	1935.7	494.4	16.157%
G360W15	3	50.5	15	380	65	94	537.7	6.1	1935.7	559.6	16.157%
G390W10	1	51.3	34	380	65	84.9	603.8	5.5	1934.3	705.1	13.290%
G390W10	1	51.3	34	380	40	91	563.3	3.6	1934.3	613.8	13.290%
G390W10	1	51.3	34	380	24	99	517.8	2.4	1934.3	518.6	13.290%
G390W10	1	51.3	15	190	24	108	474.6	2.6	1934.3	435.7	13.290%
G390W10	1	51.3	15	190	40	100	512.6	4.0	1934.3	508.3	13.290%
G390W10	1	51.3	15	190	65	95	539.6	6.2	1934.3	563.2	13.290%
G390W10	1	51.3	15	380	24	105	488.2	2.5	1934.3	461.0	13.290%
G390W10	1	51.3	15	380	40	98	523.1	3.9	1934.3	529.2	13.290%
G390W10	1	51.3	15	380	65	93	551.2	6.0	1934.3	587.7	13.290%
G390W5	1	51.2	34	190	65	91	562.5	5.9	1848.9	585.1	9.784%
G390W5	1	51.2	15	190	24	110	465.4	2.6	1848.9	400.4	9.784%
G390W5	1	51.2	15	190	40	103	497.0	4.1	1848.9	456.7	9.784%
G390W5	1	51.2	15	190	65	98	522.3	6.4	1848.9	504.5	9.784%
G390W5	1	51.2	34	190	24	103.8	493.2	2.5	1848.9	449.7	9.784%
G390W5	1	51.2	34	190	40	97	527.7	3.9	1848.9	514.9	9.784%
G390W10	2	51.0	34	380	65	91.4	558.3	5.9	1979.5	617.1	13.290%
G390W10	2	51.0	34	380	40	96.2	530.5	3.8	1979.5	557.0	13.290%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m^3)	G (MPa)	TOSW%
G390W10	2	51.0	34	380	24	103.5	493.0	2.5	1979.5	481.2	13.290%
G390W10	2	51.0	15	190	24	110	463.9	2.6	1979.5	426.0	13.290%
G390W10	2	51.0	15	190	40	100	510.3	4.0	1979.5	515.5	13.290%
G390W10	2	51.0	15	190	65	97	526.1	6.3	1979.5	547.9	13.290%
G390W10	2	51.0	15	380	24	108	472.5	2.6	1979.5	441.9	13.290%
G390W10	2	51.0	15	380	40	100	510.3	4.0	1979.5	515.5	13.290%
G390W10	2	51.0	15	380	65	95	537.2	6.2	1979.5	571.2	13.290%
G390W5	2	51.0	15	190	24	Unclear signal		0.0	1936.1	NA	9.784%
G390W5	2	51.0	15	190	24	Unclear signal		0.0	1936.1	NA	9.784%
G390W5	2	51.0	15	190	40	Unclear signal		0.0	1936.1	NA	9.784%
G390W5	2	51.0	34	190	65	Unclear signal		0.0	1936.1	NA	9.784%
G390W5	2	51.0	34	190	24	Unclear signal		0.0	1936.1	NA	9.784%
G390W5	2	51.0	34	190	40	Unclear signal		0.0	1936.1	NA	9.784%
G390W10	3	51.0	34	380	65	90.1	565.7	5.9	1925.9	616.3	13.290%
G390W10	3	51.0	15	190	24	109	467.6	2.6	1925.9	421.1	13.290%
G390W10	3	51.0	15	190	40	100	509.7	4.0	1925.9	500.3	13.290%
G390W10	3	51.0	15	190	65	96	530.9	6.2	1925.9	542.9	13.290%
G390W10	3	51.0	15	380	24	108	471.9	2.6	1925.9	429.0	13.290%
G390W10	3	51.0	15	380	40	100	509.7	4.0	1925.9	500.3	13.290%
G390W10	3	51.0	15	380	65	95	536.5	6.2	1925.9	554.4	13.290%
G390W10	3	51.0	34	380	24	104	490.1	2.5	1925.9	462.6	13.290%
G390W10	3	51.0	34	380	40	95.7	532.6	3.8	1925.9	546.3	13.290%
G390W5	3	50.9	34	190	24	102.2	497.6	2.5	1955.6	484.1	9.784%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G390W5	3	50.9	34	190	65	90.3	563.1	5.9	1955.6	620.1	9.784%
G390W5	3	50.9	34	190	40	94.9	535.8	3.8	1955.6	561.5	9.784%
G390W5	3	50.9	15	190	24	110	462.3	2.6	1955.6	417.9	9.784%
G390W5	3	50.9	15	190	40	103	493.7	4.1	1955.6	476.6	9.784%
G390W5	3	50.9	15	190	65	98	518.9	6.4	1955.6	526.5	9.784%
G390W15	1	51.4	34	380	65	88.3	582.4	5.7	1932.5	655.6	16.530%
G390W15	1	51.4	15	190	24	110	467.5	2.6	1932.5	422.4	16.530%
G390W15	1	51.4	15	190	40	103	499.3	4.1	1932.5	481.8	16.530%
G390W15	1	51.4	15	190	65	100	514.3	6.5	1932.5	511.1	16.530%
G390W15	1	51.4	15	380	24	110	467.5	2.6	1932.5	422.4	16.530%
G390W15	1	51.4	15	380	40	103	499.3	4.1	1932.5	481.8	16.530%
G390W15	1	51.4	15	380	65	100	514.3	6.5	1932.5	511.1	16.530%
G390W15	1	51.4	34	380	24	101	509.2	2.4	1932.5	501.1	16.530%
G390W15	1	51.4	34	380	40	93.1	552.4	3.7	1932.5	589.7	16.530%
G390W15	2	51.1	34	380	65	85.8	595.9	5.6	1842.9	654.4	16.530%
G390W15	2	51.1	34	380	24	98.5	519.1	2.4	1842.9	496.6	16.530%
G390W15	2	51.1	15	190	24	105	487.0	2.5	1842.9	437.0	16.530%
G390W15	2	51.1	15	190	40	100	511.3	4.0	1842.9	481.8	16.530%
G390W15	2	51.1	15	190	65	95	538.2	6.2	1842.9	533.8	16.530%
G390W15	2	51.1	15	380	24	105	487.0	2.5	1842.9	437.0	16.530%
G390W15	2	51.1	15	380	40	98	521.7	3.9	1842.9	501.6	16.530%
G390W15	2	51.1	15	380	65	93	549.8	6.0	1842.9	557.0	16.530%
G390W15	2	51.1	34	380	40	90.9	562.5	3.6	1842.9	583.1	16.530%

Table A.1 continued…

Mix Code	Sample	H (mm)	Age (days)	Load (kPa)	Freq (kHz)	Arrival Time (μs)	Vs (m/s)	L/λ	Density (kg/m³)	G (MPa)	TOSW%
G390W15	3	51.2	34	380	40	94.3	542.6	3.8	1919.6	565.2	16.530%
G390W15	3	51.2	34	380	65	90.3	566.7	5.9	1919.6	616.4	16.530%
G390W15	3	51.2	34	380	24	101.2	505.6	2.4	1919.6	490.8	16.530%
G390W15	3	51.2	15	190	24	104	492.0	2.5	1919.6	464.7	16.530%
G390W15	3	51.2	15	190	40	97	527.5	3.9	1919.6	534.2	16.530%
G390W15	3	51.2	15	190	65	92	556.2	6.0	1919.6	593.8	16.530%
G390W15	3	51.2	15	380	24	103	496.8	2.5	1919.6	473.8	16.530%
G390W15	3	51.2	15	380	40	95	538.6	3.8	1919.6	556.9	16.530%
G390W15	3	51.2	15	380	65	90	568.6	5.9	1919.6	620.5	16.530%

A. 6. Compression wave Velocity and Dynamic Poisson's Ratio Raw Data Measurements

Table A.2 Compression Wave and Dynamic Poisson's Ratio Raw Data Measurements

Mix Code	Sample	H mm	Arrival time (μs)	Vp (m/s)	Poisson's ratio
G160	1	51.0	36.3	1406	0.336
G190	1	51.3	31.9	1608	0.332
G260W10	1	51.3	32.5	1578	0.357
G260W15	1	51.4	34	1512	0.338
G290W10	1	51.2	32	1600	0.333
G290W15	1	51.1	31.7	1612	0.347
G360W5	1	51.1	64.9	787	0.253
G360W5	2	51.1	55.6	919	0.318
G360W5	3	51.2	56.1	913	0.325
G360W10	1	51.1	50.8	1006	0.301
G360W10	2	51.2	56	914	0.325
G360W10	3	51.3	55.6	923	0.253
G360W15	1	50.7	58.2	871	0.266
G360W15	2	50.1	56.8	882	0.239
G360W15	3	50.5	48.4	1043	0.287
G390W5	1	51.2	46.8	1094	0.320
G390W5	2	51	44	1159	0.331
G390W5	3	50.9	46	1107	0.325
G390W10	1	51.3	43.7	1174	0.320
G390W10	2	51	48	1063	0.309
G390W10	3	51	54.8	931	0.207
G390W15	1	51.4	46.8	1098	0.304
G390W15	2	51.1	44.3	1153	0.318
G390W15	3	51.2	45.2	1133	0.333

A. 7. Bleeding and Flowability data

Table A.3 Bleeding and Flowability Data

Mixture	Bleeding %	Flowability (mm)
G130	2.73%	205
G160	2.30%	192.5
G190	1.79%	190
G260W5	0.56%	180
G260W10	0.05%	175
G260W15	0.00%	180
G290W5	1.49%	250
G290W10	0.58%	200
G290W15	0.09%	180
G330W5	2.10%	205
G330W10	1.18%	185
G330W15	1.13%	180
G360W5	2.80%	240
G360W10	1.48%	250
G360W15	1.43%	220
G390W5	1.32%	226
G390W10	0.64%	215
G390W15	0.53%	200

A. 8. Unconfined Compressive Strength Raw Data

Table A.4 Unconfined Compressive Strength Raw Data

				Mix Proportions*				
Mix Code	**Age (days)**	**Sample**	**UCCS (kPa)**	**C%**	**FA %**	**TOSW%**	**AGG%**	**W%**
G130	28	1	580	1.4%	6.7%	0.0%	78.4%	13.5%
G130	28	2	587	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	7	1	347.0	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	7	2	364.8	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	14	2	480.4	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	14	1	499.8	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	28	2	599	1.4%	6.7%	0.0%	78.4%	13.5%
G130 - Mix 2	28	1	613	1.4%	6.7%	0.0%	78.4%	13.5%
G160	14	1	1245.5	2.7%	6.7%	0.0%	77.0%	13.5%
G160	28	2	1357	2.7%	6.7%	0.0%	77.0%	13.5%
G160	28	1	1515	2.7%	6.7%	0.0%	77.0%	13.5%
G160 - Mix 2	7	1	1125.4	2.7%	6.7%	0.0%	77.0%	13.5%
G160 - Mix 2	7	2	1236.6	2.7%	6.7%	0.0%	77.0%	13.5%
G190	7	1	2890.4	4.1%	6.8%	0.0%	75.6%	13.6%
G190	7	2	3024.8	4.1%	6.8%	0.0%	75.6%	13.6%
G190	14	1	3402.9	4.1%	6.8%	0.0%	75.6%	13.6%
G190	14	2	3812.1	4.1%	6.8%	0.0%	75.6%	13.6%
G190	28	1	4577	4.1%	6.8%	0.0%	75.6%	13.6%
G190	28	2	4964	4.1%	6.8%	0.0%	75.6%	13.6%
G260W10	7	1	1190.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W10	7	2	1278.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W10	14	2	2214.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W10	14	1	2454.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W10	28	1	2780.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W10	28	2	2900.0	2.8%	7.0%	7.9%	71.6%	10.6%
G260W15	7	1	1659.0	2.8%	7.0%	11.9%	67.8%	10.4%
G260W15	7	2	1700.0	2.8%	7.0%	11.9%	67.8%	10.4%
G260W15	14	1	2762.0	2.8%	7.0%	11.9%	67.8%	10.4%
G260W15	14	2	2799.0	2.8%	7.0%	11.9%	67.8%	10.4%
G260W15	28	1	3069.0	2.8%	7.0%	11.9%	67.8%	10.4%
G260W15	28	2	3275.0	2.8%	7.0%	11.9%	67.8%	10.4%

Table A.4 Continued…

Mix Code	Age (days)	Sample	UCCS (kPa)	Mix Proportions*				
				C%	FA %	TOSW%	AGG%	W%
G260W5	7	1	1299.0	2.8%	7.0%	4.0%	75.8%	10.4%
G260W5	7	2	1386.0	2.8%	7.0%	4.0%	75.8%	10.4%
G260W5	14	1	1734.0	2.8%	7.0%	4.0%	75.8%	10.4%
G260W5	14	2	1895.0	2.8%	7.0%	4.0%	75.8%	10.4%
G260W5	28	1	2894.0	2.8%	7.0%	4.0%	75.8%	10.4%
G290W10	7	2	2086.8	4.2%	6.9%	7.7%	69.7%	11.4%
G290W10	7	1	2190.5	4.2%	6.9%	7.7%	69.7%	11.4%
G290W10	14	2	3319.0	4.2%	6.9%	7.7%	69.7%	11.4%
G290W10	14	1	3750.0	4.2%	6.9%	7.7%	69.7%	11.4%
G290W10	28	1	3767	4.2%	6.9%	7.7%	69.7%	11.4%
G290W10	28	2	4795	4.2%	6.9%	7.7%	69.7%	11.4%
G290W15	7	1	2897.4	4.3%	7.0%	11.7%	66.5%	10.6%
G290W15	7	2	2923.0	4.3%	7.0%	11.7%	66.5%	10.6%
G290W15	14	1	4170.0	4.3%	7.0%	11.7%	66.5%	10.6%
G290W15	14	2	4333.0	4.3%	7.0%	11.7%	66.5%	10.6%
G290W15	28	1	6609	4.3%	7.0%	11.7%	66.5%	10.6%
G290W15	28	2	7087	4.3%	7.0%	11.7%	66.5%	10.6%
G290W5	7	2	1658.3	4.2%	6.8%	3.8%	72.7%	12.5%
G290W5	7	1	1735.9	4.2%	6.8%	3.8%	72.7%	12.5%
G290W5	14	2	1947.0	4.2%	6.8%	3.8%	72.7%	12.5%
G290W5	14	1	2023.0	4.2%	6.8%	3.8%	72.7%	12.5%
G290W5	28	1	4299	4.2%	6.8%	3.8%	72.7%	12.5%
G290W5	28	2	4428	4.2%	6.8%	3.8%	72.7%	12.5%
G330W10	7	1	109.1	1.5%	0.0%	13.6%	76.3%	8.7%
G330W10	14	2	121.6	1.5%	0.0%	13.6%	76.3%	8.7%
G330W10	14	1	145.7	1.5%	0.0%	13.6%	76.3%	8.7%
G330W10	28	2	157.0	1.5%	0.0%	13.6%	76.3%	8.7%
G330W10	28	1	158.0	1.5%	0.0%	13.6%	76.3%	8.7%
G330W15	7	1	123.1	1.5%	0.0%	17.4%	72.9%	8.2%
G330W15	7	2	125.5	1.5%	0.0%	17.4%	72.9%	8.2%
G330W15	14	2	140.0	1.5%	0.0%	17.4%	72.9%	8.2%
G330W15	14	1	190.9	1.5%	0.0%	17.4%	72.9%	8.2%
G330W15	28	1	183.0	1.5%	0.0%	17.4%	72.9%	8.2%
G330W15	28	2	185.0	1.5%	0.0%	17.4%	72.9%	8.2%

Table A.4 Continued...

Mix Code	Age (days)	Sample	UCCS (kPa)	Mix Proportions* C%	FA %	TOSW%	AGG%	W%
G330W5	7	2	72.2	1.4%	0.0%	9.8%	78.7%	10.0%
G330W5	7	1	94.5	1.4%	0.0%	9.8%	78.7%	10.0%
G330W5	14	1	43.7	1.4%	0.0%	9.8%	78.7%	10.0%
G330W5	14	2	50.3	1.4%	0.0%	9.8%	78.7%	10.0%
G330W5	28	2	56.0	1.4%	0.0%	9.8%	78.7%	10.0%
G330W5	28	1	88.0	1.4%	0.0%	9.8%	78.7%	10.0%
G360W10	7	2	260.3	2.9%	0.0%	13.2%	73.0%	10.9%
G360W10	7	1	286.5	2.9%	0.0%	13.2%	73.0%	10.9%
G360W10	14	1	325.9	2.9%	0.0%	13.2%	73.0%	10.9%
G360W10	14	2	354.3	2.9%	0.0%	13.2%	73.0%	10.9%
G360W10	28	2	337.0	2.9%	0.0%	13.2%	73.0%	10.9%
G360W10	28	1	403.0	2.9%	0.0%	13.2%	73.0%	10.9%
G360W15	7	1	309.5	2.9%	0.0%	16.5%	69.4%	11.2%
G360W15	7	2	366.6	2.9%	0.0%	16.5%	69.4%	11.2%
G360W15	14	1	397.6	2.9%	0.0%	16.5%	69.4%	11.2%
G360W15	28	2	414.0	2.9%	0.0%	16.5%	69.4%	11.2%
G360W15	28	1	431.0	2.9%	0.0%	16.5%	69.4%	11.2%
G360W5	7	1	305.8	2.8%	0.0%	9.7%	75.9%	11.6%
G360W5	7	2	323.9	2.8%	0.0%	9.7%	75.9%	11.6%
G360W5	14	1	342.3	2.8%	0.0%	9.7%	75.9%	11.6%
G360W5	14	2	363.9	2.8%	0.0%	9.7%	75.9%	11.6%
G360W5	28	1	279.0	2.8%	0.0%	9.7%	75.9%	11.6%
G360W5	28	2	316.0	2.8%	0.0%	9.7%	75.9%	11.6%
G390W10	7	1	752.1	4.4%	0.0%	13.3%	72.1%	10.3%
G390W10	7	2	762.2	4.4%	0.0%	13.3%	72.1%	10.3%
G390W10	14	2	789.5	4.4%	0.0%	13.3%	72.1%	10.3%
G390W10	14	1	793.9	4.4%	0.0%	13.3%	72.1%	10.3%
G390W10	28	1	1029.0	4.4%	0.0%	13.3%	72.1%	10.3%
G390W10	28	2	1056.0	4.4%	0.0%	13.3%	72.1%	10.3%
G390W15	7	1	862.8	4.4%	0.0%	16.6%	68.6%	10.4%
G390W15	14	1	966.7	4.4%	0.0%	16.6%	68.6%	10.4%
G390W15	28	1	1148.5	4.4%	0.0%	16.6%	68.6%	10.4%
G390W15	28	2	1318.0	4.4%	0.0%	16.6%	68.6%	10.4%
G390W5	7	2	621.1	4.3%	0.0%	9.8%	75.2%	10.7%
G390W5	7	1	657.0	4.3%	0.0%	9.8%	75.2%	10.7%

Table A.4 Continued…

Mix Code	Age (days)	Sample	UCCS (kPa)	Mix Proportions* C%	FA %	TOSW%	AGG%	W%
G390W5	14	1	787.3	4.3%	0.0%	9.8%	75.2%	10.7%
G390W5	14	2	903.3	4.3%	0.0%	9.8%	75.2%	10.7%
G390W5	28	1	972.0	4.3%	0.0%	9.8%	75.2%	10.7%

* C%, FA%, TOSW%, AGG% and W% are percentage of cement, fly ash, treated oil sand waste, aggregate, and water by weight consecutively

APPENDIX B

TOSW MONO-AROMATIC HYDROCARBON ANALYSIS REPORT

The analysis shown in this report were done by Newalta Corporation.

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Page 1 of 3

Exova

Analytical Report

Bill To: Newalta Corporation
Report To: Newalta Corporation
Box 6180
Drayton Valley, AB, Canada
T7A 1R7
Attn: Travis Moody
Sampled By: Jeff
Company: Newalta

Project:
ID: TCC
Name: Proof of Performance
Location: Drayton Valley
LSD:
P.O.: 4500594122
Acct code:

Lot ID: **988554**
Control Number:
Date Received: Feb 26, 2014
Date Reported: Feb 28, 2014
Report Number: 1898503

Reference Number	988554-1
Sample Date	February 25, 2014
Sample Time	NA
Sample Location	
Sample Description	Discharge
Sample Matrix	Waste - industrial

Analyte	Units	Result	Nominal Detection Limit	Guideline Limit	Guideline Comments
Physical and Aggregate Properties					
Wet Bulk Density	kg/m^3	885			
Mono-Aromatic Hydrocarbons - Leachate					
Benzene	mg/L	<0.01	0.01	0.5	Below Limit
Toluene	mg/L	<0.01	0.01	0.5	Below Limit
Ethylbenzene	mg/L	<0.01	0.01	0.5	Below Limit
Total Xylenes (m,p,o)	mg/L	<0.03	0.03	0.5	Below Limit

Appendix B

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Quality Control

Bill To:	Newalta Corporation	Project:		Lot ID:	988554
Report To:	Newalta Corporation	ID:	TCC	Control Number:	
	Box 6180	Name:	Proof of Performance	Date Received:	Feb 26, 2014
	Drayton Valley, AB, Canada	Location:	Drayton Valley	Date Reported:	Feb 28, 2014
	T7A 1R7	LSD:		Report Number:	1898503
Attn:	Travis Moody	P.O.:	4500594122		
Sampled By:	Jeff	Acct code:			
Company:	Newalta				

Physical and Aggregate Properties

Control Sample	Units	Measured	Lower Limit	Upper Limit	Passed QC
Wet Bulk Density	kg/m³	1000	997	1003	yes
Date Acquired:	February 28, 2014				
Wet Bulk Density	kg/m³	2030	1667	2267	yes
Date Acquired:	February 28, 2014				

Mono-Aromatic Hydrocarbons - Leachate

Blanks	Units	Measured	Lower Limit	Upper Limit	Passed QC
Benzene	ug/L	0	-9.99	9.99	yes
Toluene	ug/L	0	-9.99	9.99	yes
Ethylbenzene	ug/L	0	-9.99	9.99	yes
m,p-Xylene	ug/L	0	-19.98	19.98	yes
o-Xylene	ug/L	0	-9.99	9.99	yes
Date Acquired:	February 27, 2014				
Benzene	ug/L	0	-9.99	9.99	yes
Toluene	ug/L	0	-9.99	9.99	yes
Ethylbenzene	ug/L	0	-9.99	9.99	yes
m,p-Xylene	ug/L	0	-19.98	19.98	yes
o-Xylene	ug/L	0	-9.99	9.99	yes
Date Acquired:	February 27, 2014				

Calibration Check	Units	% Recovery	Lower Limit	Upper Limit	Passed QC
Benzene	ug/L	86.00	80	110	yes
Toluene	ug/L	87.00	85	115	yes
Ethylbenzene	ug/L	86.00	85	115	yes
m,p-Xylene	ug/L	92.00	85	115	yes
o-Xylene	ug/L	90.00	85	115	yes
Date Acquired:	February 27, 2014				

Client Sample Replicates	Units	Replicate 1	Replicate 2	% RSD Criteria	Absolute Criteria	Passed QC
Benzene	mg/L	<0.01	<0.01	20	0.03	yes
Toluene	mg/L	<0.01	<0.01	20	0.03	yes
Ethylbenzene	mg/L	<0.01	<0.01	20	0.03	yes
m,p-Xylene	mg/L	<0.01	<0.01	20	0.04	yes
o-Xylene	mg/L	<0.01	<0.01	20	0.03	yes
Date Acquired:	February 27, 2014					

Matrix Spike	Units	% Recovery	Lower Limit	Upper Limit	Passed QC
Benzene	mg/L	101	80	120	yes
Toluene	mg/L	103	80	120	yes
Ethylbenzene	mg/L	101	80	120	yes
m,p-Xylene	mg/L	107	80	120	yes
o-Xylene	mg/L	106	80	120	yes
Date Acquired:	February 27, 2014				

Appendix B

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Methodology and Notes

Bill To:	Newalta Corporation	Project:		Lot ID:	**988554**
Report To:	Newalta Corporation	ID:	TCC	Control Number:	
	Box 6180	Name:	Proof of Performance	Date Received:	Feb 26, 2014
	Drayton Valley, AB, Canada	Location:	Drayton Valley	Date Reported:	Feb 28, 2014
	T7A 1R7	LSD:		Report Number:	1898503
Attn:	Travis Moody	P.O.:	4500594122		
Sampled By:	Jeff	Acct code:			
Company:	Newalta				

Method of Analysis

Method Name	Reference	Method	Date Analysis Started	Location
Leachate Organic (TCLP-BTEX) DV	US EPA	* Toxicity Characteristic Leaching Procedure, SW-846, EPA 1311	27-Feb-14	Exova Drayton Valley

** Reference Method Modified*

Guidelines

Guideline Description	Class 2 Landfill (AB)
Guideline Source	AENV Waste Control Regulation, Alberta Regulation 192/96
Guideline Comments	Limits for analytes that may be required for Class 2 Landfill Acceptance may not be presented in this report. Consult the AENV Waste Control Regulation for hazardous waste limits, and ERCB D058 for dangerous oilfield waste properties.

Comments:

- Report was issued to include addition of Wet Bulk Density analysis on as requested by Bill Swartz of Newalta on February 28, 2014. Previous report 1898099

The comparison of test results to guideline limits is provided for information purposes only. This is not to be taken as a statement of conformance / nonconformance to any guideline, regulation or limit. The data user is responsible for all conclusions drawn with respect to the data and is advised to consult official regulatory references when evaluating compliance.

Please direct any inquiries regarding this report to our Client Services group.
Results relate only to samples as submitted.
The test report shall not be reproduced except in full, without the written approval of the laboratory.

Curriculum Vitae

Name:	**Ahmed Mneina**
Post-secondary Education and Degrees:	University of Benghazi Benghazi, Libya 2003-2008 B.Sc (Civil Engineering).
Related Work Experience	Teaching Assistant The University of Western Ontario 2014-2016

Publications:

Mneina, A., Soliman, A., Ahmed, A., & El Naggar, M. H. (2016). Green controlled low-strength material. *Proc. of the 69th Canadian Geotechnical Conference (GeoVancouver 2016).* Vancouver, Canada.

Other Related Experience:

- *June 2013 to August 2014*, **Albonyan Almarsos Engineering Design and Consultancy,** Benghazi, Libya. Position: Design Director.
  Responsivities:
    - Coordinate between the different engineering department (Architectural, Structural, Mechanical and Electrical) managing about 25 engineers and leading weekly meeting and monitoring the progress of 20 running design projects ranging from residential, commercial and industrial projects.
    - Attending weekly and monthly meetings with general manager and consultant projects mangers.
    - Providing engineering support for current consultant projects in the field.
    - Preparing monthly reports for design projects.
    - Meeting customers and signing design projects contracts.

- *December 2011 to August 2014,* **University of Benghazi**, Benghazi Libya. I work as a teaching assistant at the civil engineering department teaching soil mechanics and foundation engineering. The responsibilities included giving tutorials, seminars and lecturing for about 60 students each term.

- *February 2009 to March 2011*, -**Assarh Engineering Consultancy co**, Benghazi, Libya. Position: Supervising engineer for the project of "Development and maintenance of the Libyan national TV and Radio broadcasting center". Working with a team of professional engineers and university professors. The responsibilities included supervising civil and construction works and preparing daily and monthly report to the owner.

- *February 2008 to February 2009,* **Middle East Consultant Engineering Office,** Benghazi, Libya. Position: consultant site engineer for the service and residential buildings of "5000 housing units" project in Bufakhra. Libya.

- *September 2007 – February 2008*, **Faculty of engineering, Garyounis University**, Benghazi, Libya. Under Graduate Project Work: working on a full structural design of the "national oil corporation" building.

- *July 2007 - August 2007*, **RWE.dea North Africa**, Raslanuf Desert, undergraduate intern. Worked with civil works team preparing a plat form for oil excavation rig, the work included ground grading, compaction and leveling to support the load of excavation rig and reduce settlement, supervision on field service roads maintenance and construction.

- *July 2006 – August 2006,* **RWE.dea North Africa,** Al-mabrouk oil field + Marada oil field, undergraduate intern. Worked with team of experts from different countries in a civil works team responsible of:

  - Preparing roads for supply trucks and machines for the oil fields using raw materials from the site where we had to select the best subgrades soil from available resources.
  - Digging and preparing water reservoirs from site materials using geomembrane system to preserve water.
  - Preparing platforms for excavation rigs.